Nuclear Structure '06

CONFERENCE ON NUCLEI AT THE LIMITS

NS06

July 24 -28, 2006
Oak Ridge, Tennessee

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Rotating $N \approx Z$ nuclei: a search for isovector and isoscalar neutron-proton pairing condensates.

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Cranked Relativistic Mean field (CRMF), Cranked Relativistic Hartree Bogoliubov (CRHB) and cranked Nilsson-Strutinsky (CNS) approaches have been applied for a systematic search of the fingerprints of neutron-proton (np) pairing in rotating $N \approx Z$ nuclei [1]. This search has been performed in the framework of the isovector mean-field theory [2] that assumes no isoscalar $t = 0$ np-pairing. Because of the spontaneous breaking of the isospin symmetry by the isovector pair field, the np component of isovector pair field needs not to be taken into account explicitly: it is included implicitly when the isospin symmetry is restored by adding the isorotational energy $T(T+1)/2J_{iso}$ to the intrinsic energy [2].

The systematic analysis of the rotational response of $N \approx Z$ nuclei performed in [1] (the $A = 68 - 80$ mass region) and in earlier studies [3,4] (nuclei around ^{60}Zn) agrees with the picture suggested in the isovector mean field theory [2]. According to it, at low spin, isoscalar np pair field is absent while a strong isovector pair field exists, which includes a large np component, whose strength is determined by isospin conservation. Like in nuclei away from the $N = Z$ line, this isovector pair field is destroyed by rotation. Indeed, the experimental data (moments of inertia, band crossing frequencies etc) at low and medium spins are well accounted for in the CRHB calculations. In the high spin regime above the paired band crossings, the calculations without pairing (CRMF and CNS) describe accurately the data provided that the drastic shape changes causing among other things band termination are taken into account.

These results strongly suggest that the basic assumption of isovector mean field theory about the absence of isoscalar np-pairing is reasonably well justified. Additional support for this conclusion comes from the results of the calculations within the TRS approach and projected shell model which also provide good agreement with experiment for rotational properties at the $N = Z$ line (see references in [1]). Isovector mean field theory [2] provides natural framework for an understanding why these models without explicit np-pairing work so well along the $N = Z$ line. However, in the light of the limitations of existing theoretical tools, we cannot completely exclude the possibility that the rotational properties of finite nuclei are not very sensitive to the $t = 0$ np-pairing and thus the possibility of the existence of np-pairing condensate in the $t = 0$ channel.

In particular, a deeper understanding of the correlations between time-odd mean fields and isoscalar np-pairing is needed as follows from recent Skyrme Hartree-Fock studies of band crossing in superdeformed (SD) band of ^{60}Zn [5] and band terminations in the $A \sim 40 - 50$ nuclei [6,7]. Our CRMF and CRHB investigations of ^{60}Zn do not indicate that time-odd mean fields play a defining role in the band crossing seen in the yrast SD band [4,8]. The systematic study of the role of time-odd mean fields in the CRMF/CRHB approaches and their influence on the band terminations in the $A \sim 40 - 50$ nuclei, as well as their correlations with the $t = 0$ np-pairing is in progress and obtained results will be presented.

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Dynamical aspects of chiral rotation *

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Several near degenerate $\Delta I = 1$ bands with the same parity have been found in the $A = 130$ and $A = 105$ regions where triaxiality of the nuclear shape appears. Some of these have been interpreted as chiral rotational bands within the Tilted Axis Cranking (TAC) model [1]. Chiral rotation can appear in triaxial nuclei when proton and neutrons align along different principal axes and the collective rotation occurs along the third. These configurations break the chiral symmetry and that leads in the case of strong symmetry breaking to doublets of degenerate $\Delta I = 1$ bands with the same parity. Most candidates for chiral partner bands never become completely degenerate in experiment; instead they show a slowly decreasing or nearly constant energy splitting of a couple of 100 keV, or the two partner bands cross each other. This observation has been interpreted as appearance of a chiral vibration, which is a vibration of the orientation of the principal axes of the of the nucleus with respect to the angular momentum vector [2]. The chiral symmetry is not statically broken. The nucleus makes only slow excursions into the left- and right- handed configurations. The two partner bands are the zero and one phonon states of the soft chiral vibration. In the case of ^{134}Pr, the experimental intra band transition probabilities differ between the partner bands [3].

The TAC calculations of chiral bands generally give potential energy surfaces that are soft in both the orientation degrees of freedom and the γ deformation degree of freedom. This suggests that these collective vibrational excitations are in fact made up of a pure chiral vibration coupled with γ-vibration. To investigate the structure of these vibrations we performed RPA and 3D-TAC mean field calculations. This allows us studying the coupling of shape, orientation and quasi particle degrees of freedom. We will discuss how the different degrees of freedom contribute to the collective vibration. We will present the energy systematics of the of the RPA solutions and the transition rates and compare these with experimental data.

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* This work was supported by the U. S. Department of Energy Grant No. DE-FG02-95ER40934 and ANL-UND Nuclear Theory Institute

Mirror Symmetry in the Upper fp Shell

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Isospin symmetry may be examined by means of γ-ray spectroscopic studies of mirror nuclei. The current work is based on a fusion-evaporation experiment performed at the Oak-Ridge National Laboratory. In the reaction, involving ^{40}Ca at 104 MeV beam energy and a ^{24}Mg target foil, two mirror nuclei were produced: $^{61}_{31}\mathrm{Ga}_{30}$ and $^{61}_{30}\mathrm{Zn}_{31}$. The experimental set-up comprised the Ge-array CLARION, the Recoil Mass Spectrometer (RMS) and, in its focal plane, an ionisation chamber. The set-up allowed γ rays detected in CLARION to be measured in coincidence with recoils observed in the focal plane at the end of the RMS. This provides the possibility of recoil-γ identification of transitions and recoil-$\gamma\gamma$ coincidence analysis. Five excited states have been observed for the first time in the neutron-deficient ^{61}Ga isotope, and three of these were found to form a cascade [1]. Moreover, there is indirect evidence for prompt proton-decaying excited states. The decay scheme of ^{61}Zn has been considerably extended and consolidated. Experimental results are compared to predictions from different sets of large scale shell-model calculations and isospin symmetry in the upper fp shell is to be discussed.

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Structure study of the nuclei in and near the island of inversion at RIPS

AOI, Nori
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Disappearance of the *N=20* shell closure in the so-called island of inversion region has been intensively studied both experimentally and theoretically since this phenomenon was first suggested in the systematic studies of the masses and 2^+ energies [1,2]. Among them, direct reaction studies by measuring de-excitation γ-rays have provided fruitful information as one of the most efficient and clear methods to study the structure of unstable nuclei with fast RI beams. This technique was first applied to ^{32}Mg Coulomb excitation [3] to study the sudden enhancement of the collectivity in ^{32}Mg in spite of its neutron magic number *N=20*. Since then, a variety of structure studies have been performed to clarify the mechanism of the disappearance of the magicity through various direct reactions. In this paper, recent works of the γ-ray spectroscopy studies on neutron rich Ne, Na, Mg nuclei in and near the island of inversion region performed at RIPS, RIKEN will be presented.

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The ^{25}Al(p,γ)^{26}Si Reaction Rate in Novae*

D.W. Bardayan [1], J.A. Howard [2], J.C. Blackmon [1], C.R. Brune [3], K.Y. Chae [4], W.R. Hix [1], M.S. Johnson [5], K.L. Jones [6], R.L. Kozub [2], J.F. Liang [1], E.J. Lingerfelt [1,4], R.J. Livesay [7], S.D. Pain [6], J.P. Scott [1,4], M.S. Smith [1], J.S. Thomas [6], and D.W. Visser [8]

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The production of ^{26}Al in novae is uncertain, in part, because of the uncertain rate of the ^{25}Al(p,γ)^{26}Si reaction at novae temperatures. This reaction is thought to be dominated by a long-sought 3^+ level in ^{26}Si, and the calculated reaction rate varied by orders of magnitude depending on the energy of this resonance. We present new evidence concerning the spin of a level at 5.914 MeV in ^{26}Si from the ^{28}Si(p,t)^{26}Si reaction studied at the Holifield Radioactive Beam Facility at ORNL [1]. In Fig. 1, we show the angular distribution for populating this level in ^{26}Si. We find that the angular distribution for this level implies either a 2^+ or 3^+ assignment, with only a 3^+ being consistent with the mirror nucleus, ^{26}Mg. We have used the updated ^{25}Al(p,γ)^{26}Si reaction rate in a nova nucleosynthesis calculation and have addressed the effects of the remaining uncertainties in the rate on ^{26}Al production. The measurement and calculations will be presented.

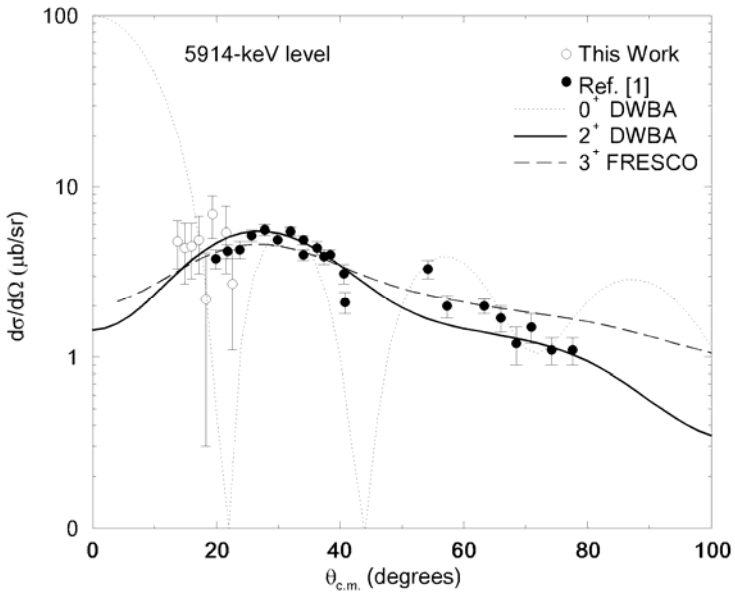

FIG. 1. The angular distribution from this work and Ref. [1] are shown as open and filled circles, respectively. We find that the angular distribution produced for the 5914-keV level is consistent with either a 2^+ or 3^+ assignment.

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*Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

New Isomeric States in ^{116}Ag and Levels in ^{116}Cd Studied via the Beta decay of ^{116}Ag*

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We have re-investigated the beta decay of ^{116}Ag at the Holifield Radioactive Ion Beam Facility (HRIBF). We produced ^{116}Ag via the proton-induced fission of Uranium at the UNISOR On-Line Test Facility (OLTF). A UC_x target, installed at the OLTF, was bombarded with a 25nA beam of 40 MeV protons. The fission products were then separated by mass at the OLTF and deposited on a moving tape collector (MTC) and subsequently moved to the counting position located at the center of an array that has been named CARDS (Clover Array for Radioactive Decay Spectroscopy) and which, for this experiment, consisted of three segmented clover Ge detectors, plastic scintillators for betas , and a high resolution Si(Li) conversion electron spectrometer.

We have observed a third isomer in ^{116}Ag. The three isomers (ground state, 47.9 keV, and 127.8 keV) were reported to have half-lives of 230(5), 20(1), and 9.8(1) s respectively. The half-lives for the two short-lived isomers were determined from the conversion electron half-lives of the 47.9 and 128.8 keV isomers [1], and the half-life of the ground state was determined from the half-life of the 513.5-keV γ-ray (2_1^+ - 0^+). Through the use of conversion electron spectroscopy, we observed that both of the meta-stable states decayed via E3 transitions. By comparing the levels populated following the beta decay of these three isomers to known levels in ^{116}Cd revealed that the decay of ^{116m1,m2,gs}Ag populated only those levels with spins less than or equal to seven. We therefore conclude that the ground state must be 0^- rather than the previously assigned 2^- [2]. This results in the three levels in ^{116}Ag having J^π and energies of 0^- (g.s.), 3^+ (47.9 keV), and 6^- (127.8 keV).

An inconsistency with the published [3, 4] data has been the non-zero beta feeding strength for the decay of ^{116}Ag to low-lying levels with spins of 2 and 3 (1951.4 keV; 2^+, 1921.7; 3^-, 1916.0; 3^+), which is not consistent with the decay of a 5^+ isomer of ^{116}Ag. Our results indicate that the feeding of these levels arises from a 3^+ isomer in ^{116}Ag. As such the beta strength feeding these levels is perfectly consistent with allowed beta transitions from the 3^+ ^{116m1}Ag isomer.

This work has greatly expanded the beta decay scheme of all three isomers of ^{116}Ag with over 80 new levels assigned in ^{116}Cd. In addition, J^π values have been assigned for many of these and previously known levels through the measurement of conversion coefficients. A discussion of the beta strengths of the three isomers as well as the levels in Cd will be presented.

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* This work has been supported by the U. S. Department of Energy under contracts DE-AC05-06OR23100 (UNIRIB), DOE-AC05-00OR22725 (ORNL), DE-FG05-88ER40330 (JIHIR), DE-FG02-96ER40958 (Georgia Institute of Technology), DE-FG02-96ER41006 (Mississippi State University), DE-FG05-88ER40407 (Vanderbilt University), DE-FG02-96ER40983 (University of Tennessee), DE-FG02-96ER40978 (Louisiana State University), and W-7405-ENG-48 (LLNL).

Near-barrier fusion and breakup of weakly bound and exotic halo nuclei

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In reactions with weakly bound nuclei, the influence on the fusion process of coupling both to collective degrees of freedom and to break-up/transfer channels is a key point for the understanding of N-body systems in quantum dynamics [1,2]. Due to the very weak binding energies of halo nuclei, such as ^{6}He, a diffuse cloud of neutrons of halo nuclei would lead higher fusion cross sections at sub-barrier energies as compared to predictions of one-dimensional barrier penetration model [1]. This was understood in terms of the dynamical processes arising from strong couplings to collective inelastic excitations of the target and projectile [3]. However, in the case of reactions where at least one of the colliding nuclei has a sufficiently low binding energy for breakup to become a competitive process, conflicting model predictions and experimental results were reported [1,2,4]. Recent experimental results with ^{6,8}He beams show that the halo of ^{6}He does not enhance the fusion probability, confirming the prominent role of one- and two-neutron transfers in ^{6}He induced fusion reactions [1,2]. The effect of non-conventional transfer/stripping processes appears to be less significant for stable weakly bound projectiles [4].

Several experiments involving tightly bound projectiles such as ^{9}Be, ^{7}Li, and ^{6}Li projectiles on targets ranging from ^{12}C to ^{209}Bi have been investigated [2]. In this talk, excitation functions for sub- and near-barrier total (complete + incomplete) fusion cross sections measured using γ-ray techniques for the ^{6,7}Li+^{59}Co reactions [3,4] are presented. The comparison with Continuum-Discretized Coupled-Channel (CDCC) calculations [5] indicates only a small enhancement of total fusion for the more weakly bound ^{6}Li below the Coulomb barrier, with similar cross sections for both reactions at and above the barrier. This result is consistent with rather low breakup cross sections measured for the ^{6}Li+^{59}Co reaction even at incident energies larger than the Coulomb barrier [4].

The investigation of the breakup process in the ^{6,7}Li + ^{59}Co,^{115}In reactions with particle techniques is also presented to discuss the interplay of fusion and breakup processes including the role of elastic scattering [4]. Coincidence data compared to three-body kinematics calculations reveal a way how to disentangle the contributions of breakup, incomplete fusion and/or transfer-reemission process.

As far as exotic halo projectiles are concerned we have initiated a systematic study of ^{4,6}He induced fusion reactions [4] with an improved three-body CDCC method [5] using a dineutron model for ^{6}He (α-^{2}n). Some of the preliminary results will be presented. However a full understanding of the reaction dynamics involving couplings to the breakup and neutron-transfer channels will need high-intensity radioactive ion beams and precise measurements of elastic scattering and yields leading to the breakup itself. The application of four-body (required for an accurate α-n-n description of ^{6}He) CDCC models under current development [6,7] will then be highly desirable.

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Measuring the Un-measurable – Surrogate Reactions using STARS+LIBERACE*

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Neutron-induced reaction cross sections on unstable nuclei play an important role in both applied nuclear science and models of astrophysical nucleosynthesis, including most notably the slow neutron capture process. However, many of these cross sections are impossible to measure directly due to the short life of the target nucleus and the inability to make intense mono-energetic neutron beams. The LLNL group has been leading an effort to deduce these cross sections using an approach referred to as the "surrogate" technique [1-4]. These measurements involve determining the probability that a composite nucleus populated in a "surrogate" direct reaction will decay into a specific exit channel where the composite nucleus is the same as in the neutron-induced reaction of interest.

In this talk we will present an overview of recent experimental work using the STARS (Silicon Telescope Array for Reaction Studies) spectrometer coupled to LiBerACE (Livermore Berkeley Array for Collaborative Experiments) at the LBNL 88-Inch cyclotron to determine the validity of various surrogate reaction techniques. Results from recent experiments determining the destruction of short lived ^{237}U ($t_{1/2}$=6.25 days) via (n,f), (n,γ) and (n,2n) reactions for applied science (see figures 1 and 2 below) and the (n,γ) cross sections on Ruthenium and Gadolinium s-process branch point nuclei for stellar nucleosynthesis models will be presented and compared to theoretical predictions. The role of nuclear structure and its impact on the surrogate technique will be discussed.

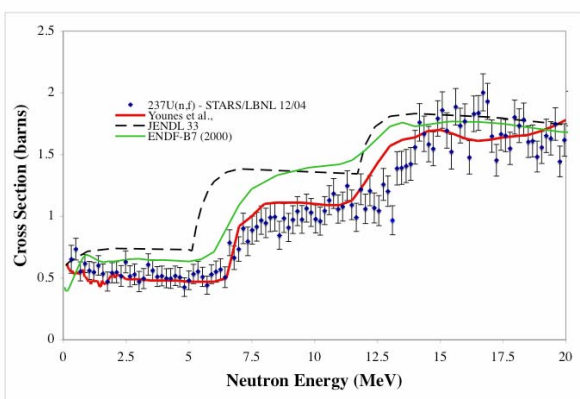

FIG. 1. ^{237}U(n,f) (left) from [2] deduced using the Surrogate Ratio technique and the known ^{235}U(n,f) cross section.

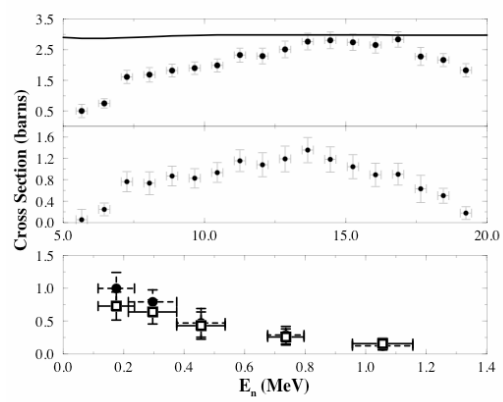

FIG. 2. ^{237}U(n,γ) (bottom), ^{237}U(n,2n) (middle) deduced using surrogate reaction techniques and the sum of ^{237}U(n,f) and ^{237}U(n,2n) (top) from surrogate measurements compared to total compound cross section from optical model calculations of the [5].

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* This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48 and Lawrence Berkeley National Laboratory under contract No. DE-AC03-76SF0098. This work was also supported by the U.S. Department of Energy and the University of Richmond and Yale University under grant numbers DE-FG-05NA-25929, DE-FG02-05ER-41379 and DE-FG02-91ER-40609.

Density Functional Theory for Fermions close to the Unitary Regime *

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We consider interacting Fermi systems close to the unitary regime and compute the corrections to the energy density that are due to a large scattering length and a small effective range. Our approach exploits the universality of the density functional and determines the corrections from the analyical results for the harmonically trapped two-body system. The corrections due to the finite scattering length compare well with the result of Monte Carlo simulations. We also apply our results to symmetric neutron matter.
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*This work was supported in part by the U. S. Department of Energy under contracts DE-FG02-96ER40963 (University of Tennessee) and DE-AC05-00OR22725 with UT-Battelle, LLC (Oak Ridge National Laboratory).

Density Functional Theory from Effective Field Theory and the Renormalization Group*

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The combination of progress in chiral effective field theory (EFT) for inter-nucleon interactions, the application of renormalization group (RG) techniques to nuclear systems, and advances in many-body computational tools and methods opens the possibility of *constructive* density functional theory (DFT) for nuclei. Effective actions provide a natural framework for the development of EFT/DFT. One approach uses EFT power counting to define an order-by-order inversion of the generating functional in the presence of a source coupled to the density. This leads directly to Kohn-Sham DFT, which is widely used in condensed matter and quantum chemistry applications. Natural extensions lead to functionals of more general densities and the incorporation of pairing, consistent with phenomenological energy functionals for nuclei, which are themselves consistent with chiral EFT power counting [1,2].

Chiral EFT offers a model-independent starting point based on the symmetries of quantum chromodynamics, including a systematic approach to many-nucleon forces [3,4]. The chiral inter-nucleon interactions are constructed with cutoffs in relative momentum considerably lower than those in conventional potentials, but this does not always result in softer interactions [5]. However, the nonperturbative nature of inter-nucleon interactions is strongly scale or resolution dependent, and can be radically modified by using the renormalization group to lower the momentum cutoff of the two-nucleon potential. If RG techniques are used to lower the chiral EFT cutoff further while preserving observables [6], Hartree-Fock plus partial second-order contributions (with consistent three-body forces included) is found to be a good, possibly perturbative, first approximation for nuclear matter [7]. The dominance of Hartree-Fock, in common with Coulomb DFT, raises hope for a quantitative microscopic construction. There are significant challenges to realizing this goal, both conceptual and technical, such as arise in extending DFT to self-bound systems [1]. But the path is reasonably clear and meshes well with on-going efforts to develop, refine, and test phenomenological energy functionals for application across the mass table.

In the short term, the density matrix expansion (DME) [8] is a natural tool for the microscopic construction of a universal energy functional for nuclei using the low-momentum potentials ("$V_{\mathrm{low}\,k}$"). The DME includes an expansion and resummation designed to preserve the correct long-distance behavior of pion exchange in uniform nuclear matter. For use with $V_{\mathrm{low}\,k}$, the DME is adapted for a momentum-space two-body potential (see Ref. [9] for a direct application to chiral EFT) and extended to accomodate three-body forces. Insight into the nature of the isovector part of the functional, the impact of two- and three-nucleon forces on spin-orbit splittings, the role of tensor interactions, and more can be directly explored. By varying the cutoff, the resolution dependence of the energy functional can also be studied.

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*This work was supported by the National Science Foundation under Grant No. PHY–0354916.

Convergence of the Born Series with Low-Momentum Interactions *

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The nonperturbative nature of nucleon-nucleon interactions as a function of a momentum cutoff is studied using Weinberg eigenvalues as a diagnostic. This investigation extends an earlier study [1] of the perturbative convergence of the Born series to partial waves beyond the $^3S_1$–$^3D_1$ channel and to positive energies. As the cutoff is lowered using renormalization-group or model-space techniques, the evolution of nonperturbative features at large cutoffs from strong short-range repulsion and the iterated tensor interaction are monitored via the complex Weinberg eigenvalues. When all eigenvalues lie within the unit circle, the expansion of the scattering amplitude in terms of the interaction is perturbative, with the magnitude of the largest eigenvalue setting the rate of convergence [2].

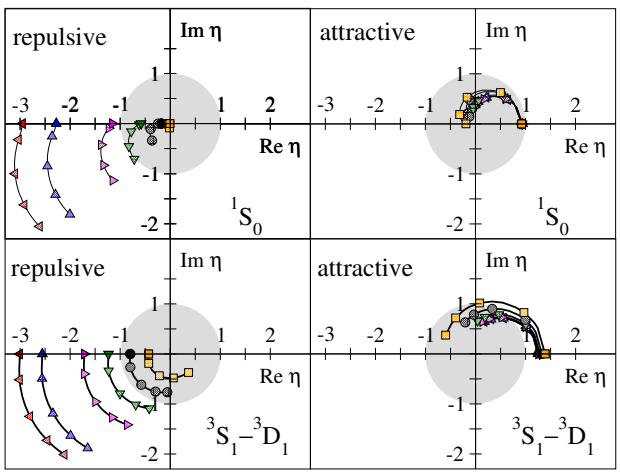

FIG. 1. Weinberg eigenvalues for the $^1S_0$ and coupled $^3S_1$–$^3D_1$ channels for the Argonne v_{18} potential as a function of the cut-off Λ for energies $E_{\rm lab} = 0$–$350\,$MeV.

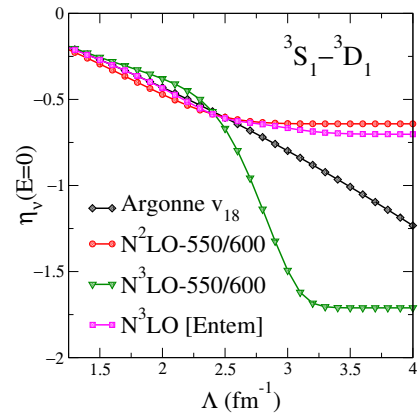

FIG. 2. Largest repulsive Weinberg eigenvalues for the coupled $^3S_1$–$^3D_1$ channel for several chiral EFT potentials at zero energy as a function of the cut-off Λ.

Major decreases in the magnitudes of repulsive eigenvalues are observed as the Argonne v_{18}, CD-Bonn or Nijmegen potentials are evolved to low momentum (see Fig. 1 and Ref. [2]), even though two-body observables are unchanged. For chiral EFT potentials [3], running the cutoff lower tames the impact of the tensor force and of new nonperturbative features entering at N^{3}LO (see Fig. 2 and Ref. [2]). In addition, separable approximations to nuclear interactions derived from the Weinberg analysis are more effective at lower cutoffs. At finite density, the Weinberg eigenvalues serve as a diagnostic for the perturbative convergence of the in-medium T–matrix.

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*This work was supported in part by the NSF under Grant No. PHY–0354916 and the US DOE under Grant No. DE–FG02–97ER41014.

Pairing Regularization in Skyrme-HFB

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Even though the divergence of the local abnormal density due to zero-range of the pairing interaction in Hartree-Fock-Bogoliubov (HFB) method with Skyrme energy density functional parametrizations has been recognized long time ago, until recently no effort to regularize it has been undertaken. In this work we discuss, how to regularize these ultraviolet divergences appearing in HFB formalism for local pairing functionals, by regularizing local densities [1]. The regularization scheme we obtain is identical to the one proposed by Bulgac [2, 3]. We test this procedure for spherical and deformed nuclei and compare results with those obtained using the commonly used renormalization technique [4].

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The interplay of single particle and collective motion in the A=70 region: magnetic moment measurements in ^{70}Ge. *

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Magnetic moments provide information about the microscopic structure of a nucleus. The transient field technique combined with Coulomb excitation in inverse kinematics [1] allows g-factor studies of states which are not accessible by other techniques. The method gives information on both the sign and the magnitude of the g factor. Thus one can study the interplay of the single particle and collective degrees of freedom. The first 2^+ states have been extensively studied. Only a few measurements of magnetic moments of 4^+ states exist. In a recent experiment, the g factor of the 4_1^+ state of $^{68}_{30}$Zn$_{38}$ was measured to be -0.37(17) [2] suggesting significant neutron $g_{9/2}$ contribution to the wave function. However, shell model calculations [2] predict a positive g factor. To obtain more information on this region the g factor of the 4_1^+(2153 keV, τ=1 ps) in $^{70}_{32}$Ge$_{38}$, an isotone of ^{68}Zn, was measured at WNSL, Yale. A positive g factor of +0.6(2) was obtained. We will discuss the experiment and the impact of the new results.

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*This work was supported by the U. S. National Science Foundation and the U. S. Department of Energy under contracts DE-FG02-91ER-40609, DE-FG52-05NA25929, DE-FG02-88ER40417.

Studying the stars with STARS: Measuring the radiative width of the triple-α state in ^{12}C

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The two main products of Helium burning in stars are ^{12}C, produced by the 3α reaction, and ^{16}O produced by $^{12}C(\alpha,\gamma)^{16}O$. In concert, these two reactions affect not only the nucleosynthesis, C and O being the 3rd and 4th most abundant elements in nature, but the future evolution of massive stars during carbon, neon, and oxygen burning. A single resonance at 7.65 MeV formed by ^{8}Be* and an alpha particle allows the creation of ^{12}C. Overwhelmingly ^{12}C formed in this resonance decays by emitting an alpha particle and breaking up into unstable ^{8}Be, which quickly decays into two alpha particles. However, there is a small gamma decay probability, which allows the excited ^{12}C nucleus to decay to its ground state. The gamma decay probability can be measured directly by populating the 7.65 MeV state via inelastic scattering and observing the fraction of the decays that proceed by gamma ray (preserving the ^{12}C nucleus) as compared to breaking up into three alpha particles.

We have measured the number of particles which scatter from the 7.65 MeV (see Fig. 1) state as well as the coincident recoiling ^{12}C nuclei (see Fig. 2) using STARS (Silicon Telescope Array for Reaction Studies) at the 88-Inch cyclotron at LBNL. STARS, with its large areas and high degree of segmentation, can be used to minimize the experimental difficulties encountered in the past and to avoid a systematic uncertainty present in prior attempts at measuring ratio of gamma-to-particle decay of the 7.65 MeV resonance. Preliminary results on our new measurement of the 3a reaction will be presented and compared to existing data.

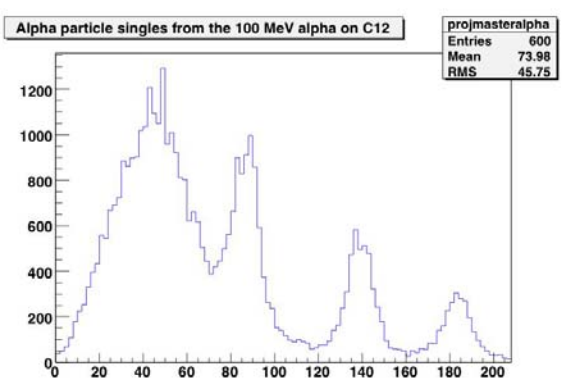

Figure 1: The α scattering singles distribution from the reaction $^{12}C(\alpha,\alpha')^{12}C$ at 100 MeV. From right to left the peaks are from scattering off the ground state, 4.44 MeV, and 7.65 MeV states of ^{12}C

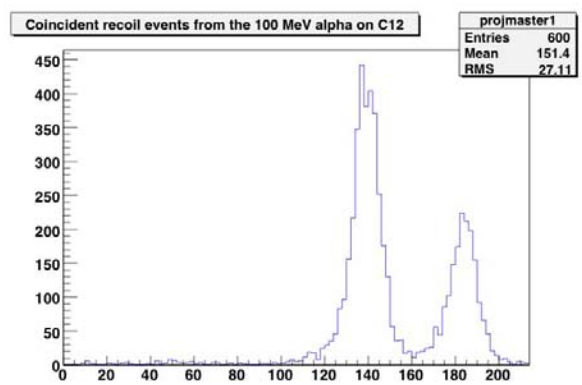

Figure 2: Same as Fig. 1 but with a required coincidence of a recoiling ^{12}C with more than 60 MeV.

* This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48 and Lawrence Berkeley National Laboratory under contract No. DE-AC03-76SF0098. This work was also supported by the U.S. Department of Energy and the University of Richmond and Yale University under grant numbers DE-FG-05NA-25929, DE-FG02-05ER-41379 and DE-FG02-91ER-40609.

Evolution of Collectivity in Silicon and Sulfur Isotopes Approaching $N = 28$ *

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Nuclear shell structure is known to evolve far from stability [1]. As nucleons are added or removed, single particle energies shift and shell gaps may widen or narrow [2]. Possible weakening of the $N = 28$ shell gap is of particular importance because this is the first shell closure due to spin-orbit splitting and could serve as a model for the evolution of similar shell gaps at large neutron excess. Study of this shell gap has focused on nuclei near ^{44}S, a highly collective nucleus at $N = 28$ and $Z = 16$. Unfortunately, the Z=16 sub-shell gap narrows significantly at $N = 28$ making it difficult to cleanly assign the rise in collectivity to a narrowing in the neutron shell gap.

To examine the weakening of $N = 28$, neutron-rich silicon and sulfur isotopes were studied by inverse kinematics, inelastic proton scattering on a liquid hydrogen target [3]. Projectile γ-ray decays detected by SeGA [4] were used to tag inelastic excitation of specific bound states [5]. For even-even isotopes, $\beta_{2,(p,p)}$ deformation parameters are deduced from inelastic excitation cross-sections. Proton and neutron contributions to collectivity are separated in cases previously studied by Coulomb excitation. New excited states resulting from inelastic excitation — and complimentary nucleon removal reactions — are presented. While large scale shell model predictions [6] faithfully reproduce the evolution of 2_1^+ excitation energies, a large offset in the predicted silicon 2_1^+ energies is observed.

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*Supported by the United States National Science Foundation under Grants No. PHY-00110253, PHY-9875122, PHY-0244453, INT-0089581 and by the Japan Society for the Promotion of Science.

Nuclear Structure Research at Jefferson Lab

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The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab is a unique tool for the study of atomic nuclei. It provides intense, cw beams of polarized electrons with energies of up to 5.7 GeV. The accelerator began delivering beam for physics research in October 1995, and has been in full operation since December 1998. CEBAF supports a broad range of nuclear physics research. A main focus of this research program is the development of our understanding of the "building blocks" of nuclear structure. This program addresses key questions such as "how nucleons are constructed from the quarks and gluons of QCD" and "how the strong force arises from the underlying QCD quark-quark interaction." An equally exciting, but less broadly appreciated focus of CEBAF research is on nuclear structure. It includes an array of experiments taking advantage of the precision, spatial resolution, and interpretability of experiments performed using electromagnetic probes to address long-standing issues in nuclear physics. Results and plans will be presented in a number of areas, including: identifying the limits of applicability of the conventional description of nuclei based on nucleons interacting via the nuclear force; quantitative investigations of short-range correlations among the nucleons in nuclei; the precision determination of the neutron radius of a heavy nucleus; and the study of the N-N force and the structure of deeply bound nucleons through the electro-production of hypernuclei.

Many-particles plus rotor description of magnetic bands at high spin

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Magnetic rotation [1] has been labeled a new mode of excitation which differs from well-known excitation modes. It occurs for relatively small deformations but gives rise to regular sequences of states. The magnetic bands observed in the lead region have been described as two protons preferring to align their angular momenta with one axis and a couple of neutron holes that align their angular momentum vector with a perpendicular axis (see [1, 2]). Spin increases through the so called shears mechanism, wich means that the nuclear spin axis remains at an essentially fixed angle when the spin increases. This requires that both the high-j protons and the high-j neutron holes have the freedom to build angular momentum both along the symmetry axis and along the perpendicular axis.

As the magnetic bands reach the maximum spin which can be built by the alignment, there is the question whether the bands terminate , i.e reach their end with the angular momentum pointing in the direction of a symmetry axis of the potential or if couplings with states outside the valence space are strong enough to generate higher spin states.

We would like to report on our present work [3] which aims at gaining an increased insight into the magnetic bands in the lead region while evaluating an alternative model. Previous theoretical descriptions have relied on the tilted axis cranking model (TAC) [1] which has been successful in describing the observed large magnetic dipole transitions [2]. In our alternative approach, the cranking model is used for the bulk of the nucleons, with several (5-6) valence particles coupled to the bulk using the particle rotor model (PRM). This approach yields wavefunctions in the laboratory frame having good total spin. From these wavefunctions, transition probabilities can be calculated not only within bands but also between bands and rotational bands can be followed as they cross the boundary from the tilted regime to the principal axis cranking regime.

We would like to start by discussing the model and the method used to extract properties of the rotor. We then make some comparisons with principal axis cranking (PAC) and compare results obtained for different divisions into particle space and core space. We move on to discuss different configurations of ^{199}Pb in some detail and compare with experiment. Finally, we demonstrate the importance of allowing the neutron spin vector tilt away from the perpendicular axis and also discuss possible evidence for band terminations.

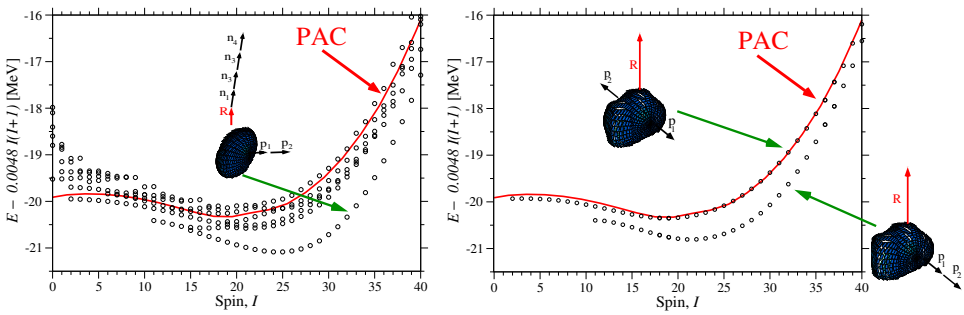

FIG. 1: Calculations for ^{198}Pb with a $\pi(\mathrm{i}_{13/2})^1(\mathrm{h}_{9/2})^1 v(\mathrm{i}_{13/2})^{-4}$ configuration at a constant deformation of $\varepsilon_2 = -0.15$. Left panel shows 2 protons and 4 neutron holes coupled to a rotor and in the right panel the neutron holes are treated as part of the core. Schematic figures illustrate the coupling schemes in the different cases. The (red) line shows the result from principal axis cranking (PAC) calculations.

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Proton Drip Line Spectroscopy with Gammasphere and the FMA*

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Between Z=51 and Z=83, the limits of nuclear stability is marked by the proton emitters. In contrast to the neutron drip line, these nuclei have been produced with heavy-fusion evaporation reactions utilizing stable beams and targets with production cross sections ranging between 1nb and 100 μb. These low production cross sections make it impossible to study the prompt γ rays emitted by these nuclei without the use of isotopic identification. By coupling Gammasphere with the Fragment Mass Analyzer (FMA), in-beam spectroscopic studies became possible by utilizing the recoil decay tagging (RDT) method which correlates γ rays produced at the target with characteristic charged particle radioactivity measured at the FMA focal plane. In addition, the use of the FMA with Gammasphere became essential in studying nuclei in the vicinity of the proton drip line near Z=82 due to the fact that nearly all the reaction cross section is associated with the fission channel. In these instances, the FMA was used to isolate γ rays associated with evaporation residues from those emitted by the fission fragments. In this talk, a review of the work done with Gammasphere and the FMA in the vicinity of the proton drip line will be given with a concentration on a few specific examples.

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*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract NO. W31-109-ENG-38.

Approaching ^{78}Ni along the N=50 line utilizing deep inelastic reactions*

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The study of doubly and semi magic nuclei have historically proven to be important in establishing for example the parameter strengths for the shell model. Until recently, these parameters were set by nuclei lying near the line of beta-stability, however, with the coming online of a number of first and second generation radioactive beam facilities, studies of exotic neutron rich nuclei at and near closed shells have begun. What has motivated many of these measurements from a nuclear structure standpoint is the fact that rearrangements of single-particle energies are observed for neutron rich isotopes. Such changes in the single-particle energies have been attributed to the attractive strength of the spin-isospin part of the effective nuclear interaction. As a result, one has observed the disappearance of certain magic numbers and the emergence of new closed shells. Our collaboration has been actively studying neutron rich nuclei in the Ca-Ti region in order to examine such a phenomenon. Specifically, we have been investigating Ti and Cr isotopes with N> 28. Recent shell model calculations using the GXPF1 Hamiltonian had suggested a new closed shell for N=32 and Z≤24 and the emergence of a shell gap at N=34 for Z≤22 [1]. Our recent results from Gammasphere using both the ^{48}Ca + ^{208}Pb and ^{48}Ca + ^{238}U reactions has confirmed the N=32 gap for ^{54}Ti (Z=22) [2] and shown that no such gap has developed at N=34 for Z=22 (^{56}Ti) [3].

With the success of our Gammasphere experiments utilizing a ^{48}Ca beam, we have extended our measurements into the region around N=50 and Z=28 (^{78}Ni). Neutron rich nuclei in this region are of particular interest due to their role in the r-process, and in particular, their contribution to the peak in the solar elemental abundance near A=80. While much is known with regards to the N=50 isotones starting at ^{86}Kr and proceeding up towards ^{100}Sn, much less is known about the isotones approaching and including ^{78}Ni with much of this knowledge coming from decay work and thus limited to low-spin levels. In order to access high-spin states in the N=50 isobars ^{84}Se and ^{82}Ge, a deep-inelastic reaction was utilized using an ^{82}Se beam at bombarding energies of 510 and 630 MeV incident on thick targets of either ^{208}Pb or ^{238}U. Gamma-rays were detected by the Gammasphere array consisting of 101 Compton-suppressed HPGe counters.

Recently, levels in ^{84}Se have been reported up to a tentative spin of 7^+ in several recent measurements [4-6]. From our measurement, we have extended the yrast structure of ^{84}Se up to a tentative spin of 12^+ and added a number of new non-yrast levels to the known level structure. For ^{82}Ge, besides the first excited 2^+ level at 1348 keV, a level at 2286 keV has recently been reported from ^{83}Ga β^- n decay [7]. We confirm this level in our data and have added two additional levels to the known level structure of ^{82}Ge. Our new experimental results will be presented along with shell model calculations which attempt to reproduce the observed level structure in both these neutron rich N=50 isobars.

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*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under contracts W31-109-ENG-38 and DE-AC05-00OR22725.

Triple Shape Coexistence in ^{181}Tl*

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The mid-shell Tl isotopes mimic the mid-shell Pb isotopes in that structures built on spherical, oblate and prolate shapes have been established in ^{183,185,187}Tl [1-3]. A comparison of the excitation energy of single-particle states associated with the different shapes shows that the excitation energy of the $13/2^+$ $i_{13/2}$ prolate state continues to decrease as one approaches mid-shell (N=102) while the oblate structure built on the $h_{9/2}$ orbital minimizes in excitation energy at N=108 and rises in energy with decreasing neutron number. In even-even Pb and Hg isotopes, the excitation energy of excited prolate states begin to rise in energy for N<102. For the Tl and Pb isotopes, the ground states remain spherical, but it remains an open question whether this same trend observed in the Pb nuclei for the prolate states continues beyond mid-shell for the Tl isotopes. In order to answer this question, we have a completed a study of ^{181}Tl (N=100).

Excited states in ^{181}Tl were populated with the ^{92}Mo(^{90}Zr,p) reaction using a 385 MeV beam delivered by the ATLAS superconducting linear accelerator at Argonne National Laboratory. Due to the large negative Q-value for this reaction, the compound nucleus is left with relatively low excitation energy, E^*~23.5 MeV, thus, minimizing competition from fission and multiple charged particle evaporation. Prompt γ rays were measured with the Gammasphere array consisting for this experiment of 101 large volume escape-suppressed Ge detectors. Gammasphere was used in conjunction with the Argonne Fragment Mass Analyzer (FMA) in order to separate the fusion evaporation channels produced with μb cross sections from the fission products produced at a cross section in excess of 100 mb. By utilizing the FMA, evaporation residues recoiling out of the target are dispersed at the FMA focal plane according to their mass-to-charge (m/q) ratio. A position-sensitive parallel grid avalanche counter (PGAC), located at the focal plane, provided the m/q information as well as time of arrival and energy-loss signals of the evaporation residues. The recoiling nuclei were subsequently implanted into a 40x40 strips, double-sided silicon strip detector (DSSD) located 40 cm behind the PGAC. The DSSD was used not only to detect the implantation of a residue, but also to measure its subsequent α decay. In addition, three clover detectors were placed around the DSDD in order to measure γ rays in coincidence with either implanted recoils or α decaying isotopes.

Before our investigation, only the ground state and an α-emitting isomeric state had been experimentally characterized in ^{181}Tl [4], however, the excitation energy of the excited state had not been measured. In our new study, the excitation energy of both prolate and oblate excitations relative to the ground state have been determined utilizing both prompt γ rays measured at the target, and delayed γ rays and α decays measured at the FMA focal plane. Our data show that the excitation energy of the $i_{13/2}$ prolate band in ^{181}Tl rises relative to both the spherical and oblate states, reversing the trend observed in the heavier odd-A Tl isotopes. In addition, we have observed a prolate rotational band feeding the ground state directly. We have associated this excitation with the ½[400] Nilsson configuration. It has been suggested that the lowest lying $1/2^+$ states in ^{185,187}Bi are associated with this orbital, marking a shape transition from oblate to prolate deformed shapes in the Bi isotopes [5]. Our new results and their implications to shape coexistence in this region will be presented.

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*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract NO. W31-109-ENG-38.

Recent Results from and Future Plans for REX-ISOLDE

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For the REX-ISOLDE and MINIBALL collaborations

The ISOLDE facility has during the past few years been expanded to include a post-accelerator to boost the low energy radioactive beams to ~3 MeV/u. This has opened up a path for new types of experiments at ISOLDE with particular emphasis on Coulomb excitation of the first 2^+ states in a number of radioactive isotopes. The main physics cases are the study of shell evolution, when approaching double shell closures, and shape coexistence. In this presentation we will discuss recent results pertaining to the neutron rich as well as neutron deficient shell closures for the Sn isotopic chain as well as recent results relevant for the regions of neutron rich Ni and Mg isotopes. The future plans for an energy upgrade of the post accelerator to 5 MeV/u and 10 MeV/u will also be presented.

Quadrupole Moment Measurement in Fragmentation Reactions; case of ^{61m}Fe

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The measurement of electromagnetic moments of excited isomeric states in neutron rich nuclei provides the most direct way to look into effects such as the vanishing of the known shell closures and the emergence of new magic numbers, the evolution of the shell structure and of deformation with increasing isospin, etc. To measure such moments one essential requirement is to have a spin aligned ensemble of nuclei. The discovery of spin alignment in neutron rich nuclei produced in intermediate energy projectile fragmentation reactions [1] gave an opportunity to researchers to start measuring nuclear moments in these neutron rich nuclei. As a result, a number of g-factor measurements of isomeric states in ^{61}Fe, ^{67}Ni and ^{69}Cu nuclei with N$\sim$ 40 [2,3] have been carried out and the role of the $\nu g_{9/2}$ intruder orbital in this mass region has been addressed. In case of ^{61}Fe the allowed space and excitations for protons and neutrons used in the Large Scale Shell Model Calculations (LSSM) to explain the known g-factor and excitation energy, is expected to introduce a sizable quadrupole deformation (β_2) in the nucleus. In order to gain insight into this issue, the quadrupole moment measurement of the $9/2^+$ ($\nu g_{9/2}$) isomeric state ($T_{1/2}$ = 239(5) ns) in ^{61}Fe has been carried out with the well known Time Differential Perturbed Angular Distribution (TDPAD) technique at the GANIL facility in France. The spin aligned ^{61m}Fe isomers were produced using the fragmentation of ^{64}Ni beam at an energy of E_{lab} $\sim$ 65 MeV/u. The extracted quadrupole moment $|Q|$ = 41 (6) efm^2 (preliminary result) gives important information about the deformation of isomeric state and also helps in fixing the predictions of the LSSM calculations to some extent. **This is the first ever measurement of an isomeric quadrupole moment in the nuclei produced via fragmentation reaction.** The success of this experiment has opened the way for future measurements in other accessible neutron rich nuclei.

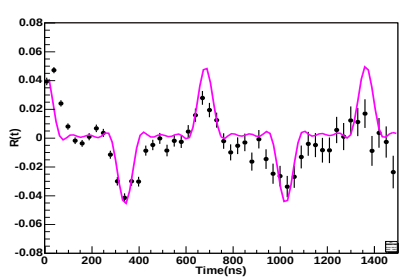

FIG. 1. Plot of R(t) function for 654 keV (M2) isomeric gamma transition in ^{61}Fe.

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g-Factor Measurement of 13^+ Isomeric State in ^{130}Sb with RISING at GSI

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The isomeric study of highly neutron rich odd-odd nuclei in the vicinity of doubly magic ^{132}Sn reveal important information on the nature of effective n-p interaction, which subsequently help in understanding important structural issues in nuclei well away from the valley of stability. So in the g-RISING campaign at GSI, special importance was given to this mass region and a number of isomeric g-factor measurements in nuclei around ^{132}Sn, using the well known (TDPAD) technique, have been done. The spin aligned isomers, were produced via relativistic projectile fragmentation of ^{136}Xe beam at 600 MeV/u. Ions in the fragmented beam were finally stopped on a Cu plate, placed between the poles of an electromagnet at the final focal plane of the FRS. The decaying gamma rays were collected with eight Cluster detectors providing an efficiency of ~ 3 % at 1.3 MeV. The present work reports on g-factor measurement on 13^+ ($T_{1/2} \sim 1.8(2)\mu s$) isomeric state in ^{130}Sb. For this nucleus, all the delayed gamma transitions of interest were observed in all the clusters. The presentation will focus on the discussion of experimental results.

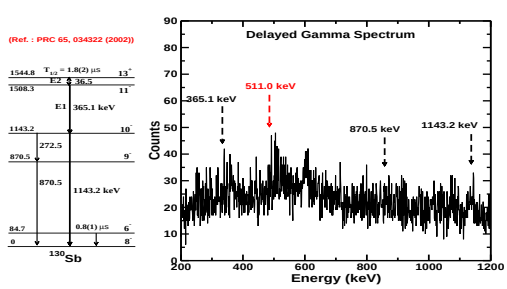

FIG. 1. Dealyed gamma spectra for ^{130}Sb obtained in the present experiment.

Probing *sd-pf* cross-shell interactions via terminating configurations in N ≈ Z scandium isotopes*

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The strengths of interactions across the *sd-pf* shell gap are not well defined in current realistic forces, in part due to a lack of experimental information. A new technique was recently developed [1-3] by which comparisons of terminating states—i.e. those states in which the valence nucleons align to the maximum spin for a given configuration—based on $(f_{7/2})^n$ and $(d_{3/2})^{-1}(f_{7/2})^{n+1}$ configurations in $N \approx Z$ nuclei in the lower *pf* shell can provide information about these two-body matrix elements. Specifically, effective interactions can be studied by examining $\pi(d_{3/2})^{-1}(f_{7/2})$ particle-hole excitations involving such terminating states; these states are expected to have simple structural purity and can be considered examples of unperturbed single-particle motion.

Several nuclei in the lower *pf* shell have been examined through shell model [1] and Skyrme-Hartree-Fock [2-3] approaches and compared with experiment; however, the relevant states in the $Z = 21$ nuclides ^{42,43}Sc had not been previously identified. The self-conjugate ^{42}Sc case is of particular importance, as $N = Z$ nuclei have been found to require special treatment in these theoretical analyses, and such examples are obviously in shorter supply than their $N \neq Z$ neighbors.

The nuclides ^{42}Sc and ^{43}Sc were produced via the *αpn* and *αp* evaporation channels, respectively, in two reactions: 84-MeV ^{20}Ne + ^{28}Si and 94-MeV ^{24}Mg + ^{24}Mg. Both experiments were performed using the Gammasphere spectrometer in conjunction with the Microball charged-particle detector array. The decay schemes for both nuclei have been considerably extended; states have been observed to excitation energies of 15 MeV and higher, and include candidates for the terminating states of interest. Angular distributions of gamma rays confirm that the spins of these states are consistent with the expected termination spins. Also, large gaps appear in the spectrum of states at higher energies, suggesting an energy-costly rearrangement of nucleons is necessary in order to generate more angular momentum above termination.

These states have now been combined with the available data set for testing the relevant interactions. Preliminary results indicate that both ^{42}Sc and ^{43}Sc have roughly the same level of agreement between experiment and theory as do the other considered cases in this study. The latest status of these analyses will be presented.

[1] G. Stoitcheva *et al.*, Eur. Phys. J. A**25**, s1.509 (2005).
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*This work was supported in part by the U.S. Department of Energy under contract DE-FG02-88ER-40406.

Alpha-Gamma Angular Correlations using Novel Position-Sensitive Detectors*

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The measurement of angular correlations of gamma rays following alpha decays is a powerful technique for extracting nuclear structure information, especially in very heavy nuclei. These techniques have not been widely used in recent years, as interesting new alpha-decay activities are generally produced with very low cross section, and have short halflives, so the development of efficient correlation experiments has been slow. Advances in position sensitive silicon and germanium detectors now offer strong possibilities for progress. We have been investigating the feasibility of efficiently measuring angular correlations using a compact setup with a large-area position-sensitive silicon avalanche photo-diode (PSAPD) for detecting the alpha particles and a large-area position-sensitive planar germanium double-sided strip detector (HpGeDSSD) for detecting the gamma rays.

The PSAPD used in these test experiments were 14 × 14 mm square with <200 μm Si thickness and a four-corner contact design, with x-y position sensitivity achieved via charge fractionation [1]. These photo-diodes had been evaluated previously for gamma-ray imaging coupled with pixellated scintillation counters, and found to have a position resolution of 0.3 mm. They were investigated as stand-alone detectors for charged-particle spectroscopy for the first time in the present studies. The operating voltage for the PSAPD was chosen by optimizing the signal-to-noise for the device. Significant analysis effort went into event-by-event correction for the inherent pin-cushion distortion effects present in four-corner contact designs.

The planar HpGeDSSD detectors were prototypes manufactured by ORTEC and being tested at Argonne [2,3], with dimensions 92 × 92 × 20 mm. The lithium and boron contacts on opposite faces were separated into 16 strips, each 5 mm wide, horizontal on one side (Li) and vertical on the other (B). This translates into a 16 × 16 segmented Ge detector of 5 × 5 mm pixels of 20mm thickness. These segmented detectors have been evaluated for specialized applications, such as Compton polarimeters for linear polarization measurements of gamma rays [3,4] and Compton cameras for gamma ray imaging [5]. In these applications, information from at least two pixels are required to analyze the Compton scattering process. In the present angular correlation studies, the analysis was confined to single-pixel events where the detector was used primarily as a large-area granular device with good angle definition.

The alpha-gamma angular correlation measurements were performed using radioactive ^{228}Th and ^{249}Cf sources. The decay of ^{228}Th to ^{224}Ra and the subsequent decay of ^{224}Ra to ^{220}Rn both involve a $0^+ \rightarrow 2^+$ alpha decay followed by a $2^+ \rightarrow 0^+$ gamma decay. This leads to strong angular anisotropy between the alpha particle and the quadrupole gamma ray, as only one magnetic substate is involved. The decay of ^{249}Cf to ^{245}Cm, on the other hand, is a $9/2^- \rightarrow 9/2^-$ alpha decay followed by a $9/2^- \rightarrow 7/2^+$ gamma decay, where the angular correlation anisotropy is washed out due to the involvement of multiple m-substates in the decay process. The californium decay data was used as a normalization for measuring the angular correlation from the thorium and radium decays.

The results from these test experiments will be shown and prospects for research into mass-separated short-lived isotopes discussed.

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[4] N.J. Hammond et al., *Argonne Physics Divn. Ann. Rep.2003,* **ANL-04/22** p.106 (www.phy.anl.gov/div/ar04).
[5] F.G. Kondev et al., *Argonne Physics Divn. Ann. Rep.2003,* **ANL-04/22** p.108 (www.phy.anl.gov/div/ar04).

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*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under contracts DE-FG02-94ER40848, DE-FG02-01ER83269 and W-31-109-ENG-38.

The Transition from Vibrational to Rotational Regimes in the Pairing Phase*

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Pair correlations in electron motion are directly related to macroscopic phenomena such as superconductivity. The concepts that were developed to describe such correlations found immediate application in nuclear physics and provided a key to understanding the excitation spectra of even-A nuclei, odd-even mass differences, rotational moments of inertia, and a variety of other phenomena. An early approach to describing pair correlations in nuclei was the development of a collective model by Bès and co-workers [1]. The collective pairing Hamiltonian was derived in direct analogy to the Bohr collective Hamiltonian which describes the quadrupole degree of freedom for the nuclear shape. The Bohr Hamiltonian has recently received renewed attention due to the suggestion that simple analytic approximations can be made to describe the critical-point of the transitions between nuclear shapes [2]. These can then serve as new benchmarks against which nuclear properties can be compared.

This contribution will describe our efforts to develop a critical-point description of the transition from a "normal" to a "superconducting" nucleus. Some of our initial work on this topic was published recently [3]. Analytical solutions of the collective pairing Hamiltonian can be found by using simple approximations to the potential in the limits of harmonic vibrations (zero deformation of the pair field corresponding to normal behavior), deformed rotation (static deformation of the pair field corresponding to superconducting behavior) and at an intermediate transitional point. In the latter situation the potential is approximated as an infinite square well. The eigenvalues are expressed in terms of the zeros of Bessel functions of integer order. Comparison to the pairing bands based on the Pb isotopes suggests that this description may provide a simple approach to explaining the observed anharmonicities of the pairing vibrational structure around ^{208}Pb (see Figure 1).

We have tested the collective solutions by comparison to the results obtained from exact solution of a two-level model. We have assumed particles moving in two levels of identical pair-degeneracy Ω separated by an energy ε with G as the strength of the pairing interaction. By using the ratio $G\Omega/\varepsilon$ as a control parameter we can describe the full transition from harmonic vibration ($G\Omega/\varepsilon \rightarrow 0$) to deformed rotation ($G\Omega/\varepsilon \rightarrow \infty$). We find a phase-transitional behavior and that the eigenvalues and matrix elements at the critical-point are in excellent agreement with those from the collective critical-point description.

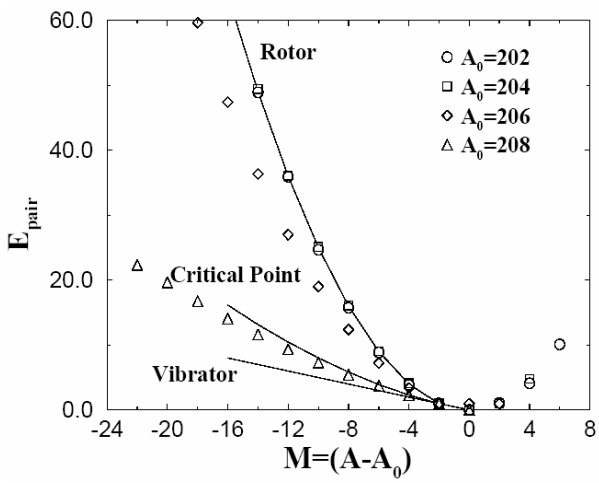

FIG. 1. Plots of the empirical neutron pair energies for the sequence formed by the 0^+ ground-states of the Pb isotopes using as a reference ^{202}Pb (open circles), ^{204}Pb (open squares), ^{206}Pb (open diamonds), and ^{208}Pb (open triangles). For comparison are shown the expectations of the pure vibrator, pure deformed rotor, and the critical-point description (solid lines).

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*This work was supported by the U.S. Department of Energy under contract DE-AC02-05CH11231.

Nuclear structure studies in both stable and neutron-rich nuclei*

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The Rochester heavy-ion detector, CHICO,[1] was developed primarily for use in conjunction with Gammasphere. The CHICO detector comprises an array of 20 position-sensitive parallel-plate avalanche detector panels with angular coverage of $12^o < \theta < 85^o$, plus $95^o < \theta < 168^o$ with 1° resolution and 280° in ϕ with 9° resolution. The detection solid angle is 67% of 4π, the minimum flight path is 13 cm, the time-of-flight resolution is 500ps, and the detector has minimal mass to reduce degradation of the γ-ray response characteristics of Gammasphere. Coincident detection of both recoiling reaction products for binary collisions allows complete kinematic reconstruction for each event providing identification of the target- and projectile-like nuclei with a mass resolution of $\Delta m/m = 5\%$ plus a measure of the reaction Q-value. When used with Gammasphere the measured masses plus recoil vectors allow correction for Doppler shift and assignment of individual γ-rays to the decay of the correct reaction product. The combination of Gammasphere and CHICO provides a powerful facility for studies of nuclear structure in both stable and neutron-rich nuclei excited by Coulomb excitation, single or multinucleon transfer reactions, deeply-inelastic reactions, and fission. For example it allowed Coulomb excitation to be extended up to spin 40 in ^{238}U while rotational bands were extended to over spin 20 in neutron-rich nuclei populated by the other reactions. During the past decade 24 separate experiments have been performed using this facility involving 58 collaborators from 17 institutions and leading to completion of 5 Ph.D. theses.

One theme of the Gammasphere/CHICO research program has focused on collective modes of motion and the underlying microscopic structure of neutron-rich nuclei. Recent examples are: The ^{238}U(α,f) reaction was used to extend rotational bands into the band crossing region in a range of neutron-rich nuclei fission fragments identifying possible shape changes [2,3]. The deep inelastic reactions involving ^{36}S and ^{48}Ca on ^{208}Pb have been used to probe the evolution of nuclear structure in s,d,f shell neutron-rich nuclei [4,5]. A study of delayed alignments and a search for oblate rotation has been performed on neutron-rich Hf nuclei [6]. Multiparticle and rotational states in ^{184}W, ^{101}Mo, and ^{103,104}Ru were studied via multinucleon transfer [7,8].

Another theme has focused on studies of collective modes in stable and neutron-rich nuclei. For example, Coulomb excitation has elucidated the fragmentation of the two-phonon octupole strength in ^{208}Pb and ^{96}Zr, as well as mapping evolution of quadrupole collectivity in several rare-earth and actinide nuclei. One example is a recent study of rotational bands built on $K = 6^+$, 8^-, and 16^+ isomeric states in ^{178}Hf plus their coupling to the low-K bands that has revealed a rapid collapse of K conservation with increasing spin in the low-K bands[9]. Another example will discuss the implications regarding K conservation revealed by a recent study of the rotational bands built on proton-neutron multiplets that were populated by Coulomb excitation of the odd-odd nucleus ^{242}Am using a unique target enriched to 98% in the 48.6 keV, $I=5^-$, $K=5^-$, $t_{½}$ = 141 year isomeric state [10].

Comments will be made regarding possible new research opportunities that will exploit the Gammasphere/CHICO when coupled to new radioactive beams facilities.

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*This work was supported by both the National Science Foundation and the Air Force Office of Scientific Research.

New data on the ternary fission of ^{252}Cf from the Gammasphere facility

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Spontaneous fission of ^{252}Cf was studied at Gammasphere with the use of ΔE×E detector telescopes implementing identification and energy measurement for long range charged particles (LRP) emitted at the ternary fission. Helium, beryllium, boron and carbon nuclei were identified and the yields and energy spectra of these LRP's were measured with energy thresholds of 9, 21, 26, and 32 MeV, respectively. The 3368 keV γ transition from the first, 2^+ excited state in ^{10}Be was observed, and a value of $N(2^+)/N(0^+)=0.160\pm0.025$ was found for the ratio of the population probabilities measured for this excited state and the 0^+ ground state of the ternary ^{10}Be cluster.

Independent yields of fragment pairs emitted in ternary fission in coincidence with specific LRP's were measured for the first time. From these yields the multiplicity distributions of prompt neutrons and charge distributions of fission fragments were deduced for the ternary fission of ^{252}Cf accompanied by the helium, beryllium and carbon LRP's.

The measured LRP yields (including the yield of ^{10}Be in the 2^+ state) and the charge distributions of fission fragments obtained for the ^{4}He, ^{10}Be, and ^{14}C ternary events were analyzed in terms of the energy cost suggested by I. Halpern [1] (see in Fig. 1 an example of this analysis). These data for the first time furnished a way to knowledge about the scission point asymmetries associated with the ternary splits. Our analysis indicates that more asymmetric pre-scission configurations are responsible for the emission of ternary LRP's.

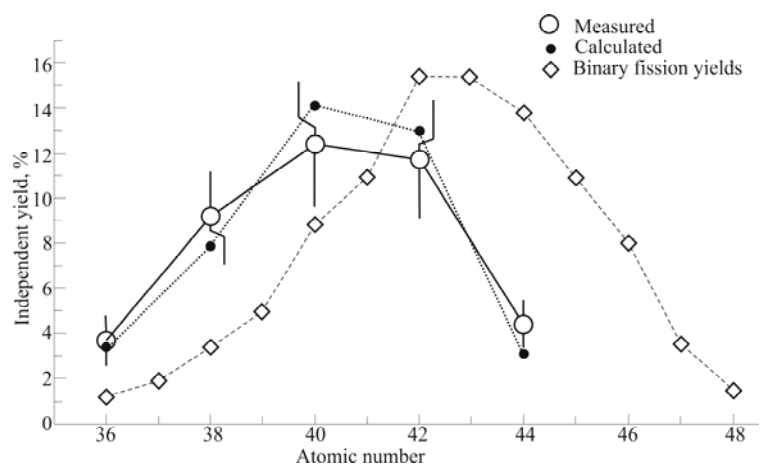

FIG. 1. Independent yields measured for light fragments emitted in ^{10}Be ternary fission of ^{252}Cf (open circles). Closed circles show the results of calculations made with the use of the energy cost values. Shown in figure is also the yield distribution known for the binary fission of ^{252}Cf [2].

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Decay spectroscopy of the lightest proton-emitting Re isotopes

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Proton emission is expected to determine the limit of experimental observation for the neutron-deficient nuclei of most elements. Proton radioactivity may be treated as a simple quantum tunnelling process through the Coulomb barrier. The barrier penetration probability (and thus the decay half-lives) for proton emitters are sensitive to the proton decay energies and the orbital angular momentum of the initial state from which emission occurs. Therefore proton radioactivity is an ideal mechanism with which to determine and characterise single-particle states beyond the proton drip line. Additionally the characteristics (short half-lives and discrete energies) of the emitted protons are ideal for tagging in γ-ray spectroscopy experiments.

A decay spectroscopy experiment has been performed at the Accelerator Laboratory of the University of Jyväskylä (JYFL), using the RITU separator in conjuction with the GREAT focal-plane spectrometer (which possesses a high efficiency for delayed γ-rays), to study the lightest Re nuclei via the reaction ^{106}Cd(^{58}Ni,pxn).

The first observation of the lightest known proton-emitting isotope ^{159}Re will be presented. In ^{160}Re the observation of γ-ray transitions feeding the known $d_{3/2}$ ground state [1] which may account for the non-observation of particle emission from the anticipated $h_{11/2}$ isomeric state is reported.

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A New Alpha-Decaying High-Spin Isomer In The Very Neutron-Deficient Nucleus, ^{158}Ta.

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The recoil-decay-tagging (RDT) [1] technique has revolutionised experimental investigations of the single-particle structures near the proton drip line. In a recent RDT experiment using the JUROGAM and GREAT spectrometers in conjuction with the RITU gas-filled separator, excited states have been investigated in the very neutron-deficient nuclide, ^{158}Ta, for the first time.

We report the observation of a high-spin isomer in the N = 85 nucleus ^{158}Ta, which decays via competing alpha and E3 gamma-ray decay branches. We present the level scheme feeding and depopulating this 6 microsecond isomer. The level scheme is compared with the yrast structures of the lighter N = 85 isotones.

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Thermal and rotational properties of N=40 nuclei*

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In this talk, I will describe investigations of the thermal and rotational properties N=40 nuclei [1,2]. Using the shell-model Monte Carlo (SMMC) method, we study the thermal properties of four N=40 medium-mass nuclei: ^{68}Ni, a substantially spherical and weakly paired nucleus; ^{70}Zn, a super-fluid spherical nucleus; ^{72}Ge, a super-fluid deformed nucleus which exhibits shape-coexistence; and the well-deformed, weakly-paired nucleus ^{80}Zr. We investigate the competition between shape deformations and pairing correlations as a function of temperature. We find that shape and pairing changes contribute to the specific heat of the nucleus in a different way. While the super-fluid-to-normal transition manifests itself as a pronounced peak in the specific heat around T=0.6-0.7 MeV, the deformed-to-spherical transition is more gradual. We then concentrate on ^{72}Ge and investigate its response to both thermal and rotational excitation. We show that the pairing decreases as one increases the rotational frequency in the system, and that the moment of inertia of the system indicates a a change from a paired state to a state with one quasi-aligned pair at a spin of approximately $\hbar\omega$ = 0.35 MeV. We will then discuss the thermal properties (non-yrast states) of ^{72}Ge at high rotational frequencies. Shown in the figure are some of the shape distribution studies at zero cranking frequency. The nuclei exhibit memory of their shapes up to about T=1 MeV after which they all melt toward spherical shapes.

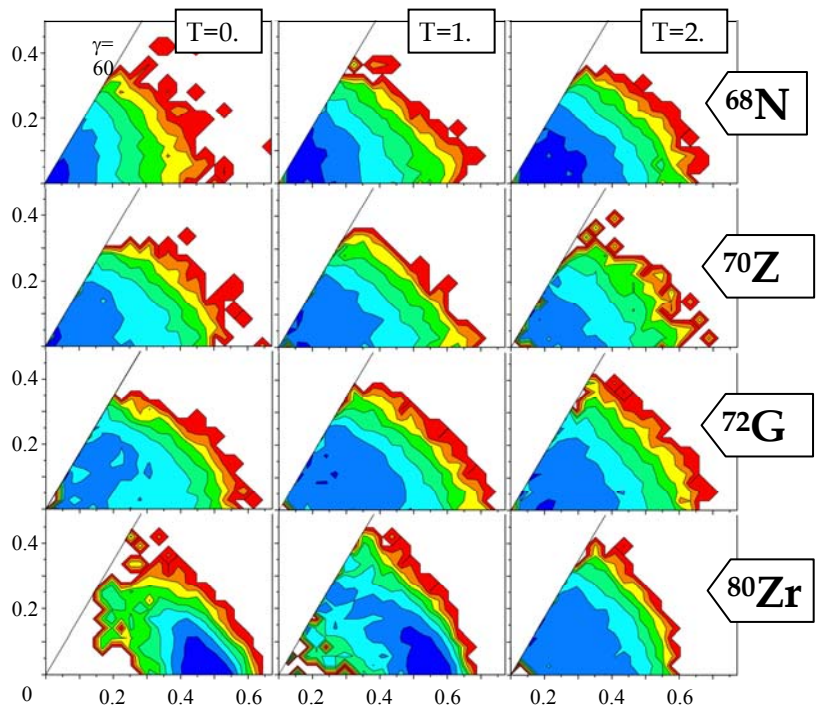

Figure: The free energy distribution in the beta-gamma plane for ^{68}Ni, ^{70}Zn, ^{72}Ge and ^{80}Zr at three temperatures, T=0.5 MeV (left column); T=1.0 MeV (middle column), and T=2.0 MeV (right column).

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*This work was supported by the U.S. Department of Energy under contract DE-AC05-00OR22725 with UT-Battelle, LLC (Oak Ridge National Laboratory).

Coupled-cluster theory for nuclei

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We employ realistic nucleon-nucleon interactions within coupled-cluster theory, and compute the ground states and low-lying excitations of ^{4}He and ^{16}O. Our results are converged with respect to the size of the employed model spaces. The dominant contibutions to the energies stem from one-particle one-hole ($1p$-$1h$), and $2p$-$2h$ cluster excitations, with minor contributions from $3p$-$3h$ cluster excitations. Our results for ^{16}O hint to deficiences of the employed Hamiltonians, and we describe the inclusion of three-body fores within coupled-cluster theory.

Collectivity at high spin in ^{139}Pm

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The nuclei in the mass $A \sim 130$ region are known to be soft with respect to the triaxial deformation parameter γ and are therefore sensitive to the γ - polarizing effects of specific quasiparticle configurations. This can lead to the co-existence of quadrupole structures of different spectroscopic character, which are determined by the configuration of the valence quasiparticle [1,2]. In this mass region $h_{11/2}$ midshell plays a crucial role for different structure features in nuclei. Gamma-soft nature in this mass region results in two structure features in odd-Z nuclei: (i) the $h_{11/2}$ neutron alignment competes with $h_{11/2}$ proton alignment and (ii) the co-existence of proton aligned collective prolate and neutron aligned collective oblate bands became possible in the same nucleus. In the present work, ^{139}Pm, an odd proton nucleus in this mass region is studied to investigate the nuclear shape behaviour upto well above the backbendings.

The high spin states in ^{139}Pm were populated using the reaction ^{116}Cd(^{27}Al, 4n)^{139}Pm at 120 MeV of beam energy delivered by the 15-UD Pelletron accelerator facility at the Inter University Accelerator Centre (IUAC), New Delhi. The target used was enriched ^{116}Cd of thickness 1.75 mg/cm^2 with a backing of Pb of thickness 90 mg/cm^2. The γ-rays were detected using the Gamma Detector Array (GDA) consisting of 12 CS-HPGe detectors with a 14 BGO element multiplicity filter. The multiplicity filter were placed (seven elements at top position and seven elements at bottom position of target chamber) at 90^0 w.r.t beam direction. In the experimental set-up the HPGe detectors were placed at angles of 143^0, 50^0 and 98^0 respectively with respect to the beam direction. A total of 643 million γ - γ coincidence events were collected in the experiment. The experimental excitation functions were measured in 5 MeV intervals between 110 and 120 MeV beam energy.

The data was sorted out off-line using the INGASORT [3] programme. A number of 4K $\times$ 4K matrices were formed with all possible combination of detectors with a dispersion of 0.5 keV/channel. For lifetime measurements of the states of ^{139}Pm two angle dependent matrices were made viz. (i) backward angle detectors *versus* all detectors and (ii) all detectors *versus* forward angle detectors. For the determination of lifetimes of nuclear states LINESHAPE programme, developed by J.C. Wells [4], is being used. The analysis of the data is underway and the latest results will be reported.

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Microscopic many-body calculations of nucleons near the Fermi energy

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A brief review of experimental data that elucidate the single-particle properties of closed-shell nuclei is presented. The theoretical understanding of these data requires the combined treatment of long-range and short-range correlations. A satisfactory understanding of the distribution of the single-particle strength is obtained for closed-shell nuclei. The importance of microscopic many-body calculations for a detailed understanding of nuclei with N very different from Z is pointed out. Short-range and tensor correlations also play a dominant role in the determination of superfluid properties of infinite matter when in-medium propagation is properly taken into account. For this purpose, the gap equation has been solved in its most general form employing the complete energy and momentum dependence of the normal self-energy contributions. Differences with standard BCS calculations of proton-neutron pairing for nuclear matter and neutron-neutron pairing in neutron matter are substantial. The latter results are compared to recent Monte Carlo calculations.

Results from the analysis of digitally acquired experimental data collected with the *AGATA* symmetric prototype detector and its implications to the *A*dvanced *GA*mma *T*racking *A*rray

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The Advanced GAmma Tracking Array (AGATA) is a European project that is aiming to construct a 4π ball of HPGe detectors for nuclear gamma-ray spectroscopy. This will achieve peak-total ratios comparable to current ESS arrays, whilst benefiting from a much increased efficiency. The implementation of on-line Pulse Shape Analysis (PSA) [1] will allow real-time γ-ray interaction position information to be read out from each of the 180 detectors in the array. This data can then be fed into Gamma-ray Tracking (GRT) algorithms [2] that can reconstruct scattered events.

The first two AGATA symmetrical segmented Canberra Eurisys (CE) prototype germanium crystals have been tested at the University of Liverpool. A highly collimated Cs-137 (662keV) beam was scanned across each detector in both singles [3] and coincidence [4] modes. The output pulse shapes from all 37 channels (one for each of the 36 segments + the centre contact) were digitised [5] and stored for offline analysis. The analysis of the characteristics of the real and transient pulse shapes from the detector (Pulse Shape Analysis), yields detailed information on its performance in relation to both the possibilities and limits of γ-ray tracking.

The coincidence scan of the first crystal was performed with 2mm step size and collimation. It has been concluded that photon interaction position determination to within this level of precision is achievable with simple parameterisation [3]. These experimental results were also compared to those theoretically derived from the electric field simulation code MGS [6]. Once validated, it is expected that a theoretical pulse-shape database can be constructed for all interaction positions within all 180 detectors. The second scan was performed with 1mm step size and collimation. The results of this ongoing analysis will be presented.

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DAMPING OF GIANT RESONANCES AT LOW TEMPERATURE

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The theoretical description of giant dipole resonances (GDR) at finite temperature T is presented. The results of calculations are obtained within the phonon-damping model (PDM) [1], thermal shape-fluctuation model (TSFM) including thermal pairing [2], and compared with the most recent experimental systematic. The emphasis is given to the low-temperature region, where it is shown that thermal pairing plays an important role in lowering the GDR width.

Within the PDM, the calculations for the GDR width in ^{120}Sn at $T \leq 5$ MeV used the thermal pairing gap obtained from the modified-BCS theory [3]. In difference with the gap given within the conventional BCS theory, which collapses at $T_c \simeq 0.79$ MeV, the modified-BCS gap never vanishes, but monotonously decreases with increasing T up to $T \simeq 5$ MeV. The results obtained show that thermal pairing plays an important role in suppressing the width at $T \leq 2$ MeV as compared to the value obtained without pairing. This improves significantly the overall agreement between theory and experiment, including the width at $T = 1$ MeV extracted in the latest experiment.

Within the TSFM, pairing fluctuations were taken into account along with the thermal shape fluctuations to calculate the GDR width in hot nuclei. The free energies were calculated using the Nilsson-Strutinsky method extended to finite temperature and taking care of the pairing correlations properly. The GDR observables are related to the shape of the nuclei through a simple anisotropic-harmonic-oscillator model with a separable dipole-dipole interaction. Considering the fluctuations, the observables were averaged over the shape parameters and pairing gap. The results of calculations show that the observed quenching of GDR width at low T in the nuclei ^{120}Sn and ^{148}Au can be understood in terms of shape effects caused by the pairing correlations. Fluctuations in the pairing field lead to a slowly vanishing pairing gap and, therefore, influence the structural properties even at moderate temperatures ($\sim$1 MeV). It is seen that the low-T structure of the GDR and hence the GDR width are quite sensitive to the change of the pairing field. This validates the pairing prescription and the parameters involved. This is an idication that if thermal fluctuations were treated properly, the GDR description within the TSFM could be more precise in providing us with the structure information.

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Superdeformation and High-Spin Spectroscopy Studies on ^{174}Hf

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High-spin states of the nucleus ^{174}Hf were populated using the heavy-ion reactions at the Atlas accelerator facility at the Argonne National Laboratory and the 88" cyclotron facility at the Lawrence Berkeley National Laboratory. The de-exciting γ rays are detected with the GAMMASPHERE spectrometer. In this nucleus, eight superdeformed bands are observed for the first time. Studies on these bands as well as eight bands with normal deformation are performed. The hypothesis for presence of a triaxial shape at high deformation in ^{174}Hf was tested via lifetime measurements of the states of the superdeformed structures. The deduced quadrupole moments of four of the these bands were compared with the Ultimate Cranker calculations and an additional search for transitions that depopulate these structures was carried out. Results from the study of these bands for possible presence of triaxiality in ^{174}Hf is presented. The investigation of the bands with normal deformation employed an extensive systematics of crossing frequencies, alignments, and Routhians. CSM and TRS calculations were performed and compared with these observables. Quasiparticle configurations for all of the bands with normal deformation were proposed, and $B(M1)/B(E2)$ and $B(E1)/B(E2)$ transition strength ratios were analyzed.

Shell structure of neutron-rich nuclei: A theoretical perspective

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Single-particle properties of nuclei are key elements of theoretical description in nuclear structure. They define the nuclear shells and influence most of the global and local ground-state observables as well as those of excited states. Since the nucleus is a strongly correlated system, single-particle states should be defined within a given theoretical framework and understood as characteristics of the whole nucleus. In the talk I will present properties of single-particle states calculated within the self-consistent theory with a particular emphasis on their relation to changes of nuclear shell structure in exotic nuclei. I will also discuss modifications of nuclear shells caused by tensor interactions and tensor terms in the energy density functionals.

Multi-quasiparticle Isomers and K-Conservation Paths in Stable and neutron-rich Yb and Lu Isotopes*

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Multi-nucleon transfer or "deep-inelastic" reactions have been used as a means of accessing a range of near-stable and neutron-rich deformed nuclei. The primary focus has been the identification of multi-quasiparticle intrinsic states and their associated collective bands as a means of clarifying the deformed potentials appropriate for this region, and to study the competing effects of individual-particle excitation and rotation. The Gammasphere array was used with time-correlations, exploiting the presence of isomeric states as a means of identifying favoured structures, and to gain increased sensitivity in reactions which are, in general, non-selective. In some cases it has been possible to develop γ–γ–angular correlation techniques to aid in spin assignments, since spectroscopic information in these reactions is usually limited.

A series of experiments has been carried out using 820 MeV ^{136}Xe beams provided by the ATLAS facility at Argonne National Laboratory, with a variety of pulsing regimes, incident on targets of ^{174}Yb, ^{176}Yb, ^{175}Lu and ^{176}Lu, aimed predominantly at nuclei populated by inelastic process or few-nucleon transfer. Results reported previously include identification of the predicted 5-quasiparticle $K^{\pi} = 39/2^{-}$ isomer in ^{177}Lu [1], a 7-quasiparticle $K^{\pi} = 49/2^{+}$ isomer in ^{179}Ta with an anomalously fast decay [2], multi-quasiparticle states in ^{174}Yb with complex decays [3] and identification of two-quasiparticle isomers in ^{172}Er and ^{174}Er, including the primary identification of excited states in ^{174}Er [4].

Emerging aspects of *K*-mixing will be presented with the main focus being on new results for ^{175}Yb and ^{176}Yb in which a number of isomers have been identified, in both cases with competing *K*-conserving and *K*-non-conserving paths that incidentally allow unambiguous placement of excited states in nuclei whose structures are otherwise isolated by the presence of long-lived isomers. Selected results for the more neutron-rich Yb isotopes and for high-*K* isomers in a range of Lu isotopes will also be presented and compared with the predictions of multi-quasiparticle calculations.

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*This work was supported by the Australian Research Council Discovery projects DP0343027 and DP0345844, the ANSTO program for Access to Major Research Facilities, and the U.S. Department of Energy, Office of Nuclear Physics, under contract No. W-31-109-ENG-38, and Grant No. DE-FG02-94ER40848

High-K Spectroscopy

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The already high sensitivity of Gammasphere is enhanced when coupled with the additional dimension of time. As we all know, a key signature of well-deformed nuclei is the existence of the projection quantum number *K*. When the paths available for decay from high-*K* multi-quasiparticle states to lower-lying states involve a large change in *K*, long lifetimes can result, providing a means for isolating and characterizing intrinsic configurations, for identifying associated collective structures, and so providing a window into coupled particle and collective modes, and for isolating nuclei which are otherwise hidden amongst the decays of more strongly populated and less interesting channels.

I will outline some of the related discoveries made during Gammasphere's reign in the context of rotation in high-*K* multi-particle states, the presence of isomers as a tool in probing shape co-existence and shape changes, and the study of heavy nuclei, and the competition between multi-quasiparticle states and collective rotation for defining the yrast line.

As well as past work, I will cover some very recent results, mainly from multi-nucleon transfer reactions, that both illustrate the sensitive techniques and that are producing a suite of spectroscopic information on neutron-rich nuclei in the Z = 68- 72 region, with some surprises in the physics, including anomalous decays, residual interactions and hints on factors that may limit high-*K* isomerism.

Compound-nuclear reaction cross sections via Surrogate measurements

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Many nuclear physics applications require nuclear structure and/or reaction information that has to be determined indirectly, due to experimental limitations. Innovative indirect approaches, such as the Asymptotic Normalization Coefficient (ANC) method, the Trojan-Horse method, and Coulomb dissociation experiments, have been developed and employed in recent years in order to determine cross sections for reactions that cannot be measured directly or calculated reliably [1]. These methods have provided useful information on direct reactions, in particular those relevant for nuclear astrophysics. Less work has been carried out on indirect methods for compound-nuclear reactions. Such reactions do, however, play a crucial role for a variety of nuclear physics applications. For instance, in the astrophysical context cross sections of many low-energy neutron-induced and charged-particle reactions need to be determined. This presentation will focus on the "Surrogate nuclear reactions method", an indirect approach for obtaining cross sections of compound-nuclear reactions.

The Surrogate method combines experiment with theory to obtain cross sections for compound-nuclear reactions, $a + A \rightarrow B^* \rightarrow c + C$, involving difficult-to-produce targets, A. In the Surrogate approach, B^* is produced by means of an alternative ("Surrogate") reaction, e.g. $d + D \rightarrow b + B^*$, and the desired decay channel ($B^* \rightarrow c + C$) is observed in coincidence with the outgoing particle b. The reaction cross section is then obtained by combining the calculated cross section for the formation of B^* (from $a + A$) with the measured decay probabilies for this state. This approach was first employed in the 1970s [2] to estimate neutron-induced fission cross sections from transfer reactions. More recently, the Surrogate method has attracted renewed attention: additional fission experiments have been carried out [3], approximations [4] and refinements [5] of the method have been studied. Applications to other mass regions are being considered as well: Experiments with the particle detector STARS [6] coupled to GAMMASPHERE and the LIBERACE array, respectively, have focused on Gd, Zr, and Ru nuclei.

While the method is very general and can in principle be employed to determine cross sections for many types of compound-nuclear reactions on a large variety of targets, there are various issues that require further study, such as the mechanisms for producing highly-excited, unbound configurations in direct reactions (both transfer and inelastic scattering reactions), the damping of such configurations into a compound nuclear system, the population of available angular-momentum values in a compound nucleus, and their impact on the compound-nuclear decay. This presentation will give a brief outline of the Surrogate approach and the challenges involved in carrying out a complete Surrogate treatment. The assumptions underlying the experimental work carried out so far will be detailed and calculations that test the validity of the approximations employed will be presented. Prospects for using the Surrogate method to obtain cross sections relevant to the astrophysical s process will be discussed.

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Nuclear Superdeformation

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The study of superdeformation was a major motivation for the construction of the large 4π gamma-ray detector arrays, Gammasphere and Eurogam/Euroball, and a major success of their science programs.

During the first decade of Gammasphere operation a large number of groups (worldwide) were involved in many experiments to determine the properties of superdeformed nuclei. Today over 250 superdeformed structures have been identified spanning the nuclear chart from A~40 to A~200. These data now provide a solid experimental foundation to our understanding of nuclear superdeformation.

The experimental program on superdeformation was accompanied by an equally vigorous theoretical effort. The theoretical tools developed to successfully describe the properties of superdeformed nuclei are finding important application in other areas of nuclear structure research.

In this talk I will review the progress made, the physics learned, and the current status of nuclear superdeformation, as well as touching on some future opportunities.

Spectroscopy of the lightest nuclei in the Lanthanide region

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One of the most exciting subjects in contemporary nuclear physics is the study of nuclei at the limits of stability with respect to particle emission. Recently, there has been an intensive experimental activity in measuring the proton decay and a large variety of proton emitters were observed in the region of heavy nuclei with $50 < Z < 82$. Very recently the proton radioactivity from ^{117}La [1], ^{121}Pr [2], ^{131}Eu and ^{141}Ho [3] has been identified. The proton decay rates deviates significantly from calculations assuming spherical configurations, thus indicating the onset of large deformations in the drip line nuclei below Z=69. However, a detailed study of the structure of these nuclei can only be performed by means of γ-ray spectroscopy using large detector arrays coupled with efficient light charged particles detectors, since the cross section for their population with the presently available stable beams are very low.

The lightest nuclei in the lanthanide region for which spectroscopic information has been published are ^{123}La [4], ^{124}Ce [5], ^{125}Pr [6] and ^{128}Nd [7]. These data indicate a strong quadrupole deformation β_2~0.35.

In order to establish the lowest single-particle excitations close to the point of the predicted [8] maximum deformation in this mass region (N,Z=64), we have studied the structure of the $^{122}La_{65}$, $^{123}Ce_{65}$ and $^{127}Nd_{67}$ nuclei using the ^{40}Ca+^{92}Mo reaction, with a 200 MeV ^{40}Ca beam of 5 pnA intensity and the GASP+ISIS+neutron ring setup. The data of the present experiment were summed to the data of our previous experiment [9] performed at a beam energy of 190 MeV, getting therefore a total of 5.9×10^9 Compton-suppressed events. The events were sorted according to the number of charged particle and neutron detectors that fired in coincidence. For each charged particle and neutron combination Eγ- Eγ and Eγ - Eγ - Eγ matrices were produced off-line for further analysis.

We report preliminary results on only one of the nuclei of interest populated in the reaction, ^{122}La. One of the observed bands has properties (aligned single-particle angular momentum, signature staggering, etc.) similar to the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands observed in the neighboring odd-odd nuclei. In order to see how the level spacing in the two signature partners changes with decreasing neutron number, we plotted the systematics of the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in the sequence of the odd-odd lanthanum nuclei, and observe that there is a significant decrease of the level spacing between ^{124}La and ^{122}La, nuclei with N=67 and N=65, respectively. This could be related to the closeness to N=66, the neutron number for which maximum deformation is expected in this region.

The data analysis is in progress, and we hope to identify new excited states also in the other nuclei at the limit of stability, ^{123}Ce and ^{127}Nd, that are also unknown from the spectroscopic point of view.

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A First Test of the E(5/4) Bose-Fermi Symmetry: the Structure of ^{135}Ba*

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The standard geometric symmetries of the harmonic vibrator, γ-unstable rotor, and deformed symmetric rotor represent stable limits of structure. A new class of geometrical symmetries, called critical point symmetries, has been proposed in the past few years for systems undergoing phase transitions between dynamical symmetries.

Very recently, the first case of a critical point Bose-Fermi symmetry for odd-mass nuclei was developed. Called E(5/4), it describes, analytically, a γ-soft critical point E(5) core coupled to a j = 3/2 particle, where E(5) represents a second order phase transition from a vibrator U(5) to a γ-soft rotor O(6). Since ^{134}Ba has been found to be an empirical manifestation of E(5), we carried out a β-decay experiment to study levels in ^{135}Ba, where the last neutron can occupy the $2d_{3/2}$ orbit, as the natural initial test of E(5/4). To complement this test and provide a perspective, we performed shell model and interacting boson-fermion approximation (IBFA) calculations.

We will present the work and discuss the results. We will show that E(5/4) can account for some of the observables in ^{135}Ba but that it does not provide a fully satisfactory description. Specifically, many of the collective and forbidden B(E2) values of E(5/4) agree well with the data. That the comparison with E(5/4) is mixed is perhaps not surprising: E(5/4) is an extremely simplified scheme and critical point nuclei show a delicate balance of phases which can be disturbed by the addition of a fermion. Therefore, symmetries such as E(5/4) may be more significantly broken than their counterparts in even-even nuclei.

*This work was supported by the NSF Grant PHY 0204811, the Research Corporation Grant CC5494, USDOE Grants DE-FG02-91ER-40609 and DE-FG02-88ER-40417, and the Flint Fund.

New T=1 and T=0 states in N=Z ^{74}Rb and the np pairing gap*

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Odd-Odd, N=Z nuclei are interesting laboratories for studying many nuclear structure effects, including neutron-proton correlations and the breakdown in analog symmetry. Charge symmetry breaking in nuclei is usually small but is important for extracting reliable Fermi matrix elements from superallowed beta-decays and testing CVC theory, a topic of current interest. We have used the ^{40}Ca(^{36}Ar,pn)^{74}Rb and ^{40}Ca(^{40}Ca,αpn)^{74}Rb reactions at 108 MeV and 123, 160 MeV, respectively, to populate ^{74}Rb and determine the analog distortion through comparison of T=1 states in ^{74}Rb with their corresponding ^{74}Kr levels. We have traced the analogs of the ^{74}Kr groundstate band in ^{74}Rb to spin J=8 and determined the Coulomb Energy Differences (CEDs). They are small, positive and increase smoothly with spin. New information was found on the T=0 states which delineate the deformed band structure and clarify the de-excitation from high spin [1]. A new T=0 band was found, together with several other candidate bandheads, revealing the distinct "np pairing gap" originally suggested by Rudolph et. al. [2] between the highly correlated T=1 groundstate and other excited configurations. Despite a careful search, no evidence was found for gamma decay to or from a low-lying $J^{\pi}=0^{+}$ state in ^{74}Rb.

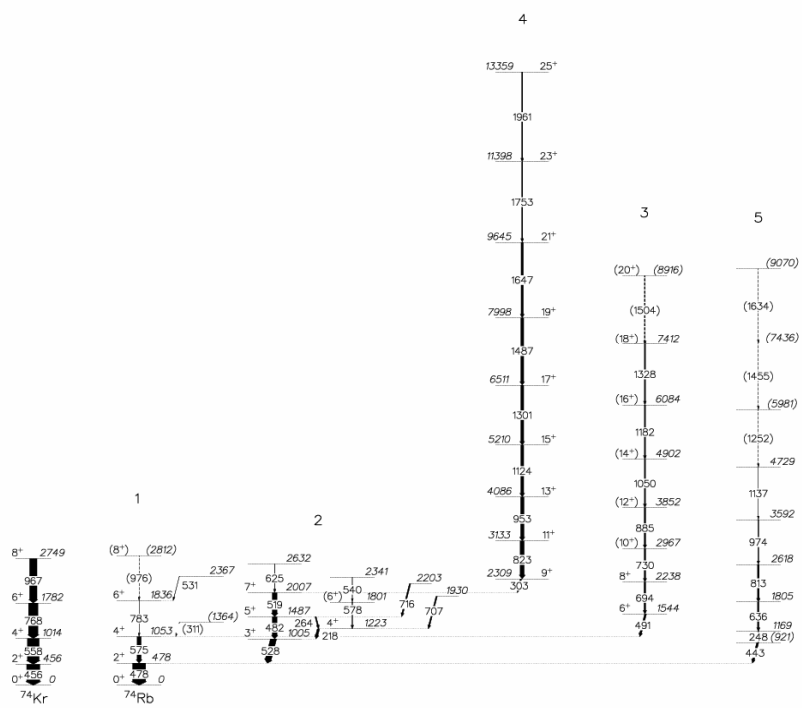

Figure 1. The new ^{74}Rb decayscheme derived from this work and previous studies [1,2]

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*This work was supported by the U.S. Department of Energy Office of Science under contracts W-109-31-ENG38, DE-AC05-00OR22725 and by NSF research grants PHY95-14157 and PHY-0244895.

Production of Transactinide Elements in Cold Fusion Reactions at LBNL*

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So-called "cold" fusion reactions have been successfully used in the production of transactinide elements, most notably in the discoveries of elements 107-111 (see [1] for a review) and the reported production of elements 112 [2] and 113 [3]. The reaction of a medium-mass projectile ($A \sim 50$-70) with ^{208}Pb or ^{209}Bi targets results in a compound nucleus with an excitation energy typically only 10-20 MeV, giving the compound nucleus a relatively high probability to survive against fission. In comparison with the ^{48}Ca-induced "warm" fusion reactions investigated at the Joint Institute for Nuclear Reactions in Dubna, Russia (see [4] for a review), cold fusion reactions tend to have larger maximum cross sections for the same element, but the decrease in cross section with increasing Z is significant.

Recent experiments [5, 6] to study cold fusion reactions at the Lawrence Berkeley National Laboratory 88-Inch Cyclotron using the Berkeley Gas-filled Separator have focused on the odd-Z transactinide elements. If the same compound nucleus can be formed in both even-Z- and odd-Z-projectile reactions, then the excitation functions for these reactions provide information on the entrance channel in each case. In preparation for an experiment to study the ^{208}Pb(^{65}Cu, n)^{272}Rg ($Z = 111$) reaction, an excitation function was completed for the ^{208}Pb(^{64}Ni, n)^{271}Ds ($Z = 110$) reaction. In total, seven ^{271}Ds decay chains were observed, and the maximum cross section was 20^{+15}_{-11} pb at a lab-frame center-of-target energy of 311.5 MeV. These data, when combined with previous results [7], were used with the "Optimum Energy Rule" proposed by Świątecki, Siwek-Wilczyńska, and Wilczyński [8] to estimate the bombarding energy for the ^{208}Pb(^{65}Cu, n)^{272}Rg experiment. In this second experiment, one ^{272}Rg decay chain was observed with a cross section of $1.7^{+3.9}_{-1.4}$ pb. This result indicates that odd-Z-projectile reactions can have cross sections comparable to those for the corresponding even-Z-projectile reaction.

It was desirable to study the entrance channel effect using a reaction with a larger cross section, and the reaction ^{208}Pb(^{55}Mn, n)^{262}Bh ($Z = 107$) was selected. An excitation function for this reaction was measured for the first time and is shown in Fig. 1. In total, 33 decay chains of ^{262}Bh and two of ^{261}Bh were observed. The existence of an alpha-decaying isomer in ^{262}Bh was confirmed, and a new alpha group in ^{262}Bh^{g} was observed. The unusually large measured cross section will be discussed in terms of the "Fusion by Diffusion" model [8], also proposed by Świątecki, Siwek-Wilczyńska, and Wilczyński. This production reaction may be the optimum one for observing alpha-gamma coincidences in the decay of ^{262}Bh; such information would be useful in determining the daughter states populated by the isomeric alpha decay.

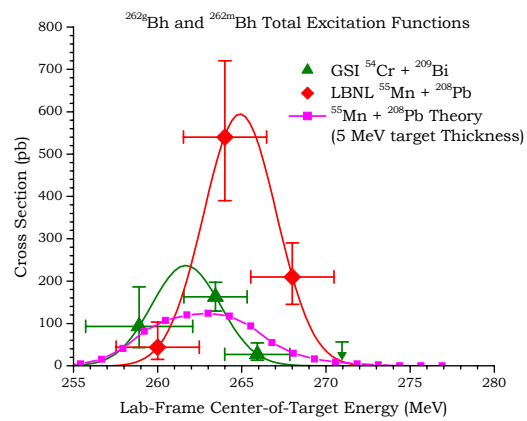

FIG. 1. Excitation function measured for the ^{208}Pb(^{55}Mn, n)^{262}Bh reaction.

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*This work was supported by the U.S. Department of Energy under contract DE-AC03-76SF00098.
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A close up of the spinning nucleus

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GAMMASPHERE is like a microscope permitting us to zoom into the nucleus at high spins. The experiments have largely refined our picture of the rotating nucleus. The original image of a rotating droplet of nuclear matter, which was later augmented by decoupling few nucleons from this collective flow, has been resolved into a tightly bound assembly of nucleonic gyroscopes. The rotational response of such a system is very different from other rotating system known to us. This difference will be discussed by means of examples as magnetic rotation, band termination, chirality, and nuclear tidal waves.

A New Microscopic Shell-Model Approach to Neutron-Rich Carbon Isotopes

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The anomalously hindered $E2$ transition strength between the first 2^+ and the ground 0^+ states in ^{16}C has recently been found experimentally as $B(E2; 2_1^+ \to 0_1^+) = 0.63^{\pm 0.11(\mathrm{stat})}_{\pm 0.16(\mathrm{syst})}\ e^2\mathrm{fm}^4$ [1]. The dominance of neutron excitation is also suggested for the same transition [2]. Although several calculations have been performed to theoretically investigate such interesting properties, none of them can reproduce the extremely hindered $B(E2)$ value [3–5]. This may be due to the fact that those methods do not include certain exotic features of unstable nuclei because of their foundation in and near stable nuclei.

Recently, we have proposed a new microscopic shell-model approach to neutron-rich carbon isotopes including ^{16}C [6]. The model space contains the orbits from the $0s$ up to the $1p0f$ shells and thus is no-core type. The effective two-body interaction is microscopically derived from a high-precision modern NN force and the Coulomb force through a unitary transformation theory which is employed in the unitary-model-operator approach (UMOA) [7]. In the present study, we use the bare charges in calculating the electric transition strength for simplicity. We shall show that $B(E2; 2_1^+ \to 0_1^+)$ values and low-lying excited levels of $^{14-18}$C can be well described by the new shell-model framework.

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Systematic Study of High-spin Isomers in N=83 Isotones

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High-spin isomers were reported systematically in N=83 isotones [1]. Their lifetimes range from 10 ns to a few μ sec. The excitation energies of those isomers are close each other in a range of 8.5-9.0 MeV except for ^{151}Er. Figure 1 shows experimental systematics of the high-spin isomers in N=83 isotones. The isomerism may be originated from a sudden shape change from near spherical to oblate. Recently, studies of the proton-rich N=83 nuclei ^{150}Ho(Z=67) and ^{151}Er(Z=68) have been performed using techniques of in-beam gamma-ray spectroscopy. Experimental results are discussed comparing with a deformed independent particle model (DIPM) calculations [2]. As a result, the candidate configuration of high-spin isomers in ^{150}Ho and ^{150}Er are different from these of other N=83 members.

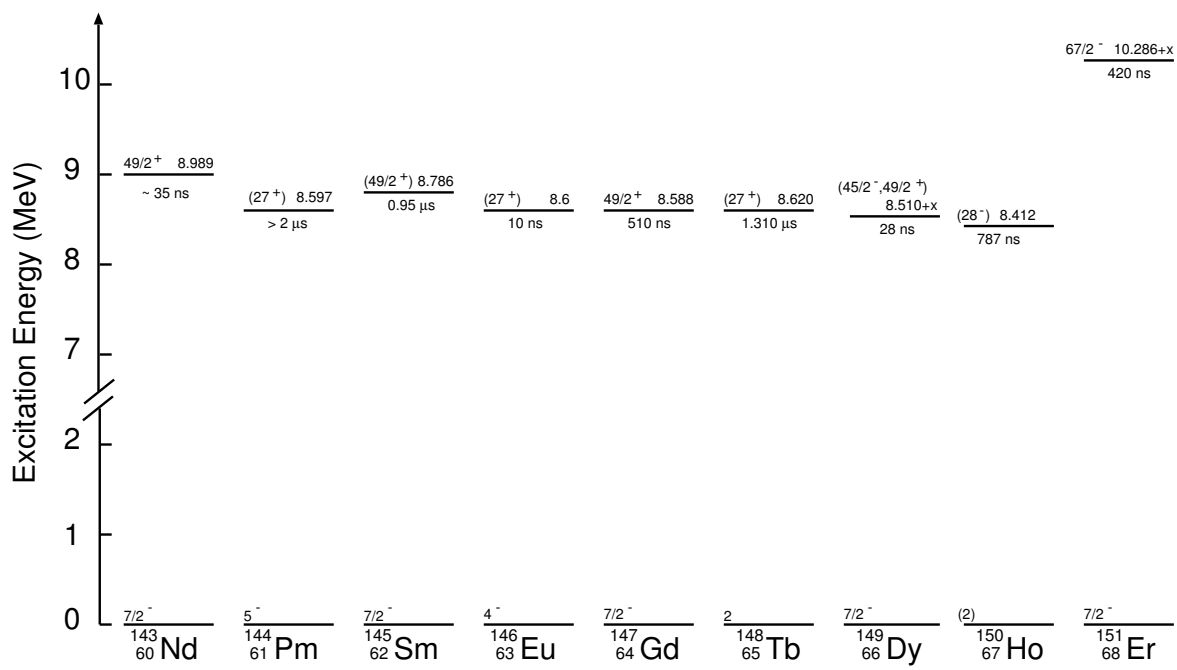

FIG. 1: Experimental systematics of the high-spin isomers in N=83 isotones.

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Alpha cluster states in ^{12}C and ^{16}O

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As one of the typical issues of nuclear structure problems, many works have been made focusing on an alpha clustering nature in light nuclei [1]. In particular, recent investigations of alpha cluster states with dilute gas-like structure are of a special interest. Taking into consideration the exsistence of the α gas states naturally leads to an idea that all α particles can condense into the same lowest S-orbit. Those states can be expected to exsist in the vicinity of the α-breakup threshold, and the 0_2^+ state at 7.65 MeV of ^{12}C, which is called Hoyle state and known as playing a special role in the synthesis of ^{12}C in stars, was shown to be a strong candidate of the 3α condensed state [2]. The previous work on ^{12}C by the present authors gave a decisive evidence that the Hoyle state is the 3α condensate by showing that a 3α condensate model wave function of 3α dilute gas-like character is almost equivalent to the 3α cluster model wave function obtained by solving the RGM equation without any model assumption with respect to the inter-α-cluster motions [3]. It is also reported that in the Hoyle state the occupation probability of α particles into a single S-orbit amounts to 70 % [4]. Furthermore, we propose that the recently observed 2_2^+ state at 9.9 ± 0.3 MeV [5] can be regarded as a family of the Hoyle state [6]. This state can be described by making one of the three α particles jump into the D-orbit, while the other two stay in the S-orbit. This way of description is based on a different picture from that of rotational excitation, where the third α particle of D-wave rotates around the ground state of ^{8}Be. The calculated r.m.s. radius of this state amounts to 5.4 fm, which corresponds to a tenth of the ground state density, and hence it can be called "an α-halo state".
The next study of great interest is to find the 4α condensate in ^{16}O. The candidate of 4α condensate was recently observed near the 4α threshold [7]. The 4α condensate model wave function reproduces the energy and α-decay width of the new state. A preliminary experimental data of angular distribution of (α, α') inelastic scattering also seems to be correponding to our calculation. It should be noted that in ^{16}O there exsist two 0^+ states at 6.06 MeV and 12.05 MeV with α+^{12}C structure, which is considered to be quite different from that of the 4α condensed state of dilute gas character. In order to investigate the 4α condensate which should be constructed above the α+^{12}C states, it is very important to take into account the both cluster structures as well as the compact shell structure in the ground state. Since the 4α condensate model wave function seems to have a difficulty in the description of the α+^{12}C structure, we apply 4α orthogonality condition model (OCM) so as to reproduce those structures simultaneously. We, in this contribution, will summarize the previous results of ^{12}C mentioned above and report recent results about ^{16}O which are made based on the 4α condensate model wave function and the 4α OCM.

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See also http://www.rcnp.osaka-u.ac.jp/ annurep/2002/sec1/wakasa2.pdf

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Nuclear-structure studies in the vicinity of $N = 28$

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Observations in exotic nuclei have demonstrated that the sequence and energy spacing of single-particle orbits is not as immutable as once thought: some of the familiar magic numbers disappear and new shell gaps develop [1]. This talk will summarize some of the recent results on the changes of shell structure in the vicinity of $N = 28$.

A particularly rich ground for the study of modifications to the shell structure far from stability is provided by neutron-rich species with protons in the *sd* shell and neutrons in the *fp* shell. For example, the Coulomb excitation of the $N = 28$ nucleus ^{44}S showed enhanced collectivity, unexpected for a nucleus with an $N = 28$ closed shell [2]. The question of whether this is due to a breakdown of $N = 28$ or the collapse of the $Z = 16$ gap is much discussed (e.g., [3,4]). To isolate the changes in the shell structure around $N = 28$, we studied excited states in ^{40}Si ($Z = 14$, $N = 26$) where the $Z = 14$ sub-shell gap remains large [5]. Results and implications will be presented.

A complementary approach, sensitive to the neutron single-particle structure, is given by one-neutron knockout reactions. We report on the study of the $N = 28$ nucleus ^{46}Ar from the ^{9}Be(^{46}Ar,^{45}Ar+γ) one-neutron removal reaction and present the implications for the $N = 28$ shell gap in the chain of Ar isotopes [6].

Just four neutrons above $N = 28$, a new sub-shell closure at $N = 32$ has been predicted for neutron-rich Ca, Ti and Cr isotopes [7,8]. Cross-shell excitations, arising from the promotion of nucleons across shell gaps, probe changes in shell structure. They are, however, not always readily identifiable in nuclear spectra. We demonstrate that two-proton knockout reactions can examine, selectively, cross-shell *proton* excitations in *neutron*-rich systems. The two-proton knockout reaction ^{9}Be(^{54}Ti,^{52}Ca+γ) has been studied at 72 MeV/nucleon. Sizable cross sections were found to feed only the ^{52}Ca ground state and a 3^- level with an excitation energy near 4 MeV, bypassing completely the first 2^+ level at 2.6 MeV. These observations can be reproduced qualitatively by calculations which assign the 3^- level to the promotion of protons across the $Z = 20$ shell gap. In addition, the data confirm the presence of a neutron sub-shell closure at $N = 32$, the subject of much recent attention [7-12].

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Proton cross-shell excitations: The Study of ^{52}Ca *

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Observations in exotic, neutron-rich nuclei have demonstrated that the sequence and energy spacing of single-particle orbits is not as immutable as once thought: some of the familiar magic numbers disappear and new shell gaps develop [1]. Cross-shell excitations, arising from the promotion of nucleons across shell gaps, probe changes in shell structure. They are, however, not always readily identifiable in nuclear spectra. We demonstrate that two-proton knockout reactions can examine, selectively, cross-shell *proton* excitations in *neutron*-rich systems.

The two-proton knockout reaction ^{9}Be(^{54}Ti,^{52}Ca+γ) has been studied at 72 MeV/nucleon. The ^{54}Ti secondary ions were produced by fragmentation of a 130 MeV/nucleon ^{76}Ge beam, delivered by the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory, onto a ^{9}Be fragmentation target. The ions were selected in the A1900 large-acceptance fragment separator [2], which was operated with two settings during different phases of the experiment, 1% momentum acceptance and no momentum restriction, respectively. The secondary beam interacted with another, 375(4) mg/cm^2 thick, ^{9}Be foil located at the target position of the high-resolution S800 spectrograph [3]. The ^{9}Be reaction target was surrounded by SeGA, an array of seventeen 32-fold segmented HPGe detectors [4], arranged in two rings (90° and 37°). The combination of particle spectroscopy with a magnetic spectrograph and γ-ray detection allowed to untangle the knockout going to individual final states.

Sizable cross sections were found to feed only the ^{52}Ca ground state and a 3^- level with an excitation energy near 4 MeV, bypassing completely the first 2^+ level at 2.6 MeV. These observations can be reproduced qualitatively by calculations which assign the 3^- level to the promotion of protons across the $Z = 20$ shell gap. In addition, the data confirm the presence of a neutron sub-shell closure at $N = 32$, the subject of much recent attention [5-10].

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*This work was supported by the National Science Foundation under Grants No. PHY-0110253 and PHY-0244453, by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W31-109-ENG-38, the UK Engineering and Physical Sciences Research Council (grant EP/D003628) and by Polish Scientific Committee Grant No. 1P03B 059 29.

Secondary Radioactive Beam facilities in Europe: At the dawn of a new era

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The advent of intense secondary radioactive ion beams made possible the exploration of a new territory of nuclei with extreme N/Z ratios. Selected examples of new physics phenomena recently observed with the first generation of Radioactive Beam Facilities (RIB) in Europe will be presented. To pursue the investigation of this terra incognita several projects, all aiming at the increase by several orders of magnitude of the RIB intensities are now under discussions worldwide. Two ambitious second generation RIB European facilities, aiming to increase by several orders of magnitude of the RIB intensities are being built: SPIRAL2@ GANIL based on the ISOL method and FAIR@GSI for the "In Flight" technique. Technical performances, innovative new instrumentation and methods, and keys experiments in connection with these second-generation RIB facilities will be discussed.

T=1 and T=0 states in the N=Z=43 nucleus, ^{86}Tc*

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The low-lying structure of ^{86}Tc has been studied using isomer-decay spectroscopy at GSI in the first experiment of the Stopped-Beam phase within the Rare ISotope INvestigation at GSI (RISING) campaign. Following projectile fragmentation of a 750 MeV/u beam of ^{107}Ag, reaction products were separated and unambiguously identified using the FRagment Separator (FRS) in combination with its ancillary detectors. The ions were made to stop in a plastic stopper at the final focus of the FRS in the centre of the Stopped RISING γ-ray spectrometer. This high-efficiency, high-granularity array consists of 15 germanium cluster detectors in a compact configuration which provides a full photopeak efficiency in excess of 15% at 1.3 MeV. Internal decay of the previously identified [1] microsecond isomer in ^{86}Tc was confirmed with the addition of two previously unobserved γ-rays which help to determine the excitation energy and spin of the isomeric state. As in other heavy odd-odd N=Z nuclei a notably lower density of states below 1 MeV excitation energy compared with neighbouring odd-odd nuclei away from the N=Z line [2] is observed with the lowest T=0 state identified in the preliminary analysis being a $J^{\pi}=3^{+}$ state located 1176 keV above the T=1 [3] groundstate. Results from this experiment will be discussed along with assignments of structure made from shell model calculations and systematics of N=Z nuclei.

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* This work was partially supported by the EPSRC (UK) and the U. S. Department of Energy under grants DE-FG02-91ER-40609 and W-31-109-ENG-38. ABG would also like to acknowledge financial support from Nexia Solutions Limited, a subsidiary of BNFL.

Nuclear In-Beam and Decay Spectroscopy with RISING

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Nuclear spectroscopy using radioactive isotope beams requires dedicated set-ups. State-of-the-art Ge arrays recently started to provide valuable γ spectroscopic data. At the SIS/FRS facility at GSI exotic beams at relativistic energies (100 ... 400 A·MeV) were employed for Coulomb excitation and secondary fragmentation experiments with the fast beam RISING set-up [1] shown in fig. 1. Beams of radioactive isotopes were produced by fragmentation or fission of heavy stable nuclei on a production target. Isotopes of interest were selected by the dipole magnets and the degrader of the FRS, and identified ion by ion in mass and charge by measuring Bρ-ToF and ΔE. In addition position and direction tracking was performed. After the secondary target the CATE Si-CsI(Tl) array served to determine scattering angle, charge and total energy of the projectile-like fragment. 15 Euroball Cluster detectors forming a forward wall were employed to measure γ rays emitted in secondary reactions. A full energy efficiency of 3% at 1.3 MeV γ-energy and about 1% energy resolution was achieved.

In a series of experiments shell evolution far off stability, pn-pairing, symmetries and nuclear shapes were studied in nuclei ranging from ^{36}Ca to ^{136}Nd. Selected results will be discussed.

In another Ge-detector configuration a series of g-factor experiments was performed. Most recently the compact detector arrangement of RISING -providing about 18% full energy efficiency- went into operation. Seniority isomers in medium heavy nuclei at the proton drip line have been investigated as well as new isomers found in neutron rich nuclei, e.g. ^{204}Pt. The observation of a I = 27 ħ state demonstrated that high spin states can be obtained in massive fragmentation reactions. This and the large sensitivity of both relativistic in-beam as well as stopped decay experiments open a rich ground for advanced nuclear structure studies.

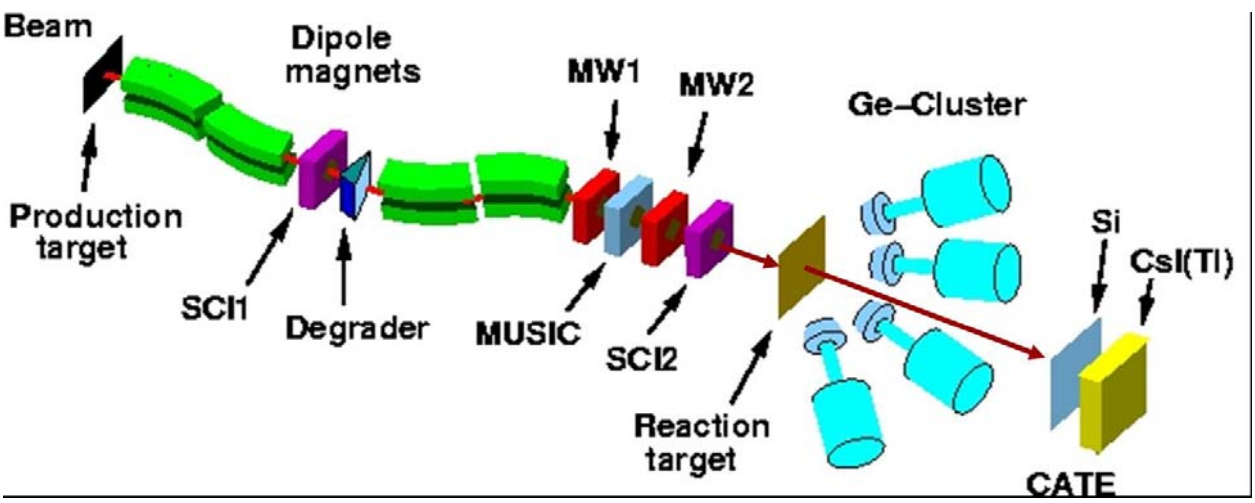

FIG. 1. A schematic drawing of the RISING fast beam set-up.

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Role of the entrance channel dynamics on the products of massive nuclei reactions

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We study the effects of the entrance channel on the formation probability of reaction products (evaporation residues or/and fission fragments) and their characteristics, in establishing, in particular, the optimal conditions for the synthesis of superheavy elements.
The objective is to understand the role of the relevant parameters characterizing [1,2] the heavy ion collision (beam energy, orbital angular momentum, mass asymmetry parameter, shell structure and *A/Z*-ratio of nuclei, orientation angles of deformed nuclei) in the evolution of the dinuclear system (DNS) which determines the main characteristics of the reaction mechanism [2,3] (quasifission, fusion, fast-fission, fission, evaporation).

We discuss the advanced theoretical model suitable to interpret the observed characteristics of the reaction products and their dependence on the entrance channel reaction [4]. We also discuss, in particular, the results about the ^{92,96}Zr+^{124,132}Sn reactions where ^{132}Sn is a nucleus with a double shell closure of protons and neutrons.

The investigation of the above-mentioned reactions allows us to have information about the dependence of the reaction products on the isotopic composition of reacting nuclei and effective deformation of nuclei at collision, and on the lifetime of the dinuclear system as a function of the projectile energy. Fig.1 shows the excitation functions of capture and complete fusion versus the beam energy, E_{cm} , for various values of the DNS lifetime, $t_{DNS,}$ for the ^{96}Zr +^{124}Sn reaction. Fig.2 shows the excitation functions of capture and fusion versus E_{cm} for various DNS lifetime for the ^{96}Zr+^{132}Sn reaction.

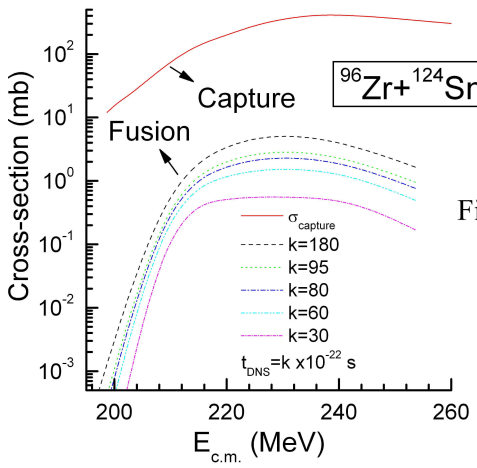
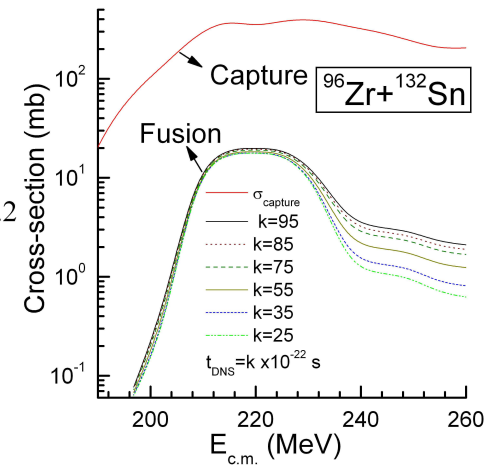


Fig.1

Fig.2



By comparing the trend of the fusion cross-sections for the two reactions we obtain that at lower energies the fusion cross-section is more sensitive to t_{DNS} for the first reaction, while at higher energies the trend of the fusion cross-section is strongly sensitive for both reactions. At lower energies of the ^{96}Zr+^{132}Sn reaction the fusion cross-section changes a little with t_{DNS} because the relevant shell effect of the double closure of ^{132}Sn. The fusion excitation function is sensitive to the t_{DNS} values because the competition between quasifission and fusion is affected by the probability of population of the configuration (Z, Z_{tot}-Z) at $E^*_{DNS}(Z)$, and the angular momentum ℓ [3]. The transport master equations with the transition coefficients calculated microscopically are solved numerically for multinucleon transfer for a given interaction time.

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Search for low lying dipole strength in the neutron rich nucleus ^{26}Ne

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We carried out the Coulomb excitation of the neutron-rich nucleus ^{26}Ne at 58 MeV/n, in order to search for a pygmy dipole resonance above the neutron emission threshold [1]. The experiment, performed at the RIKEN Accelerator Research Facility, included a gamma-ray multidetector, a charged fragment hodoscope and a neutron detector wall. Using the invariant mass method in the ^{25}Ne+n decay channel to reconstruct the excitation energy spectrum, a sizable amount of strength between the one neutron and the two neutron emission thresholds is extracted. (see Fig. 1 *Left*).
A multipole decomposition of the corresponding ^{26}Ne differential cross-section (Fig. 1 *Right*) allows to extract an E1 contribution exhausting $5.6 \pm 2.1\%$ of the corresponding Thomas-Reiche-Kuhn energy weighted sum rule. The reduced dipole transition probability is $B(E1) = 0.54 \pm 0.18$ e^{2}fm^2. For the first time, the decay pattern of pygmy resonances was also extracted. We compared our result to mean-field and shell model calculations.

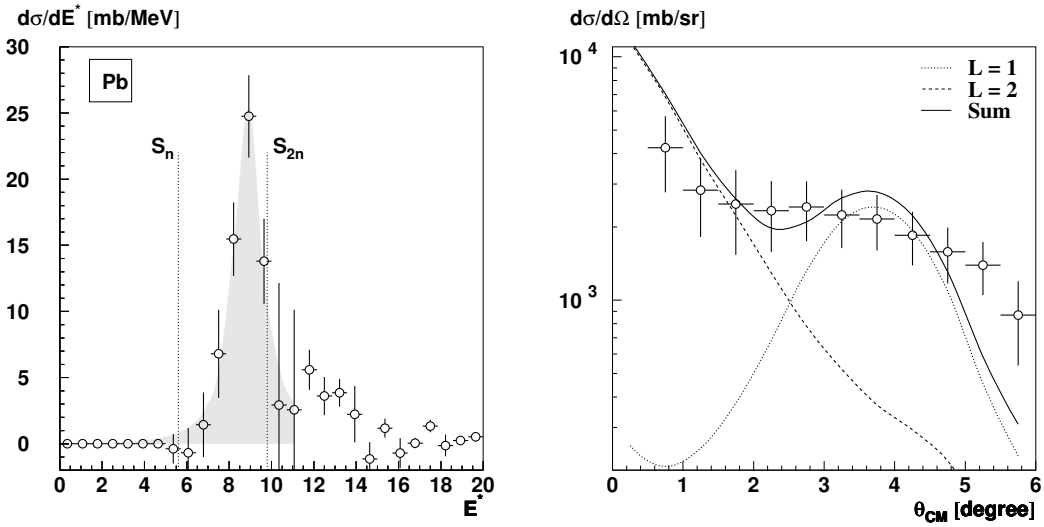

FIG. 1: Left: ^{26}Ne excitation function rebuild from ^{25}Ne+n decay channel Right: Experimental angular distribution (open cirlce) fitted with corresponding calculated $L = 1$ and $L = 2$ scattering angular distributions.

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Nucleon-nucleon symmetry potential term and GDR γ-ray emission

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The study of the isospin dependence of the nuclear equation of state (EOS) at Fermi energies in recent years has triggered a wide interest of the nuclear physicist community. At a density far from the saturation value, the poorly known symmetry term can strongly influence phenomena like the evolution of supernovae and neutron stars and can affect the structure of exotic nuclei. An intense activity in this field has produced quite interesting results from the theoretical and experimental points of view. These results concern mostly the study of the behavior of hadronic probes produced through nucleus-nucleus collisions in which at least one of the two partners is a neutron rich nucleus. The unusual charge/mass asymmetry ratio of a hot compound, obtained through the collision of nuclei (projectile and/or target) with a high neutron excess, can highlight the "stiffness" of the symmetry term. In particular, the scaling properties of the fragment isotopic and isotonic distributions, the differential neutron-proton flow and the degree of isospin diffusion have been considered for this purpose(se as some examples refs.[1-6]).
At the same time, starting from the first experiments reported in refs.[7], it was shown that systems with a large difference in the charge/mass asymmetry between projectile and target can produce pre-equilibrium giant dipole resonance (GDR) emission. This was observed as an extra-yield compared to the analogous charge/mass symmetric system. Other experiments have confirmed this observation in different systems and at incident energies between 8-25 MeV/nucleon in both central and mid-peripheral collisions [8,9]. For the ^{40}Ca+^{48}Ca system, as discussed in refs.[10,11], this pre-equilibrium yield can be directly related to the "isospin" equilibration mechanism leading to charge/mass equilibration.

The aim of this contribution is to show results obtained from the investigation of the sensitivity of the GDR γ-ray emission to the "stiffness" of the symmetry energy term for the ^{40}Ca+^{48}Ca system at 45 MeV/nucleon . In particular we will try to highlight this sensitivity by studying the dynamics of the above mentioned system and the GDR γ-ray emission mechanisms by means of the Constrained Molecular Dynamical model CoMD-II [11]. As an example we study central and mid-peripheral reactions in the charge/mass asymmetric system ^{40}Ca+^{48}Ca at 45 MeV/nucleon. The calculations show that the balance between the dynamical and the statistical emission is very sensitive to the "stiffness" of the symmetry term. This sensitivity can be highlighted by measuring the degree of coherence and the anisotropy ratio related to the dynamically emitted radiation. We think that these kind of studies could integrate and be usefully compared with the results obtained from the observation of hadronic probes. This can give further information for the constraint the EOS of asymmetric nuclear matter.

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High Spin States in ^{52}Cr

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Most of the nuclei from ^{40}Ca to ^{56}Ni are well described by a shell model in which the most important configurations are $(f_{7/2})^n$ and $(f_{7/2})^{n-r}$ $(f_{5/2}\ p_{3/2}\ p_{1/2})^r$, where n is the number of particles outside the closed shell and r =1,2,... [1-2]. In addition, states of opposite parity arise due to the excitations of the core sd shell nuclei. Yrast spectroscopy of the majority of f-p shell nuclei follows the shell model expectation, exhibited by somewhat irregular level spacing, often with a marked discontinuity at the termination of the $f_{7/2}$ band. The nuclear structure is particular apparent in the nuclei near N or Z=20, 28 where low-spin states roughly follow a J (J+1) energy rule with a large B (E2) values [3]. These two features together suggest a collective rotation. At higher spin, but well below J_{max} (~16ħ) irregularities in the level spacing occur. These may be taken as the evidence of either a level crossing with consequent back-bending, or alternatively as breakdown of collectivity and reappearance of the shell model behaviour. Coexistence of spherical and deformed shapes take place rather predominantly in or near the semi-magic or double magic nuclei. Recently spherical-deformed shape coexistence has been experimentally found in the doubly magic nucleus ^{56}Ni [4] and was also suggested for ^{54}Fe and ^{52}Cr [5].

The study of high spin states in N ~ Z, $f_{7/2}$ nuclei is of current interest. We have therefore studied the high spin states in ^{52}Cr via ^{27}Al(^{28}Si, 3p)^{52}Cr fusion evaporation reaction. The 70 MeV ^{28}Si beam was provided by the 15UD Pelletron facility at Nuclear Science Centre (NSC), New Delhi India. An isotopically enriched 500 μg/cm^2 thick ^{27}Al target was used. The de-exciting gamma rays were detected using the Indian National Gamma Array (INGA) facility consisting of eight clover detectors combined with the heavy Ion Reaction Analyzer (HIRA) and four neutron (5″ × 5″) detectors. The level structure of ^{52}Cr has been established up to E_x ~10 MeV with spins up to J~13ħ. In addition to the transitions reported earlier using only two simple HPGe detectors of about 17% efficiency [6], we have observed about twelve new transitions in the present work. Linear polarization measurements have also been done along with the angular correlation measurements of the observed γ-rays to assign the multipolarity to the unknown transitions. The band structures are discussed in the framework of the shell model calculations.

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High Precision Half-Life Measurement of the Superallowed β^+ Emitter ^{18}Ne via γ-ray Counting*

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As part of a broad experimental program in superallowed Fermi β decay studies at the Isotope Separator and Accelerator (ISAC) facility at TRIUMF in Vancouver, Canada, the half life of the superallowed β^+ emitter ^{18}Ne has been determined from a γ-ray counting experiment using the 8π γ-ray Spectrometer.

Half-life measurements at the level of precision required (~ 0.05 %) to distinguish between model dependencies of the isospin symmetry breaking corrections in superallowed Fermi β decay have only been achieved through the method of β counting. This technique, although widely applicable, is ideal only when the decay of interest can be cleanly separated from contaminant decays or when the half lives of the daughters and contaminants differ significantly from the decay of interest. A new technique for determining nuclear half lives to sufficiently high precision from the γ-ray activity following the β decay is therefore becoming increasingly important. In γ-ray counting experiments, applying a γ-ray gate on identifiable γ-ray transitions can be used to distinguish particular decays and suppress unwanted contaminant and daughter activities. Measurements of this type, however, have not reported comparable precision to β counting because of systematic rate-dependent pulse pile-up effects.

A new technique has been developed that corrects γ-ray gated decay data for detector pulse pile-up, and has been verified through radioactive ^{26}Na beam experiments with the 8π Spectrometer and an extensive Monte Carlo simulation study. Application of this new method to the determination of the half life of ^{18}Ne via γ-ray counting is the first of a series of superallowed half-life experiments envisioned at ISAC. The result of this work represents the most precise superallowed half-life measurement ever obtained from a γ-ray counting experiment and establishes the ^{18}Ne half life to ± 2 ms, a result which is four times more precise than the current world average of 1672 ± 8 ms.

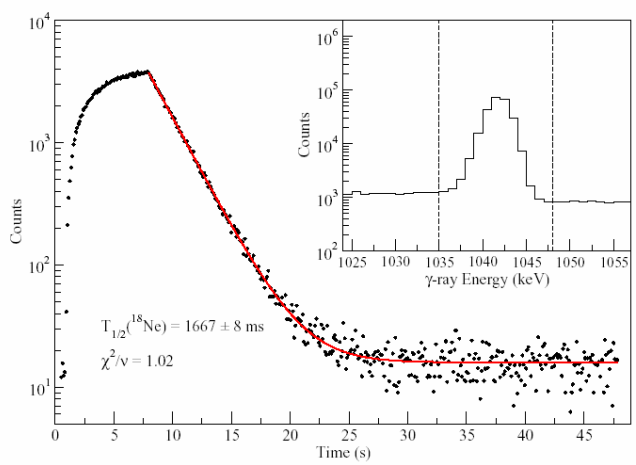

FIG. 1. Typical ^{18}Ne decay curve, obtained from a γ-ray gate on the 1042 keV transition in the daughter ^{18}F (inset).

*This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).
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^{128}Cs as the best candidate revealing chiral symmetry breaking phenomenon

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Resluts of the DSAM lifetime measurements in supposed chiral partner bands of ^{128}Cs and ^{132}La will be shown. The Experimental reduced transition probabilities in ^{128}Cs will be compared with theoretical calculations done in the frame of Core Quasi Particle Coupling model. The electromagnetic properties and energy pattern of partner bands show that ^{128}Cs is the best candidate revealing the chiral symmetry breaking phenomenon.

One of the most interesting symmetry discussed since a few years is the chiral symmetry. The results of theoretical calculations (TAC [1], CPHC [2], self-consistent H-F [3] calculations) pointed to the possibility of spontaneous breaking of chiral symmetry in intrinsic reference frame of atomic nucleus. In laboratory reference frame this phenomenon manifests itself as two rotational bands (chiral partner bands) with the same spins and parities, nearly identical excitation energy and very characteristic gamma decay properties [4,5]. Such partner bands were found in ten nuclei in the A≈130 and two nuclei in A≈100 mass regions. Among these nuclei a detailed study of chiral partner bands based on the $\pi h_{11/2}\otimes(\nu h_{11/2})^{-1}$ configuration was done in ^{132}La [2] and ^{128,130}Cs [5]. The aim of experiments described in this presentation was lifetime measurements of excited levels belonging to the partner bands in ^{132}La and ^{128}Cs.

A theoretical study of transition probabilities and selection rules for idealized case of chiral partner bands are presented in [6], where Hamiltonian of rigid triaxial rotor coupled to the proton (particle) and neutron (hole) in chiral configuration is investigated. The characteristic electromagnetic properties of the partner bands described in [6] are confirmed by our experimental data of ^{128}Cs.

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Fast α-decay near doubly-magic ^{100}Sn: the discovery of ^{109}Xe and ^{105}Te

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The existence of an island of alpha emission above the neutron-deficient Sn region provided the initial evidence that the N=Z=50 shell closure holds in this exotic region, indicating the doubly-magic character of ^{100}Sn. Above ^{100}Sn and close to the N=Z line protons and neutrons are expected to fill identical orbitals and proton-neutron correlations become important. This, and/or the double magicity of ^{100}Sn, is expected to enhance the preformation of alpha particles with respect to the ^{208}Pb region and give origin to the so-called "superallowed" alpha decay [1] characterized by the large decay probability. Further interest in the decay rates around ^{100}Sn comes from astrophysical processes, where this region has been cited as the end of the rp-process due to the Sn-Sb-Te cycle [2].

The newly observed isotope ^{109}Xe was produced by using the ^{58}Ni(^{54}Fe,3n) fusion-evaporation reaction with a beam energy of 222 MeV at the HRIBF at Oak Ridge National Laboratory. The recoiling products were separated by means of the Recoil Mass Spectrometer [3] and implanted into a Double-sided Silicon Strip Detector. Recoil and decay signals were analyzed using a digital data acquisition system based on XIA-DGF modules [4]. The large recoil pulses were allowed to have their amplitudes extracted by the real time on-board algorithm, while for decay pulses below 9 MeV, the 25 μs-long images were transfered to the main acquisition CPU and have their pulse shapes analysed with floating point algorithms. The novel data acquisition technique allowed for the resolution of the two overlapping alpha particles signals into two separate energies despite the sub-microsecond half-life of ^{105}Te.

The lightest mass α-radioactivity identified to date, ^{105}Te, was detected through the ^{109}Xe$\rightarrow^{105}$Te$\rightarrow^{101}$Sn alpha decay chain. This marks the closest experimental approach to the N=Z line above ^{100}Sn . The results, including the reduced width of the observed, enhanced alpha transitions and deduced decay schemes will be presented. Additionally, fine structure in the millisecond alpha decay of ^{109}Xe to ^{105}Te was identified and the energy difference between the $\nu d_{5/2}$ ground state and the $\nu g_{7/2}$ first excited state was determined to be 150$\pm$13 keV in ^{105}Te.

Prospects for discovery of the alpha decay chain ^{108}Xe$\rightarrow^{104}$Te$\rightarrow^{100}$Sn, with xenon and tellurium isotopes as candidates for a superallowed transition, will be discussed.

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Internal Conversion Coefficient Measurements of Transitions in ^{167}Lu *

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Experimental internal conversion coefficients (ICCs) can be used to determine the multipolarities of electromagnetic transitions between nuclear energy levels and thus are valuable for assigning or confirming spins and parities of excited states.

One of the experimental methods to measure in-beam ICCs is the use of Mini Orange Spectrometers (MOS) [1] together with γ ray spectrometers in coincidence mode. The ICEBALL [2] (Internal Conversion Electron Spectrometer) is a MOS type of electron spectrometer located at WNSL, Yale University. It consists of six Si(Li) detectors and Mini Orange Filters (MOF). Each Si(Li) detector attached to a MOF. Each MOF has several permanent magnets attached to a central absorber made by a heavy element to block the γ rays and the heavy charged particles emitted during the reaction.

The normal and highly deformed bands of ^{167}Lu were populated by the ^{123}Sb(^{48}Ca,4n) fusion evaporation reaction at a beam energy of 203 MeV. Gammasphere and ICEBALL spectrometers were used to detect the coincidence events. The events were recorded when at least five or more compton suppressed Ge detectors or two compton supressed Ge detector and one Si(Li) detector were fired. γ - γ and γ - e matrices as well as γ - γ - γ and γ - γ - e cubes were produced to analyze the coincidence data. Internal conversion coefficients were determined for transitions in ^{167}Lu and multipolarities were deduced.

The preliminary results of the analysis will be presented.

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*This work was supported by the U.S.D.O.E grants DE-FG02-88ER40417, DE-FG02-91ER-40609, DE-FG-05NA25929, DE-FG02-05ER41379, by the NSF grant number PHY-0300673 and in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W-31-109-ENG-38.

Entropy of Heated Nuclei

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The level density of atomic nuclei at moderate temperatures ($T < 1$ MeV) is mainly determined by the number of free single quasiparticles. Typically, the breaking of one nucleon Cooper pair produces $30 - 50$ times more states. For rare earth nuclei, rotational and vibrational motion contribute only $10 - 15$ % at around 8 MeV of excitation energy. Thus, excited single particles are essential for the description of nuclear thermodynamic properties [1].

In this talk the concept of single particle entropy will be presented. It will be shown that this quantity is approximately extensive (additive) for mid-shell nuclei. Figure 1 demonstrates how the single particle (or hole) in ytterbium nuclei contributes with an entropy of $S_1 \sim 2$ (in units of the Boltzmann's constant k_B) compared to the even-even core [2]. Various applications of single particle entropy in heated nuclei will be discussed.

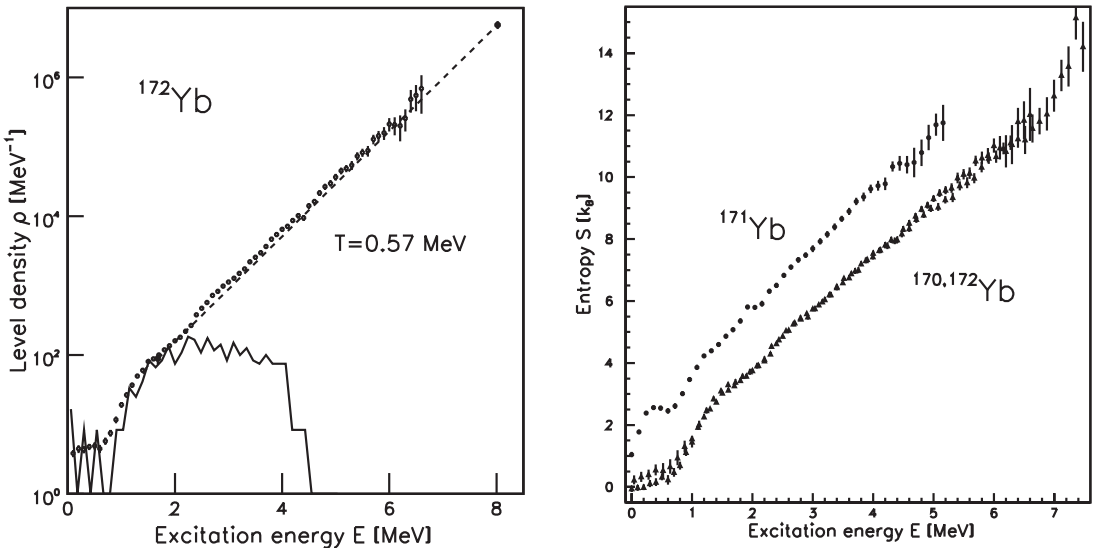

Figure 1: Left panel: Experimental level density deduced from the (^{3}He,α) reaction using the Oslo method. The Oslo data cover the unknown excitation region between 2 and 7 MeV. Right panel: Experimental entropies for ^{170,171,172}Yb. The full circles correspond to ^{171}Yb, and full and open triangles correspond to ^{170}Yb and ^{172}Yb, respectively.

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This work was supported by the Norwegian Research Council (NFR).

A Test of Chiral Doubling Vs. Accidental Degeneracy

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High spin states in ^{106}Mo, ^{108,110,112}Ru have been studied by detecting the prompt γ-rays in the spontaneous fission of ^{252}Cf with Gammasphere. With our very high statistics data, pairs of $\Delta I = 1$ bands with nearly degenerate energies were observed in all four of these even-even neutron-rich nuclei. The levels in ^{106}Mo were observed first and tilted- axis-cranking (TAC) calculations supported their interpretation as chiral vibrational doublets [1]. There are, however, in ^{105}Mo, two nearly degenerate, one-neutron quasi-particle bands [2]. Thus, it is possible that accidental degeneracy might occur by adding an $h_{11/2}$ neutron to a pair of bands in ^{105}Mo could give rise to the doublet bands in ^{106}Mo. To test this idea, in both ^{106}Mo and ^{110,112}Ru, calculations were made for various quasi-particle configurations with negative parity for both an axial shape with $\gamma = 0^o$ and a triaxial shape with $\gamma = 30^o$. It turns out in all these cases the intra-band cascade-to-crossover branching ratios of the two lowest bands differ typically by an order of magnitude when comparing the ratios for states of the same spin. We have carefully analyzed these ratios for ^{106}Mo in addition to those for ^{108,110,112}Ru [3]. In all four cases, these branching ratios from the two 7^- states to the two 12^- states for these pair of bands are similar. These data rule out the interpretation of these pair of bands being built on two different quasi-particle states in ^{106}Mo or ^{110,112}Ru and support the chiral vibrational assignment.

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^{62}Ni(n,γ) and ^{102}Pd(n,γ) cross section measurements with DANCE

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Most of the nuclei heavier than Fe are produced via neutron capture reactions in the so called s or r-process. The ^{62}Ni(n,γ) cross section is important for the understanding of the weak s-process component during helium burning in massive stars of 10 to 25 solar masses. The weak s-process, which produces elements with $60 \leq A \leq 90$, is much less understood than the main s-process component. Since this process operates in massive stars it is ultimately linked with the abundance contributions of explosive nucleosynthesis in supernovae.

The nuclei on the proton rich side of the valley of stability cannot be produced by neutron capture reactions, and are mainly produced via photo disintegration on heavier nuclei (p- process). Since the p-process produces free neutrons, which can be captured, neutron capture cross sections are important for understanding this process.

The neutron capture cross section of the ^{62}Ni and the proton rich nucleus ^{102}Pd were measured with the Detector for Advanced Neutron Capture Experiments (DANCE) at the Los Alamos Neutron Science Center. The targets were a 210 mg Ni ball (96% enriched ^{62}Ni) and a 2 mg Pd foil (78% enriched ^{102}Pd). They were held by thin Mylar bags, which were selected after comparing different thicknesses of Kapton and Mylar for their scattering background. A ^{12}C sample was used to determine the scattering background. Results of the ^{62}Ni(n,γ) and ^{102}Pd(n,γ) cross sections for neutron energies from 260 eV to 200 keV are presented.

This work has benefited from the use of the Los Alamos Neutron Science Center at the Los Alamos National Laboratory. This facility is funded by the US Department of Energy and operated by the University of California under Contract W-7405-ENG-36. The Colorado School of Mines group is funded via DOE Grant: DE-FG02-93ER40789.

First results from GABRIELA, a new array for transfermium γ-ray and conversion electron spectroscopy.

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The heaviest elements provide a unique laboratory to study nuclear structure and nuclear dynamics under the influence of large Coulomb forces and large mass (A). The stability of nuclei beyond the spherical "doubly-magic" ^{208}Pb (Z = 82, N = 126) decreases rapidly until the transfermium region (Z > 100) where a lowering of the level density of single-particle states for nuclei in the neighbourhood of the deformed doubly-magic $^{270}_{108}$Hs reverses this trend locally [1]. However, the position of the spherical doubly-magic nucleus beyond ^{208}Pb remains controversial: recent calculations predicting Z = 114, 120, or, 126 for the next magic proton shell, and N = 172 or 184 for neutrons [2]. It is therefore crucial to determine the relative excitation energies of single–particle states in the transfermium region [3] to reduce the extrapolation required in predicting the position of this "island of stability" for the very heaviest nuclei [4]. Moreover, the deformed isotopes in the Fm-Sg (Z=100-106) region sample most of the nucleonic orbits which are involved in the stabilisation of the predicted spherical super-heavy elements. In addition, their less-neutron-deficient representatives (some of which are barely known or not even charted) are members of the alpha decay chains of the newly synthesized elements (Z=114,116 and 118). Hence, the systematic study of the structure and decay properties of deformed transfermium elements is essential, and probably for many years, the only available way to reach an understanding of the structure at the upper end of the nuclear chart.

A detection system dedicated to the spectroscopy of transfermium nuclei has recently been constructed at the focal plane of the VASSILISSA separator at the FLNR, Dubna, by a Franco-Russian collaboration. The details of this array, named **GABRIELA** [5] (**G**amma **A**lpha **B**eta **R**ecoil **I**nvestigations with the **E**lectromagnetic **A**nalyser VASSILISSA), will be given. The first results from two one-month long campaigns will be presented : the excited states in ^{249}Fm following the alpha decay of ^{253}No [6], isomeric decay in ^{253}No, excited states in ^{251}Fm populated via the alpha decay of ^{255}No, and the alpha decay properties of ^{255}Lr. Planned improvements and future experiments will be discussed.

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Decay of the r-process waiting point nucleus ^{138}Sn and adjacent nuclei

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The r-process path is sensitively dependent on the lifetimes and decay modes of the extremely neutron rich nuclei[1]. The vast majority of r-process nuclei are not experimentally accessible, hence their calculated abundances are dependent on models and extrapolations. Far from stability predictive models may have significant differences with experimental values, as was recently found with measurements for ^{130}Cd [2]. The r-process rates are especially dependent on lifetimes and decay branches of waiting point nuclei and so it is of paramount importance to obtain experimental inputs for nuclei with the highest N/Z ratios possible. For the neutron-rich closed-proton shell Sn nuclei, results for the decay of ^{135,136,137}Sn have been recently presented [3].

In this paper, new results for the decay of the r-process waiting-point nucleus ^{138}Sn are reported. Sn nuclei were produced at CERN/ISOLDE in the fast-neutron induced fission of ^{238}U and selectively ionized with the Resonance Ionization Laser Ion Source (RILIS). The high-resolution mass separator (HRS) was used to obtain mass selection prior to implantation of the ions onto a tape centered in the Mainz Neutron Long Counter where decay of the selected nuclide was studied. From these data and using the new results for the decay of ^{137,138}Sb,[4] half-life and neutron-emission probabilities (P_n) values for ^{138}Sn were extracted.

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Trans-Fermium Spectroscopy*

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Superheavy elements have always provided a great testing bed for nuclear model calculations. The heaviest systems are created at the single atom level and constitute a major triumph of modern experimental techniques which provides stringent tests for theoretical models of any persuasion. However, it is the somewhat lighter, well deformed nuclei of the nobelium region that we have chosen to be the focus of our nuclear structure studies aimed at revealing the underlying single particle structure. In these lighter systems cross sections are still large enough for in-beam spectroscopic studies using ^{48}Ca beams on various targets around ^{208}Pb. Over the last years a wealth of data on heavy, well deformed nuclei such as ^{248,250}Fm, ^{251}Md, ^{252,253,254,255}No and ^{255}Lr has been collected using in-beam conversion electron and gamma ray spectroscopy as well as detailed decay spectroscopy at the focal planes of various recoil separators [1].

Recent highlights are the in-beam gamma spectroscopy experiments on ^{253}No, ^{251}Md and ^{255}Lr. In addition, decay spectroscopy is sensitive to the presence of isomeric states, which serve as a highly sensitive probe into the spectrum of quasiparticle excitations. Recently data has been obtained on isomeric states in the nobelium isotopes ^{252,253,254,255}No.

The talk will focus on the experimental results obtained in the last year, focus especially on the newly observed isomers in ^{254}No [2]. Here detailed quasiparticle assignments can be made to isomeric states.

The experimental challenges and necessary instrumentation to take this subject forward will be highlighted.

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* This work has been supported by the European Union Fifth Framework Programme “Improving Human Potential – Access to Research Infrastructure, Contract No HPRI-CT-1999-00044 and the EU 6th Framework programme "Integrating Infrastructure Initiative - Transnational Access", Contract Number: 506065 (EURONS). Support by the Academy of Finland under the Finnish Centre of Excellence Programme 2000-2005 (Project No. 44875, Nuclear and Condensed Matter Physics Programme at JYFL) is gratefully acknowledged. Funding is also gratefully acknowledged from the UK EPSRC. This work was supported in part by the NSF under contract PHY-0140324. This research is supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W-31-109-ENG-38, DE-FG02-94ER40848

†*on behalf of the GREAT and JUROGAM collaborations.*

New interpretation of doublet bands in terms of a pair-truncated shell model

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The band structure with the $\nu h_{11/2} \otimes \pi h_{11/2}$ configuration in the doubly-odd nucleus ^{134}La is investigated within the framework of a pair-truncated shell model (PTSM). In the model, the shell-model basis states of doubly-odd nuclei are constructed by adding an unpaired neutron and an unpaired proton to the even-even core, which consists of angular momentum zero (S) and two (D) collective pairs. We use the pairing plus quadrupole type interaction, whose force strengths are determined so as to reproduce the energy levels of the even-even nuclei in the mass $A \sim 130$ region [1].

The measured spectrum based on the $\nu h_{11/2} \otimes \pi h_{11/2}$ configuration for ^{134}La is compared with the theoretical result. The energy levels for the yrast states are almost perfectly reproduced. Concerning the yrare states, our theoretical result also provides a successful description of the energy levels, though only four levels are observed experimentally. We also calculate the ratios $B(M1)/B(E2)$ for the yrast states, and obtain a good agreement with experiment.

In search of the microscopic origin of the electromagnetic properties, we analyze the reduced matrix elements of $M1$ operators, and compare the $B(M1)$ values for two-nucleon system of one neutron and one proton both in the same $0h_{11/2}$ orbital with those of actual calculations. We also calculate the effective angles between the angular momenta of the neutrons and protons in the $0h_{11/2}$ orbitals. It turns out that the closing of two angular momenta enhances the $B(M1)$ values, and the odd-spin yrast states have a fully aligned configuration of two angular momenta with angular momentum 11. Similarly, the even-spin yrast states ($I-1$), the odd spin states ($I-2$) and the even spin states ($I-3$) are formed mainly with the configurations of angular momentum 10 9, and 8, respectively. We conclude that the level scheme of ^{134}La arises from the chopsticks configurations of the unpaired nucleons in the $0h_{11/2}$ orbitals, weakly coupled with the quadrupole collective excitations of the even-even part of the nucleus [2-3].

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Importance of Time-Odd Mean Field on Large Amplitude Collective Motion

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A microscopic theory of large-amplitude collective dynamics is a long-standing and fundamental subject of nuclear structure physics. In particular, the microscopic determination of collective mass (inertia mass) is a difficult issue. The Inglis-Belyaev cranking mass, which is derived by using the adiabatic perturbation theory, has been widely used in the literature, although it does not take account of contributions of the residual interactions. Especially e ects of the time-odd components of the moving mean- eld are completely neglected. Such time-odd e ects of the particle-hole interaction to the collective mass is evaluated on the basis of the adiabatic time-dependent Hartree-Fock theory [1]. However, there are very few papers trying to evaluate the time-odd e ects of the pairing interaction.

We develop a microscopic theory of large-amplitude collective motions in nuclei with superfluidity, which is called the adiabatic self-consistent collective coordinate (ASCC) method [2]. Recently the ASCC method was applied to the oblate-prolate shape coexistence phenomena in ^{68}Se and ^{72}Kr nuclei [3]. In this work the pairing plus quadrupole interaction Hamiltonian was adopted. In order to study the time-odd contributions to the collective mass, however, we need to use a more general Hamiltonian including, for instance, the quadrupole pairing interaction, because the time-odd contributions from the pairing plus quadrupole interaction are known to vanish.

We extend the multi-$O(4)$ model, which is regarded as a simpli ed version of the pairing plus quadrupole interaction model, to include the quadrupole pairing interaction, and apply the ASCC method to the extended multi-$O(4)$ model and study the collective mass of the many-body tunneling motion [4]. Comparing results with those of the exact diagonalization, we show that the ASCC method succeeds in describing gradual change of excitation spectra from an anharmonic vibration about the spherical shape to a doublet pattern associated with a deformed double-well potential possessing the oblate-prolate symmetry. The collective mass is signi cantly increased by the quadrupole-pairing contribution to the time-odd components of the moving mean eld. In contrast, the cranking mass based on the constrained mean eld, which ignores the time-odd components, is smaller than the ASCC mass and fails to reproduce the exact spectra.

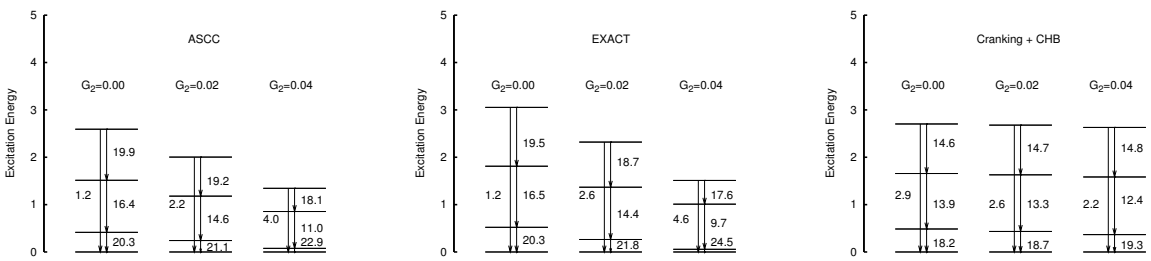

Figure 1: Energy spectra and transition matrix elements, obtained by the ASCC method (*left*), by the exact diagonalization (*middle*) and by the use of the cranking mass + CHB potential (*right*).

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Microscopic Approach to Oblate-Prolate Shape Coexistence Phenomena in Nuclei around ^{68}Se and ^{72}Kr

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We have been investigating the oblate-prolate shape coexistence phenomena in nuclei around ^{68}Se and ^{72}Kr by means of the adiabatic self-consistent collective coordinate (ASCC) method [1]. We have found that the collective path runs approximately along the valley that exists in the triaxial region and connects the oblate and prolate local minima in the collective potential energy landscape [2]. If the axial symmetry is imposed in the calculation, we obtain another path going through the spherical shape, but the barrier along this path is higher than the collective path breaking the axial symmetry. In this previous calculation, the pairing plus quadrupole (P+Q) force was used as an e ective interaction. Meanwhile, using a solvable model of oblate-prolate shape coexistence, we have found that the collective mass parameter (inertia function) is signi cantly enhanced by time-odd components of the pairing eld [3]. Because the P+Q e ective interaction does not contain the time-odd components, the result of Ref. [3] indicates that we need to take into account the quadrupole-pairing interaction in addition to the monopole-pairing interaction for a better calculation of the collective mass parameter. Thus, taking into account the quadrupole-pairing force in addition to the P+Q force, we have carried out the ASCC calculation for the oblate-prolate shape coexistence phenomena in nuclei around ^{68}Se and ^{72}Kr. A typical example of the numerical results is presented in Fig. 1. The leftmost gure shows that the collective path runs approximately along the valley connecting the oblate and prolate local minima through the triaxial region. By comparing the solid and dashed lines in the middle and rightmost gures, we see that both the barrier height and the collective mass increase when the quadrupole-pairing e ects are taken into account. We have con rmed that the signi cant increase of the collective mass is due to the time-odd components of the pairing mean eld associated with the quadrupole pairing force. Physical implication of these results of microscopic calculation will be discussed at the NS06 conference.

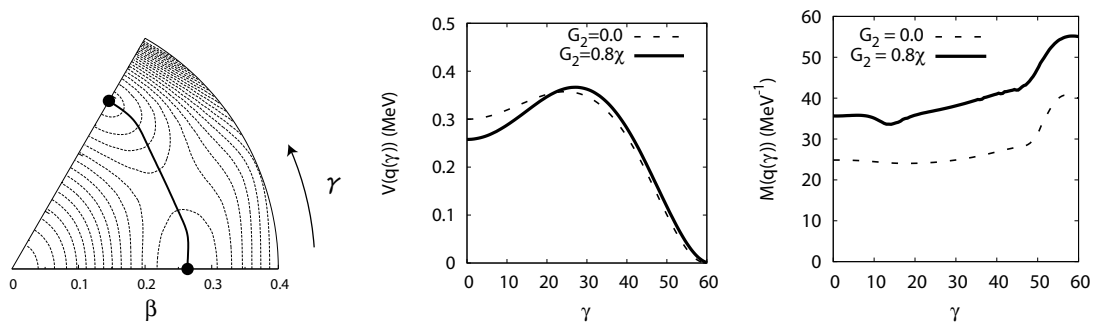

Figure 1: The collective path in the (β,) plane [*left*], the collective potential plotted as a function of [*middle*] and the collective mass (inertia function) plotted as a function of [*right*], obtained by the ASCC method for ^{68}Se.

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On the Role of the $g_{9/2}$ Neutron Orbital in the Structure of Fe Isotopes Toward N=40

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New developments for fp-shell nuclei in recent years have stimulated growing progress toward a better understanding of the properties of increasingly neutron rich systems. For nuclei approaching N=40, the question has persisted as to the structural implications of the g9/2 neutron orbital in the presence of varying numbers of protons. Studies of neutron rich Cr isotopes have indicated a strong influence from this orbital as well as its quadrupole partner, the d5/2 orbital from above the N=50 shell gap [1,2]. However, until recently, such studies have been supported primarily by 2+ energy systematics owing to the experimental difficulties in studying these nuclei with traditional prompt spectroscopic methods. We will report on the production and spectroscopic identification of the nucleus 64Fe, and discuss the results with respect to both systematics and recent shell model calculations. We have identified levels up to 6+ and tentatively to 10+ with the deep inelastic reaction of a 450-MeV ^{64}Ni beam on a thick ^{238}U target. Gamma-ray detection was achieved with the Gammasphere array at Argonne National Lab, and spin assignments are supported by angular correlations.

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Study of high-spin states in neutron-rich Ti and Ca by using a fusion reaction with ^{46}Ar beam

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In recent years, superdeformed (SD) bands were discovered in ^{40}Ca[1] and ^{36}Ar[2]. The coexistence of the spherical and deformed states in the doubly magic nucleus ^{40}Ca has attracted great interest. Onset of such large deformation is understood by the presence of deformed shell gaps in Z=18, 20 as shown in Fig. 1. Observed SD bands in Ni region [3] also support the presence of N=28 deformed shell gap. Due to the Z=20, 22 and N=28 deformed shell gaps in ^{48}Ca and ^{50}Ti, similar deformed collective states are expected to appear at high spin. It is interesting to examine the presence of deformed shell gaps in neutron-rich Ca and Ti.

In order to investigate such deformed structure at high-spin states in ^{48}Ca and ^{50}Ti, we have developed energy-degraded (~4MeV/A) RI beam, ^{46}Ar, and performed an in-beam gamma-ray measurements by using fusion-evaporation reaction of ^{46}Ar+^{9}Be. Experiment was performed at RIPS facility in RIKEN. ^{46}Ar beam was produced by the fragmentation of ^{48}Ca primary beam of 63 MeV/A with 1.625 mm thick ^{9}Be target. Energy of the secondary beam was lowered by using an Al wedge-shaped degrader at first momentum dispersive focal plane (F1) and a rotatable degrader placed at second focal plane (F2). The secondary beam was transported to the final focal plane (F3) to bombard a secondary ^{9}Be target of 10μm thickness. Beam intensity and energy of ^{46}Ar beam at F3 was 1×10^{6}pps and 4±2 MeV/A, respectively. Gamma rays and evaporated charged-particles from the secondary reaction were measured by using the CNS GRAPE[4] and Si barrel array consists of 15 Si detectors, respectively. We will present the experimental results obtained by the above experiment.

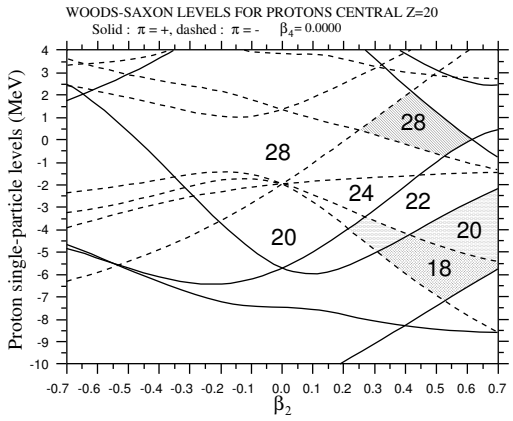

FIG. 1. Woods-Saxon orbital as a function of the deformation, β_2, for particle numbers near N=Z=20.

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Collectivity of pygmy resonance in spherical and deformed neutron-rich Ni and Fe isotopes

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The possible occurrence of the pygmy dipole resonances has been studied experimentally and theoretically. The appearance of the low-lying dipole modes were observed not only in unstable nuclei (for example, neutron-rich $N = 82$ nuclei, ^{132}Sn, ^{138}Ba, ^{140}Ce) but also stable nucleus ^{208}Pb. On the theoretical side, the dipole response has a zero-energy mode corresponding to the spurious center-of-mass motion. Thus, self-consistency is important for decoupling of spurious states from phiscal solutions. In this presentation, we present the first results of fully self-consistent Skyrme RPA calculations for low-lying dipole modes in the spherical nuclei ^{68,78}Ni and deformed nucleus ^{72}Fe.

The RPA calculation was carried out by means of the mixed representation[1,2]. In the mixed representation, particles are described in the coordinate representation while holes are represented in the HF single-particle basis. There are several merits in this approach: Firstly, it is relatively easy, in comparison with the Green's function method, to take into account all terms of the residual interaction including spin-orbit, Coulomb terms and time-odd components. Secondly, the upper energy cut-off is very high. Thirdly, thanks to the use of the coordinate representation, we can treat deformed nuclei on the same footing as spherical nuclei. In these calculations the continuum is discretized.

We obtained the low-lying dipole state in ^{68}Ni at the vicinity of the neutron threshold energy, which exhausts 1.0 % of the TRK sum rule. This state consists of a superposition of some neutron excitations of hole states close to the Fermi level to loosely bound states and resonant states. The contribution of non resonant continuum states is This dipole state has collectivity although it is not so large. The transition density plot in Fig. 1 shows large contribution at the region out of nucleus, which is the pygmy-type transition density.

The deformed nucleus ^{72}Fe has also the low-lying dipole strengths. However, the strengths are fragmented because the dipole modes are coupled with the higher angular momentum modes in deformed nuclei. Thus, each peak has small collectivity compared with those in spherical nuclei.

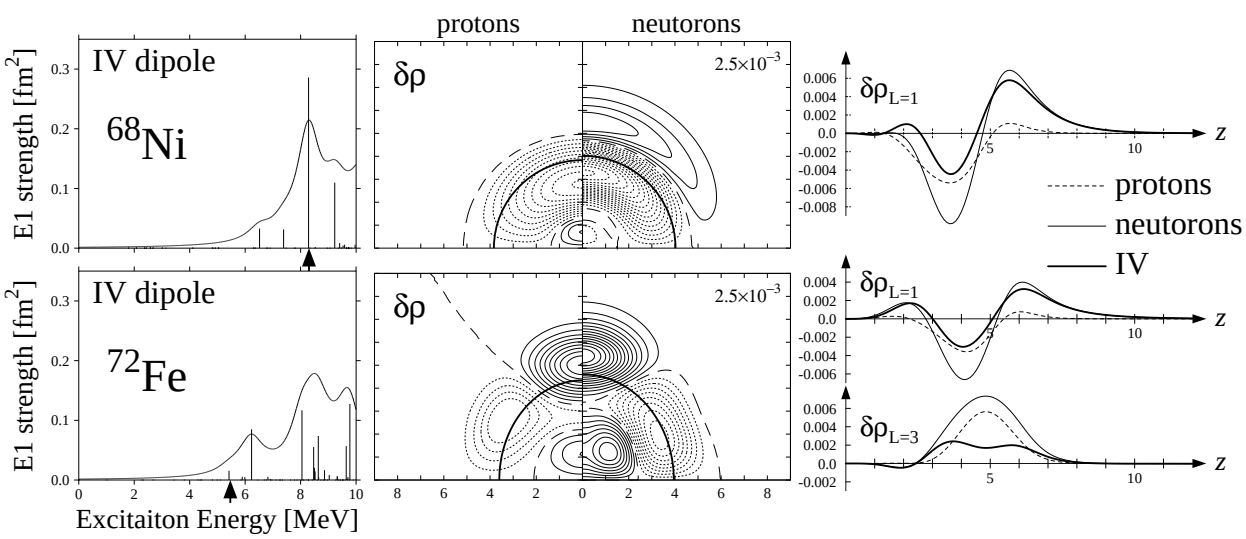

FIG. 1. Low-lying isovector E1 strengths, contour maps of transition densities, and projected transition densities to dipole and octupole modes, in ^{68}Ni and ^{72}Fe.

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Non-adiabatic dynamics in ^{10}Be with the α+α+N+N model

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Developments of experiments with secondary RI beam have extensively proceeded the studies on light neutron-rich nuclei. In particular, much efforts have been devoted to the investigation of molecular structure in Be isotopes (=α+α+N+N...) . Theoretically, molecular orbitals such as π and σ orbitals around two α-particles has been shown to give a good description of the observed low-lying states of this isotopes. Furthermore, the "He-molecules" such as ^{10}Be=α+^{6}He and ^{12}Be=^{6}He+^{6}He have been observed through the recent experiments [1]. Therefore, it is very interesting to study the structural changes in Be isotopes between the molecular orbitals and the He molecules as well as the reaction mechanism in a unified manner.

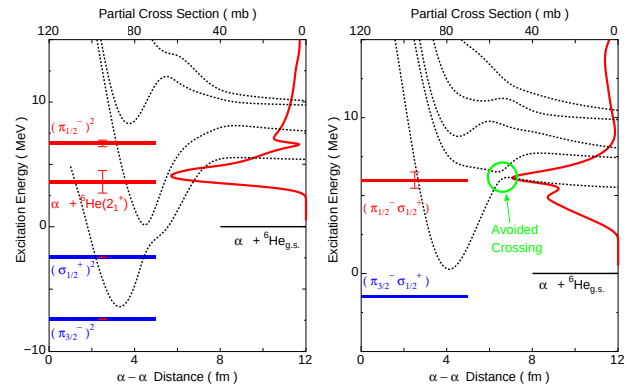

Figure 1: Left panel : Energy spectrum in ^{10}Be(0^+). The red curve in the right part shows the cross section of the inelastic scattering to α+^{6}He(2_1^+). Right panel : Same as the left one but for ^{10}Be(1^-). In both panels, the dashed curves show the adiabatic energy surface as a function of the α–α distance. In right panel, the avoided crossing is shown by a green circle.

In order to do a unified study on the structure and the reaction, we proposed a "generalized two-center cluster model" (GTCM) based on the microscopic cluster model [2]. In this model, the total wave function is expressed by a linear combination of the 0p-wave "atomic-orbitals" (AO) around two α-cores. The mixing coefficient of AO and the α–α distance are employed as the variational parameters. This model naturally describes the molecular orbitals at a small α–α distance as well as the asymptotic channels of α+^{6}He and ^{5}He+^{5}He at a large α–α distance. Therefore, it is possible to treat the nuclear structures and the scattering problems in a unified way.

We applied the model to the ^{10}Be=α+α+N+N system [2] and the results for the $J^\pi = 0^+$ (left panel) and $J^\pi = 1^-$ (right panel) are shown in Fig 1. In both panels, the ordinate and the abscissa mean the excitation energy measured from the α+^{6}He$_{g.s.}$ threshold and the α–α distance parameter, respectively.

We found that the molecular-orbital and the atomic-orbital structures coexisted in this system. Furthermore, we observed the strong enhancement in the inelastic scattering from α+^{6}He$_{g.s.}$ to α+^{6}He(2_1^+). The enhancement is due to the appearance of the resonance pole with α+^{6}He(2_1^+) configuration (0_3^+ in left panel), while it is generated by the Landau-Zener level crossing (green circle in right panel) in the negative parity state. The resonant elastic-scattering in $J^\pi = 4^+$, which has just observed in the latest experiment [3], will also discussed in the present report.

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Visualization of the three-body dynamics in ^{11}Li

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Reaction mechanism in weakly bound systems is one of current subjects in nuclear physics. In particular, the breakup reaction of two neutron halo system is very interesting in connection to the two neutron correlation in the weak bound systems.

In order to understand the reaction mechanism of the three-body breakup clearly, we have been developed a time dependent wave-packet approach [1]. In this method, the relative motions among the three particles are described by the wave packets and its time evolution is exactly calculated by solving the time-dependent Schrödinger equation [1]. This method makes it possible to visualize the wave-packet dynamics and hence, we can obtain intuitive picture for the three-body breakup process. This method has succeeded in describing the fusion reaction of the halo nuclei [2].

In the present study, we apply the method to the linear response of the ^{11}Li. The computational process is quite simple. First, we prepare the wave function of the ground state of ^{11}Li (ψ) within the ^{9}Li+N+N three-body model. Second, the dipole field ($\hat{Z}$) operates on the ground state ($\hat{Z}\psi$) and we calculate its time evolution ($\chi(t) = \exp(-i\hat{H}t/\hbar)\cdot\hat{Z}\psi$). In the present calculation, we assume the simple Woods-Saxon (WS) potential for the ^{9}Li–N (V_{NC}) and V_{NN} interactions.

The time evolution of the density distribution is shown in Fig. 1. We can clearly see the enhanced density along the diagonal line corresponding to $r_1 = r_2$. It means the di-neutron correlation in the breakup process. In Fig. 2, we show the calculated $d^2B(E1)/d\epsilon_1 d\epsilon_2$ which has just observed in the latest experiments by Nakamura group [3]. To investigate the interaction dependence of the linear response, we adopted the several sets of (V_{NN}, V_{NC}). We found that this observable is quite sensitive to the adopted potential and hence, it is useful to investigate properties of the three-body Hamiltonian. In the present report, the visualized three-body dynamics and its interaction dependence will be discussed.

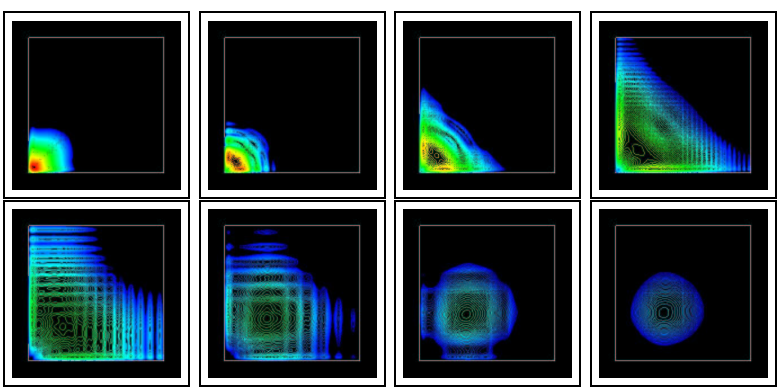

Figure 1: Time evolution of the density distribution of ^{11}L1. The vertical and horizontal axes denote the radial coordinate (r_1, r_2) of the valence neutron measured from the center of ^{9}Li.

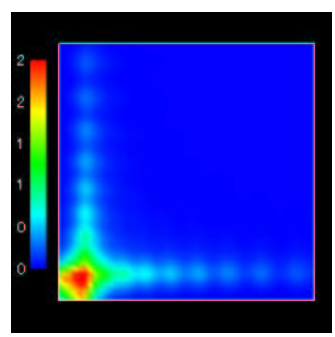

Figure 2: $d^2B(E1)/d\epsilon_1 d\epsilon_2$ for the ^{11}Li→^{9}Li+N+N reaction. The individual axes show the relative energy of ^{9}Li–N ($\epsilon_i = 0 \sim 5$ MeV).

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Proton decay in the A$\sim$ 60 region: The 10^+ isomer in ^{54}Ni

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Following an overview of current attempts of studying proton-emitting high-spin states in medium-mass nuclei, the talk will focus of the most recent case: an isomeric 10^+ state in the neutron-deficient nucleus ^{54}Ni, which decays both by $E2$ and $E4$ γ rays and proton line(s) into the daughter nucleus ^{53}Co. The results arose from the so-called stopped-beam campaign within the *Rare Isotopes Investigations at GSI* (Rising) project. This campaign is a major new initiative focussing on nuclear structure studies at extreme isospin values by means of isomer spectroscopy.

In one of the three first experiments exotic nuclei were produced using relativistic projectile fragmentation of a 550 MeV/u beam of ^{58}Ni provided by the SIS synchrotron at GSI. The fragments produced were separated and identified event-by-event using the FRagment Separator (FRS). The final reaction products were stopped in a 4 mm thick beryllium plate at the final focal point of the FRS and viewed by the high-efficiency, high-granularity Rising γ-ray spectrometer in a compact configuration. This new array comprises 15 germanium cluster detectors from the former Euroball array, providing a singles γ-ray photon efficiency in excess of 15% at 1.3 MeV.

Time-correlated γ decays from individually identified nuclear species have been measured, allowing a clean identification of isomeric decays in a range of exotic nuclei along the proton drip-line.

The presentation concentrates on one highlight from the very successful first campaign, namely the study of isospin symmetry in the $T_z = \pm 1$ system $^{54}_{28}\mathrm{Ni}_{26} - ^{54}_{26}\mathrm{Fe}_{28}$. This includes the first observation of isomeric proton radioactivity produced in fragmentation reactions, which competes with γ-ray emission from the newly established 10^+ isomeric state in ^{54}Ni. This state represents the mirror state to an well-established and well-known 10^+ isomer in ^{54}Fe.

The impact of the results is discussed based on large-scale shell-model calculations.

The work has been supported in part by the U.S. DOE Grant No. DE-FG02-91ER-40609.

Precision measurements of ground-state masses for nuclear structure and nuclear astrophysics

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Commissioning of the JYFLTRAP facility has been performed by mass measurements of neutron-rich nuclei in the transitional region from Ge (Z=32) to Pd (Z=46). This has resulted in more than 100 new atomic masses of neutron-rich nuclei with a precision of 10 keV or better [1,2]. Some of the most exotic isotopes measured were ^{121}Pd, ^{118}Rh, ^{110}Mo, ^{105}Zr, ^{97}Rb and ^{92}Br. The studied mass region offers an interesting playground to look for nuclear structure signatures in the mass surface, relevant also for the astrophysical predictions. The obtained data is used to extract relative binding observables, like one and two neutron separation energies (S_n, S_{2n}), pairing (Δ_n, Δ_p) and shell gap energies. These results are compared to other spectroscopic information and theoretical studies. In addition, we will compare our results to the recent Atomic Mass Evaluation [3] and selected models of astrophysical interest [4].

We have also initiated a project to measure the binding energies of nuclei located in the expected region of the rp-process and νp-process paths. These measurements include $^{80\text{-}83}$Y, $^{83\text{-}86,88}$Zr and $^{85\text{-}88}$Nb isotopes, of which ^{84}Zr has been measured for the first time. The obtained data has improved considerably S_p and Q_{EC} values for astrophysically important nuclides. These results and outlook for similar studies will be discussed.

A combination of IGISOL-separator and Penning trap measurements is well suited for the precision determination of Q_{EC}-values of super-allowed beta decays, which test the CVC hypothesis and the unitarity of the CKM-matrix [5]. We have recently performed series of measurements with sub-keV precision for Q_{EC} value. Some of the cases to be mentioned are ^{62}Ga [6], and more recent measurements of ^{26m}Al, ^{42}Sc, and ^{46}V.

This work has been supported by the EU-FP6 I3-EURONS activity TRAPSPEC and by the Academy of Finland under the Finnish Centre of Excellence Programme.

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Discovery of proton emission from $^{141g.s.}$Ho and ^{141m}Ho to the excited state in ^{140}Dy

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Fine structures in the proton emission from the $7/2^-[523]$ ground state and the $1/2^+[411]$ isomeric state in the deformed nucleus ^{141}Ho were discovered in a high sensitivity experiments. Proton transitions to the 0^+ ground state and to the first excited 2^+ state at 202 keV in ^{140}Dy [1] with branching ratios of $I_p^{gs}(2^+)$=0.9 ± 0.1% and $I_p^m(2^+)$=1.7 ± 0.4% were identified in two independent experiments. The $^{141g.s.}$Ho and ^{141m}Ho ions were produced in the fusion-evaporation reaction of ^{54}Fe ions of high intensity (20 to 35 pnA) beam accelerated to 300 MeV or 290 MeV energy, with ^{92}Mo nuclei in the thin (1 mg/cm^2 or 0.6 mg/cm^2) isotopically enriched target. Reaction products were separated according to their mass over charge ratio by the Recoil Mass Spectrometer [2] of the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. Selected recoils were implanted into a Double-sided-Silicon-Strip-Detector (DSSD). During the experiment on the $T_{1/2}$=4.1ms $^{141g.s.}$Ho activity, signals from all detectors were read by Digital Gamma Finder (DGF) modules [3] programmed for recording only arrival times and amplitudes for charged particle signals induced in DSSD.

For the measurement of the short lived $T_{1/2}$=7.41μs isomeric decay of the ^{141m}Ho, the DGF modules worked in a so-called proton-catcher mode [4]. In this mode the digital electronics is programmed to selectively record only those events where the signal of the implanted recoil is followed by the decay signal within the 40μs time range [5]. The 50 μs-long snapshots of the pulse taken with 40 MHz sampling rate, containing both recoil and decay signals were stored for further offline analysis.

The structure of the $^{141g.s.}$Ho and ^{141m}Ho wave functions, in particular, the components responsible for the proton emission process, will be discussed. The decay properties of $^{141g.s.}$Ho can be explained by postulating a small contribution of the triaxial deformation ($\gamma \approx 5^o \quad 10^o$). The same model fail to explain the observed ^{141m}Ho decay properties. The observed $I_p^m(2^+)$value is much higher than current theoretical expectations. The experimental observations suggest only a small (3%) contribution of the $s_{1/2} \otimes 0^+$ component to the $1/2^+$ [411] isomeric state wave function.

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Superdeformation in Nuclei: Order Embedded in Chaos

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Shell structure in nuclei can lead to the creation of an excited minimum characterized by large deformation. With larger spin, the energy (above the yrast line) of the superdeformed (SD) minimum decreases and its well depth increases.

As the hot, chaotic compound nucleus cools, a small fraction of gamma cascades populates the superdeformed well, flowing through excited rotational bands, which exhibit properties never before observed. The spectrum of cooling, statistical γ rays evolves into a broad E2 peak, indicating a hot, elongated nucleus. In ^{194}Hg, E_γ-E_γ correlations reveal exceptionally narrow (FWHM ~ 10 keV) ridges, parallel to the diagonal, which is nearly empty of counts. The ridges exhaust nearly all of the 1-dimensional E2 strength, are constituted from 30-150 bands, and have a $J^{(2)}$ moment of inertia identical to that of the yrast SD band. The situation is very different from that in nuclei with normal deformation, where the E2 strength in excited states exhibit both a weak (<10% intensity) narrow (~30 keV) component and a broad (~200 keV) one. There is no evidence of a broad component in ^{194}Hg. The multitude of bands and theory both suggest large mixing among the bands, with wave functions having many (2-8) mean-field components, so that a chaotic regime is approached, where transition strengths would be expected to have fluctuating (Porter-Thomas) strengths. Yet, as predicted by Mottelson [1], rotational coherence and flow are preserved, with E2 matrix elements connecting unique states differing in spin by $2\hbar$. This situation suggests that the transition from chaos to order evolves through a nearly ergodic regime. The very narrow spread of E2 strength in ^{194}Hg is explained by a small dispersion of rotational frequencies $\Delta\varpi$, which leads to an unexpected case of motional narrowing, and is intimately related to nearly identical $J^{(2)}$ values found in SD discrete bands in Hg nuclei.

Cascades trapped inside the SD well reach the "ground" band of the minimum, where cold ordered rotation gives rise to impressive set of nearly equi-spaced sharp lines. Here ordered states exist, with good quantum numbers, even though they are embedded in a dense sea of chaotic, highly excited states from the primary minimum.

Tunneling out of the superdeformed well precipitates a sudden decay out of the minimum, which is mediated by weak coupling between ordered superdeformed and chaotic normal-deformed states. The decay spectrum has a statistical shape similar to that of neutron-capture gamma rays. Finally, the nucleus settles to the ground state through gamma decays, which are governed by selection rules imposed by conserved quantum numbers. Hence, the "life" of a superdeformed nucleus reflects an unusual double cycle of chaos-to-order transition, as well as new regime of chaos-to-order transition.

Gammasphere has played a definitive role in elucidating many aspects of the feeding and decay-out of superdeformed bands in both the A=150 and 190 regions.

It is a pleasure to acknowledge the stimulating collaboration of colleagues at Argonne, Berkeley, Copenhagen, Niigata and Orsay, in particular, Thomas Døssing, Torben Lauritsen and Waely Lopez-Martens. This research is supported by the U.S. Department of Energy, under Contract No. W-31-109-ENG-38.

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Many-Particle and Many-Hole States of the Nuclei with Odd Neutron Number in the Island of Inversion

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The low-lying level structure of the nuclei with the odd neutron number in the island of inversion will be discussed based on the theoretical study by the deformed-basis AMD+GCM method.

The breaking of the N=20 magic number in the neutron-rich nuclei around ^{31}Na has been experimentally and theoretically investigated and the systematic breaking of the N=20 magic number has been confirmed in even-even and odd-even nuclei such as ^{31}Na and ^{32,34}Mg. The nuclei with odd neutron number are good probe to investigate the change of the shell structure in the neutron-rich side, since the properties of the last neutron particle (hole) will be directly reflected to the properties of the total system. Indeed, the increasing experimental data for odd neutron number nuclei such as ^{31}Mg and ^{33}Mg is providing us the important knowledge of the breaking of the magic number.

The theoretical framework of the deformed-basis AMD had been applied to the nuclei in the Island of Inversion such as ^{32}Mg and ^{28,30}Ne. In those applications, the properties of these nuclei had successfully described and the existence of the low-lying intruder states with many kinds of particle and hole configurations. Since the deformed-basis AMD does not assume the time reversal symmetry of the intrinsic wave function, we can investigate the properties of the odd mass nuclei.

The present study has shown the systematically large deformation of the odd mass nuclei in the island of nuclei. For example, it will be shown that the ground state of ^{31}Mg purely consists of the intruder 2p3h configuration with respect to the N=20 shell closure and have a large static deformation. Using the calculated wave function, the observed spin and parity of the ground state, magnetic moment and the strength of the β decay from ^{31}Na are successfully reproduced. It will be also shown that the states with the neutron 0p1h, 1p2h and 3p4h configurations lie within the small excitation energies (Fig. 1 and 2).

In this talk, the calculated low-lying level structure of ^{33}Mg and Al isotopes will be presented together with that of ^{31}Mg. Based on these results, the behavior of the single particle levels, the border of the island of inversion, the role of the nuclear interaction to breakdown the N=20 magic number will be discussed.

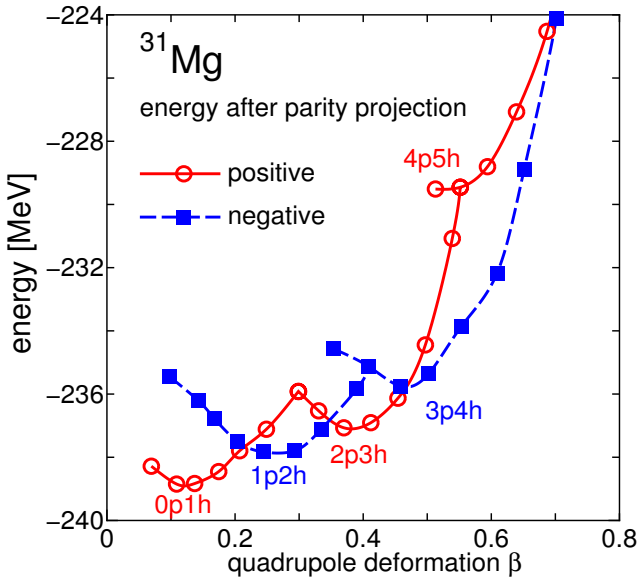

Fig.1 : Calculated energy surface of ^{31}Mg for positive-parity (solid-line) and negative-parity (dashed line) states.

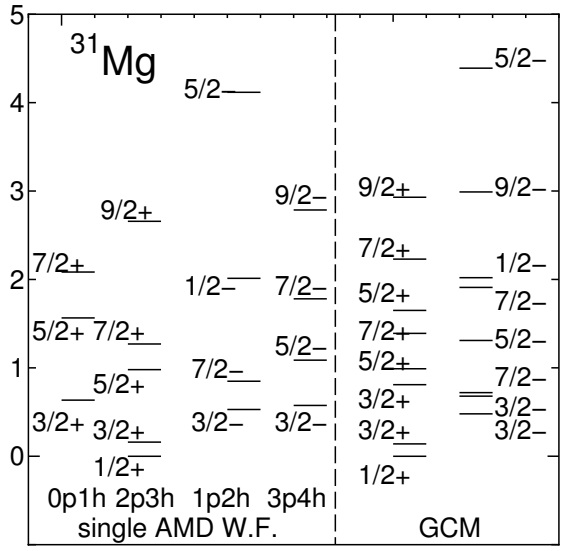

Fig. 2: Calculated level scheme of ^{31}Mg by the angular momentum projection (left) and by the angular momentum projection + GCM (right).

Molecular-Orbital and Di-Nuclei States of ^{22}Ne

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In this talk, the molecular-orbital states and di-nuclei states of ^{22}Ne will be reported and discussed based on the theoretical study by the deformed-basis AMD+GCM method.

The successful description of Be isotopes by assuming the molecular-orbital structure suggests a new type of clustering that is peculiar to $N \neq Z$ nuclei. It is of importance to investigate whether the molecular-orbital structure exists not only in Be isotopes but also in heavier system. Ne isotopes are the promising candidates, since the core nucleus ^{20}Ne has a prominent $\alpha+^{16}$O cluster structure.

Among the obtained spectra, the excited bands that show considerable α clustering are plotted in Fig. 1, together with the ground band that does not have a cluster structure. The excited bands which have α cluster structure are classified into two types. The first type is the molecular-orbital bands that have an $\alpha+^{16}$O cluster core and two valence neutrons that orbit around the core. The $K\pi=0^+_2$ and 0^-_1 bands belong this type. They have the similar intrinsic wave function in which two valence neutrons occupy the σ-type molecular orbital (Fig. 2). This orbital is an analogue of the σ-molecular-orbital of Be isotopes. The most important difference between the σ-orbital of ^{22}Ne and that of Be isotopes is the parity asymmetry which is due to the parity asymmetry of the $\alpha+^{16}$O cluster core. This explains why there is a doublet of $K\pi=0^+_2$ and 0^-_1 bands with almost the same wave intrinsic wave function. These bands are built a few MeV below the $\alpha+^{18}$O threshold energy and correspond to the observed states with large α reduced widths [1].
The second type is the di-nuclei bands that have the $\alpha+^{18}$O cluster structure and excitation energy is higher than that of molecular-orbital bands and $\alpha+^{18}$O threshold energy. The $K\pi=0^+_3$ and 0^-_2 bands belong this type. In these bands, two valence neutrons orbits only around the ^{16}O. We consider that these bands corresponds to the observed $\alpha+^{18}$O molecular resonances[2].

From the present result, we suggest two different kinds of α cluster structure in ^{22}Ne. The first one is the molecular-orbital structure and the second one is the di-nuclei (molecular resonance) structure.

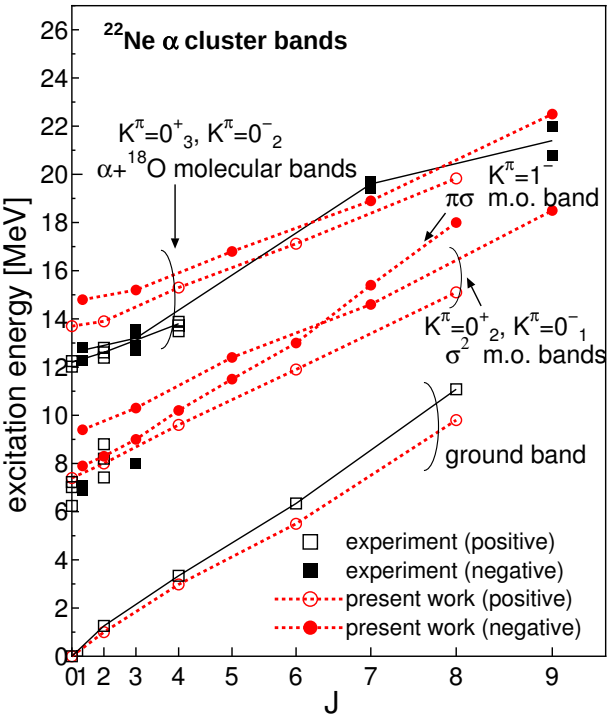

Fig 1 : The observed and calculated level scheme of the ground band and the excited bands with α cluster structure

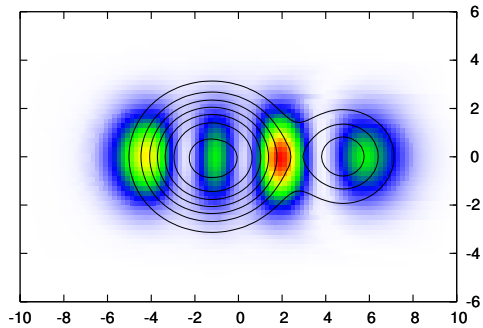

Fig 2 : Density plot of the σ-molecular-orbital (color map) and of the $\alpha+^{16}$O core (solid line).

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Coulomb excitation of neutron-rich ^{138,140,142}Xe at REX-ISOLDE *

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Recent experiments in the surrounding of the doubly magic ^{132}Sn have shown that for very neutron-rich nuclei far off the valley of stability the $B(E2; 0^+_{\rm gs} \rightarrow 2^+_1)$ values are lower than expected from systematics [1,2]. Proposed explanation is a reduced neutron-pairing above $N = 82$ resulting in a large neutron contribution to the wave functions [3].

Aim of our research programme performed at the REX-ISOLDE facility at CERN is to extend such studies in this region in order to clarify the underlying physics. In our first campaign we investigated the neutron-rich isotopes ^{122,124}Cd. Our preliminary $B(E2)$ values for these isotopes are consistent with expectations for vibrational nuclei [4]. Above the $N = 82$ closure, we studied in a subsequent experiment the isotopes ^{138,140,142}Xe.

We employed γ-spectroscopy following "safe" Coulomb excitation of radioactive Xe beams at an energy of 2.84 MeV/u impinging on a ^{96}Mo target. The γ-rays from deexciting the nuclei were detected by the highly efficient MINIBALL spectrometer consisting of 8 triple clusters of six-fold segmented HPGe detectors. The reaction kinematics was determined by detecting the scattered particles in a double-sided segmented Si detector (DSSSD).

For all three isotopes, we collected high statistics for the $2^+ \rightarrow 0^+$ transitions. Additionally, also the excitation of the first 4^+ state has been observed. The $B(E2)$ values of ^{138,142}Xe will be determined for the first time, whereas for ^{140}Xe the contradiction between the two different values existing in literature will be resolved.

We will present the status of our analysis and discuss the perspectives for future experiments.

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*This work is supported by the German BMBF under grant No. 06MT190.

Systematics of Light Neutron-Rich Nuclei Produced by Projectile Fragmentation *

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The location of the drip-lines is of great importance in determining how much the shell structure can change as one moves away from β-stability. The location of the neutron drip-line is only known up to the oxygen isotopes. This area of the chart of nuclides is of great interest because the addition of one proton to the ^{24}O core allows six additional neutrons to be bound. This pattern is seen nowhere else on the chart of nuclides. It has been postulated that the changing shell structure in this region may add stability to the heaviest fluorine isotopes. Many theoretical models predict ^{31}F to be located on the neutron drip-line [1,2]. The only way to determine the location of the fluorine drip-line is to show that ^{33}F is particle unbound. The method of choice to produce nuclei in this region is projectile fragmentation.

Two experiments using projectile fragmentation were run at the National Superconducting Cyclotron Laboratory to produce nuclei in the vicinity of the neutron drip-line. The first experiment was performed to study the effect of the neutron excess of the target on the yields and the second experiment was done to determine the location of the drip-line above oxygen. No new nuclei were observed. The A1900 fragment separator [3] was used to identify the observed fragments and to measure their momentum distributions. The effect of the neutron excess of target and the production of ^{31}F has been examined. The effect of the target on the cross-sections can be seen in Fig. 1. Eight ^{31}F isotopes have been identified with a cross-section comparable to what was found at RIKEN [4] and GANIL [5]. The cross-sections of the neutron-rich nuclei along with systematic observables will also be presented in comparison with theoretical models and data from RIKEN.

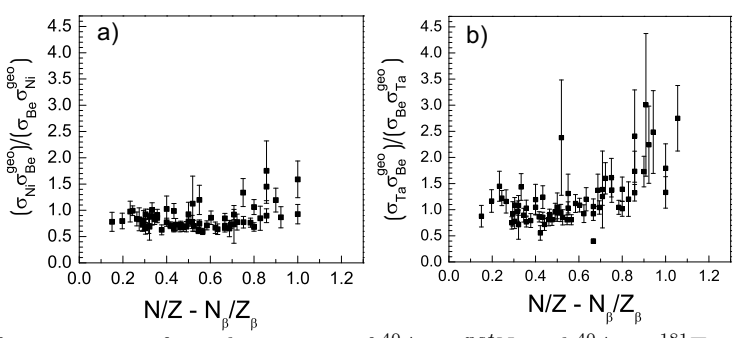

FIG. 1. The ratio of cross-sections from the reaction of ^{40}Ar + ^{nat}Ni and ^{40}Ar + ^{181}Ta with respect to ^{40}Ar + ^{9}Be are shown in figures a) and b), respectively. The effect of the target neutron excess can be seen in the most neutron-rich isotopes.

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*This work was supported by the U. S. National Science Foundation under the grant PHY-01-01523.
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Identification of the $(\pi h_{11/2})^{-2}\otimes(\nu i_{13/2})^{-2}$, $I^{\pi}=22^{+}$ isomer in ^{204}Hg*

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The low-lying structure of nuclei with only a few particles and/or holes outside of ^{208}Pb provides sensitive tests of the purity of shell-model wavefunctions as well as crucial information regarding the basic building blocks from which more complicated many-particle configurations are constructed. However, despite decades of study, many simple configurations have eluded identification, especially in neutron-rich nuclei, due to limited possibilities for populating the relevant states in conventional reactions with stable beams. Substantial progress has been made in recent years utilising deep-inelastic [1,2,3] and relativistic-fragmentation reactions [4], which, although they populate many nuclei simultaneously, can be sensitive to unique reaction products through the identification of characteristic isomeric states.

The τ_m=65s, α-decaying isomer in ^{212}Po is formed from the coupling of four valence particles (two protons and two neutrons) outside the doubly-magic ^{208}Pb core and has a long history [5,6,7]. However, it is only relatively recently [7,8] that the spin and configuration of the 65s isomer has been assigned with some confidence as the $I^{\pi}=18^{+}$ state from the fully-aligned $(\pi h_{9/2})^{2}(\nu g_{9/2}i_{11/2})$ configuration, there being some ambiguity between several alternative configurations. The analogous four valence hole configuration in ^{204}Hg would be a 22^{+} state from the $(\pi h_{11/2})^{-2}(\nu i_{13/2})^{-2}$ configuration, which in this case is unambiguously predicted to be favoured. The 22^{+} state is expected to decay via E3 γ-transitions with an anticipated lifetime of a few μs. Until the present work, the highest spin state known in neutron-rich ^{204}Hg was 9^{-} [9].

We have performed a range of measurements using different beams and targets to populate high-spin states in nuclei near ^{208}Pb. The two experiments which provided the current results for ^{204}Hg used pulsed beams of 330 MeV ^{48}Ca ions and 1360 MeV ^{208}Pb ions from the ATLAS accelerator incident on 50 mg/cm^2 enriched ^{238}U targets. Gammasphere was used to observe the gamma-rays emitted from the products of deep-inelastic and multi-nucleon transfer reactions.

We will present a new level scheme for ^{204}Hg extending up to a candidate for the 22^{+} isomer and compare the results with OXBASH shell model calculations which include all proton and neutron orbitals between ^{132}Sn and ^{208}Pb without restriction.

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* This work was supported by Australian Research Council Discovery Grants DP0345844 and DP0343027, Polish Ministry of Education and Science Grant 1 P03B 059 29, the ANSTO program for Access to Major Research Facilities, and the U.S. Department of Energy, Office of Nuclear Physics, under contract No. W-31-109-ENG-38.

High-K multi-quasiparticle states and anomalous γ-ray decays in ^{184}W*

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Traditional heavy-ion fusion reactions with stable beams and targets cannot be used to populate high-spin states in the stable and neutron-rich nuclei of the A=180 region where some of the best examples of high-K isomers based on multi-quasiparticle intrinsic states are known. This has motivated extensive efforts to use more exotic techniques such as relativistic fragmentation [1] and deep-inelastic / multi-nucleon transfer reactions [2].

Using a deep-inelastic reaction, Wheldon et al [3] have identified a $T_{1/2}$=188ns isomer in the stable nucleus ^{184}W, and observed its decay towards the γ-vibrational and ground state rotational bands through a series of excited states with unknown spin and parity. We have clarified and significantly extended the level scheme in an experiment which used a pulsed beam of 820 MeV ^{136}Xe ions from the ATLAS accelerator at Argonne National Laboratory, incident on a gold-backed, 5 mg/cm^2 ^{185}Re target. The gamma-rays from the products of deep-inelastic and multi-nucleon transfer reactions, including the 1p transfer channel leading to ^{184}W, were observed with Gammasphere.

The lifetime of the isomer has been remeasured and the complex decay through previously unknown multi-quasiparticle and gamma-vibrational states has been characterised. Time-correlated spectroscopy across the isomer has resulted in the discovery of higher-lying excited states which appear to be mostly of a multi-quasiparticle nature with very little development of rotational structure. A number of short-lived isomers (lifetimes of a few ns) have also been observed, including an isomer which exhibits anomalously fast gamma-ray decays that can be explained through a chance degeneracy between the isomeric state and a level in the γ-vibrational band.

The new experimental results for ^{184}W will be presented and the observed spectrum of intrinsic states will be compared with the results of multi-quasiparticle calculations. The deduced interaction between a K-isomer state and a γ-vibrational state will be discussed in the context of chance degeneracies in the A=180 region between multi-quasiparticle intrinsic states [4,5].

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* This work was supported by Australian Research Council Discovery Grants DP0345844 and DP0343027, the ANSTO program for Access to Major Research Facilities, and the U.S. Department of Energy, Office of Nuclear Physics, under contract No. W-31-109-ENG-38, and Grant No. DE-FG02-94ER40848.

Level densities and radiative strength functions of ^{50,51}V and ^{44,45}Sc

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Nuclear level densities and radiative strength functions are essential quantities for the study of nuclear structure. Understanding level densities and radiative strength functions is also important for applied nuclear physics, e.g, modeling the nucleosynthesis in supernovae and for transmutation of nuclear waste. However, the level density is difficult to determine experimentally at high excitation energies, when there are more than $\sim$ 100 levels per MeV. Also the radiative strength function is scarcely known at low γ-ray energies.

The Oslo Cyclotron group has developed the so-called Oslo method, which gives the opportunity of extracting both level density and γ-strength function of warm nuclei for excitation energies up to the neutron separation energy. With the multidetector system CACTUS at the Oslo Cyclotron laboratory, this extraction can be done in one and the same experiment from primary γ spectra. The method relies on the Brink-Axel hypothesis, which states that the primary γ spectrum is proportional to both the level density and the radiative transmission coefficient.

We report on experiments done on the nuclei ^{50,51}V and ^{44,45}Sc. The experimentally found level densities and radiative strength functions will be presented. A surprising enhancement of the radiative strength functions at low γ-ray energies, most apparent for ^{50,51}V, will be discussed.

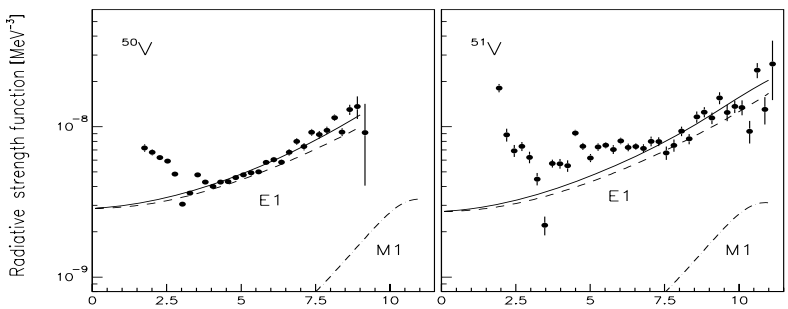

FIG. 1. The radiative strength functions of ^{50,51}V. The dashed and dash-dotted line show the extrapolated tails of the giant electric and giant magnetic dipole resonance, respectively. The solid line is the summed strength for the giant dipole resonances.

*This work was supported by the Norwegian Research Council (NFR)

Rotational Damping, Ridges and the Quasicontinuum of γ rays in ^{152}Dy

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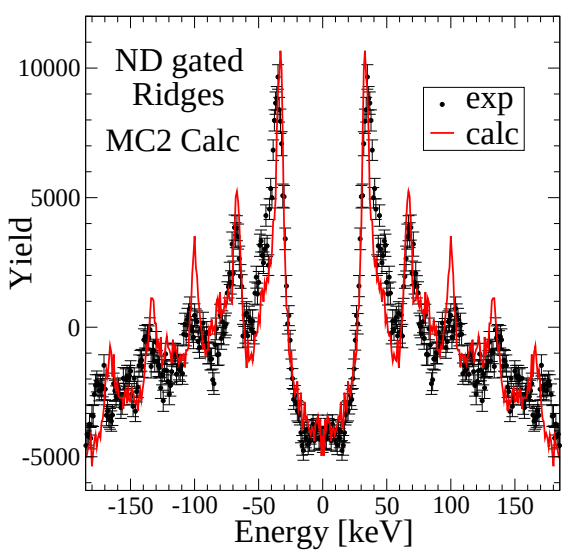
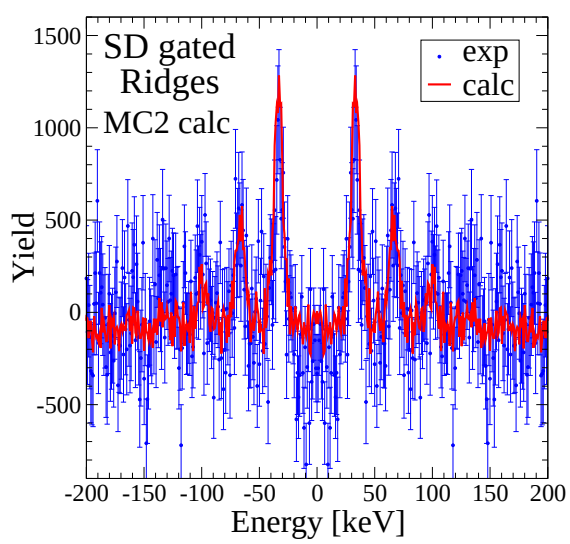
[1] *Argonne Nat. Laboratory, Argonne, Illinois 60439, USA.* [2] *Lawrence Berkeley Nat. Laboratory, Berkeley, California 94720, USA.* [3] *C.S.N.S.M, IN2P3-CNRS, F-91405 Orsay Campus, France.* [4] *Niels Bohr Institute, DK–2100, Copenhagen, Denmark.* [5] *Greenville College, Greenville, Illinois 62246, USA.* [6] *University of Massachusetts, Lowell, MA 01854, USA.* [7] *A.W. Wright Nuclear Struct Lab, Yale University, New Haven, CT 06520, USA.* [8] *Department of Physics, University of York, Heslington, York YO10 5DD, UK.*

In a heavy–ion fusion evaporation reaction, the compound nucleus cools first by particle evaporation and then by emission of γ rays. At finite temperature, above the yrast line, the level density is high and the γ rays form a quasi–continuum spectrum from which individual transitions cannot be resolved [1]. Only when the γ cascades reach states near the yrast line will discrete transitions be observed. The quasi–continuum of γ rays from the feeding and decay of superdeformed and normal bands in the nucleus ^{152}Dy have been extracted in 1 – and 2 – dimensional spectra. The E_γ–E_γ correlations in the latter reveal strong ridges associated with superdeformed and normal states in this nucleus. The entry distributions for normal and superdeformed bands have also been extracted from measured fold and sum–energy distributions. A Monte Carlo model was developed to *simultaneously* describe all the quasi–continuum and ridge spectra, as well as the feeding intensity of the superdeformed bands.





The narrow ridges from γ rays emitted in the SD well are prominent in both the spectra obtained when coincidence gates are placed on clean ND and SD lines in ^{152}Dy – see figures above. Also shown are Monte Carlo simulations of the data which make use of renormalized theoretical functions [2] of the narrow Γ_μ, wide Γ_{rot} and narrow fraction I_{nar} of rotational damping functions in the ND and SD wells. The *simultaneous* reproduction of the experimentally measured QC spectra and ridges constitutes a determination of the rotational damping in the two wells.

This work was supported in part by the U.S. Dept. of Energy, Office of Nuclear Physics, under Contract No. W–31–109–ENG–38, DE–AC03–76SF00098, DE-FG02-91ER-40609 and DE-FG02-94ER40848, and the Danish Natural Science Foundation.

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Progress in Development of Gamma-Ray Tracking Detectors*

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A gamma-ray tracking detector can identify the position and energy of individual interactions of gamma rays with the detector. Then, using tracking algorithms, the scattering sequences can be reconstructed. Such an array will give high peak efficiency, peak-to-background ratio, and good position resolution. A number tracking detector projects have been started recently in US, Japan, Canada and Europe.

The US project, GRETINA, will consist of 7 detector modules, each with four 36-fold segmented coaxial germanium crystals, and will cover ¼ of the 4π solid angle. The project was started in 2004 and is scheduled to be completed in 2010. Progress has been made in four key areas of development; 1) production and testing of prototype detectors 2) design and fabrication of signal digitizer modules 3) develop signal processing methods for determining energy, time, and position from pulse shapes, and 4) develop tracking algorithm to identify interaction points and scattering sequence belonging to a particular gamma ray. Currently, the first detector module is on order and the delivery is expected in November 2006. A prototype data acquisition system was in operation since 2005, and it was being used for the testing of prototype detectors. Computer programs for signal decomposition and tracking were developed and were being improved based on experiences gained from prototype detector testing. The design of the mechanical structure, as shown in Figure 1, was completed, and it was intended to accommodate a number of potential sites in the US. The detailed design of the data acquisition system is on going. The purchasing of additional detector modules and the production of the mechanical and data acquisition systems will begin in the fall of 2007.

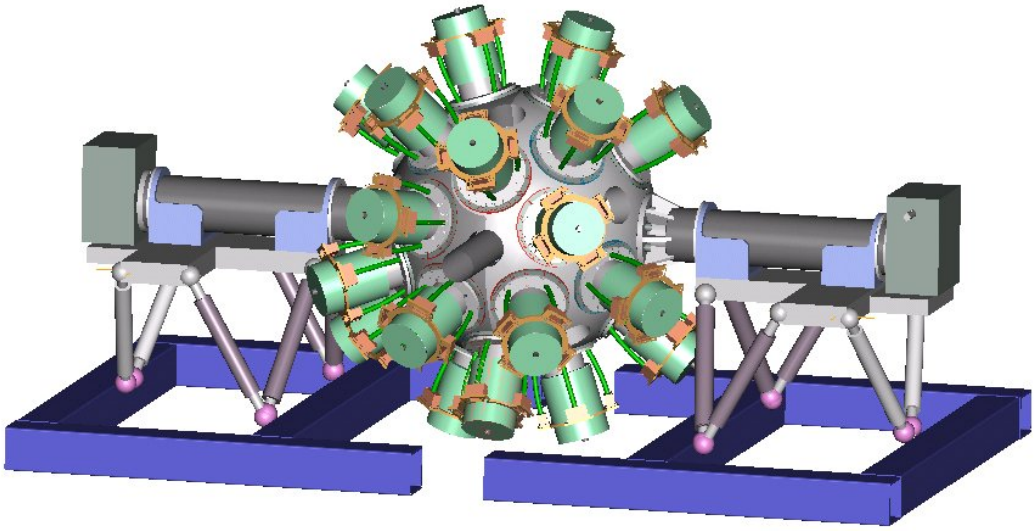

FIG. 1. Design of GRETINA mechanical structure, more than seven detectors was shown.

The European project, AGATA demonstrator, will have five 3-crystal detector modules. It will cover about 8% of the 4π solid angle. It is scheduled to be installed, at the end of 2007, at Legnaro.

*This work was supported by the U.S. Department of Energy under contracts DE-AC02-05CH11231.

Quantum Tunneling in Excited Superdeformed ^{151}Tb and ^{196}Pb rotational nuclei

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The study of the nucleus at extreme conditions of excitation energy and angular momentum has improved our knowledge on the properties of highly excited nuclei and on the order-to-chaos transition in the atomic nucleus, for which a theoretical description beyond mean field is required. Up to 4-5 MeV of excitation energy above the yrast line the thermal response of the nucleus can be studied experimentally through the analysis of quasi-continuum spectra formed by rotational transitions among excited bands. This topic has been rather well investigated in normal deformed systems, while scarce information is available on largely elongated nuclei, for which the thermal response is strongly coupled to its angular momentum dependence, giving rise, for example, to abrupt shape changes from superdeformed (SD) to spherical (ND) configurations (the decay-out process)[1]. Two EUROBALL experiments on SD ^{151}Tb and ^{196}Pb nuclei will be compared in terms of quasi-continuum γ-ray spectra. Ridge structures with moment of inertia similar to the corresponding SD yrast band are observed both in the total matrices selecting high-fold cascades and in γ–γ spectra in direct coincidence with the SD yrast (see figure). The analysis of the ridge structures in terms of intensity, FWHM and number of decay-paths indicates that such ridges are populated by numerous discrete rotational bands of SD nature. In particular (see figure), the total number of SD rotational bands (N_{path}), as a function of transition energy (spin), shows a decrease with decreasing spin, pointing to a quantum tunneling from super-deformed to normal-deformed configurations in the transition region from ordered to chaotic motion. The experimental results are in good agreement with cranked-mean field calculations at finite temperature for neighboring nuclei and, especially in the case of the ^{196}Pb nucleus, provide information on quantities, such as the level density and the pairing gap, which play a crucial role in the decay-out process [2].

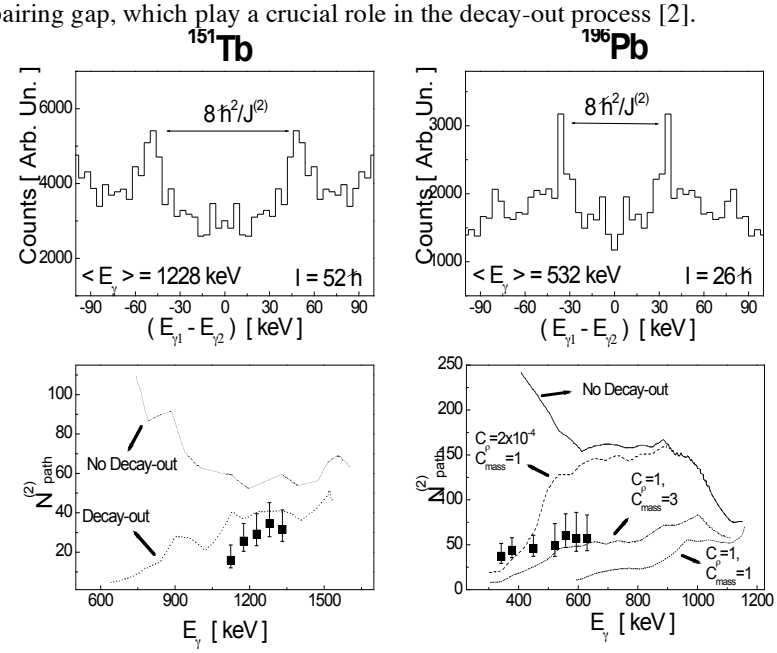

FIG. 1. Top row: examples of SD ridge-valley structures observed in γ–γ matrices selecting high-folds cascades in ^{151}Tb and ^{196}Pb nuclei. Bottom row: comparison between the total number of discrete excited SD states obtained from the fluctuation analysis of the ridge structures (symbols) and cranked shell model calculations (lines) at finite temperature (including or excluding the decay-out process between the SD and ND minima in the nuclear potential).

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Deducing the ^{233}U(n,f)/^{235}U(n,f) cross-section using the Surrogate Ratio Method

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Neutron-induced fission cross-sections of Uranium isotopes are of interest to Stockpile Stewardship Science, as well as, nuclear astrophysics in supernovae explosions. Unfortunately, these measurements are difficult to obtain due to the short half life of some targets and the low incident neutron flux which can be produced. To overcome these problems, the Surrogate Ratio Method has been employed, where a stable target and stable beam are used to measure the reaction probability of the same compound nucleus formed by a different reaction. The 88 Inch Cyclotron at LBNL and the Silicon Telescope Array for Reaction Studies (STARS) spectrometer were used to deduce the ^{233}U (n,f)/^{235}U (n,f) cross section ratio using the surrogate ratio technique [1,2]. The surrogate ratio method is a powerful tool which allows the inference of an unknown cross-section of one isotope when the other is known. In this experiment, ^{234}U and ^{236}U targets were bombarded with a 55 MeV alpha beam and the fission fragments in coincidence with outgoing alpha particles were measured. The STARS array which consists of two silicon cd detectors , an E detector, 1000 microns thick and a delta E detector, 140 microns thick. Each detector had 24 rings and 8 sectors which allowed for angle dependent identification of particles. The fission fragments were detected using a third silicon detector at backward angles from the target. The neutron induced cross sections of interest were found from induced fission in ^{236}U(α,α'f) and ^{234}U(α ,α 'f) which are surrogate reactions for ^{235}U(n,f) and ^{233}U(n,f) respectively. This talk will present an of the surrogate ratio method and the preliminary results of our measurement.

This work is a University of Richmond, Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory and Yale University collaboration and was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48 and Grant Nos. DE-FG-05NA25929, DE-FG52-06NA26206, and DE-FG02-05ER41379.

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Finite-N Aspects of Quantum Shape-Phase Transitions in Nuclei *

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Quantum shape-phase transitions have recently become a topic of great interest in nuclear structure, following the recognition that nuclei at the critical-points are amenable to analytic descriptions [1,2]. These analytic benchmarks of criticality were obtained in the geometric framework of a Bohr Hamiltonian for macroscopic quadrupole shapes. In particular, the E(5) benchmark [1] is applicable to a second-order phase transition between spherical and γ-unstable deformed nuclei, and the X(5) benchmark [2] is relevant to a specific first-order phase transition (with an extremely low barrier) between spherical and axially-deformed nuclei. Empirical examples for such benchmarks have been presented, *e.g.* ^{134}Ba [3] for the E(5) case, and ^{152}Sm [4], ^{150}Nd [5], ^{154}Gd [6] for the X(5) case, and the search for additional critical-point nuclei is on-going [7]. A key issue near criticality is to understand the modifications brought in by the fact that nuclei consist of a finite number of nucleons. This aspect is particularly important for sorting out the phase diagram and structure-evolution of stable and unstable nuclei, as a function of protons and neutrons. This issue can be addressed in the framework of the interacting boson model (IBM) [8] which describes low-lying quadrupole collective states in nuclei in terms of a system of N monopole and quadrupole bosons representing valence nucleon pairs. The three dynamical symmetry limits of the model: U(5), SU(3), and O(6), describe the dynamics of stable nuclear shapes: spherical, axially-deformed, and γ-unstable deformed. Phase transitions for finite N have been studied extensively by IBM Hamiltonians involving terms from different dynamical symmetry chains [9]. The critical U(5)-O(6) and U(5)-SU(3) Hamiltonians capture the essential features of the corresponding E(5) and X(5) models. In the present contribution we report on a general procedure, developed recently [10,11,12], for studying finite-N properties of critical-point IBM Hamiltonians for second- and first-order (with low and high barriers). A suitable IBM Hamiltonian for a first-order phase transition with an arbitrary barrier can be constructed by resolving it into intrinsic and collective parts [12]. The resulting spectrum exhibits coexisting spherical and deformed states, with characteristic signatures which differ from those of a low barrier. Initial empirical indications for such deviations from the X(5) predictions have been reported [13]. Considerable insight of the dynamics at the critical-point can be gained by employing number-conserving intrinsic states with an effective deformation. The latter is determined by variation after projection onto the appropriate symmetry. For the above mentioned second-order phase transition, the relevant symmetry is O(5) [10]. For the first-order phase transition, the symmetry is O(3), and is combined with two-level mixing [11,12]. IBM wave functions of a particular analytic form are used to derive accurate finite-N estimates for energies and quadrupole rates at the critical points.

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*This work was supported by the Israel Science Foundation.

Fusion of Radioactive ^{132}Sn and ^{64}Ni

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Fusion reactions are used to synthesize heavy elements. A great deal of effort has been put into finding optimal conditions for the production reactions. Experiments have been performed to study the dynamics of compound nucleus formation in light systems. With the advent of neutron-rich radioactive beams, one can explore the influence of massive neutron transfer on fusion. This may pave the way for producing new neutron-rich heavy nuclei once the intensity of short-lived fission-fragment beams is sufficiently high such that it is practical for use in heavy element synthesis experiments.

At the Holifield Radioactive Ion Beam Facility, neutron-rich radioactive beams are produced by proton induced uranium fission. A beam of doubly magic ^{132}Sn was used to bombard a ^{64}Ni target and measure fusion excitation functions near the Coulomb barrier. The evaporation residues (ERs) were identified by their energy loss in an ionization chamber located at zero degrees and by time-of-flight. The fission fragments were detected by an annular double-sided silicon strip detector. The fragment-fragment coincidence and angular distributions were used to distinguish fission events from other reaction channels.

The fusion cross sections for ^{132}Sn and ^{64}Ni below the barrier are enhanced as compared to other stable Sn isotopes on ^{64}Ni. The enhancement is essentially due to the larger radius of ^{132}Sn which lowers the Coulomb barrier. At energies well above the barrier, the ER cross section saturates at higher values than for the other stable Sn isotopes. The capture cross sections, which are the sum of fission and ER cross sections, can be well described by statistical model predictions, as shown in Fig. 1(a). Figure 1(b) presents the results of coupled-channel calculations. The calculation including inelastic excitation of the projectile and target, and neutron transfer is in good agreement with the measurement. Detailed data analysis and model comparisons will be presented.

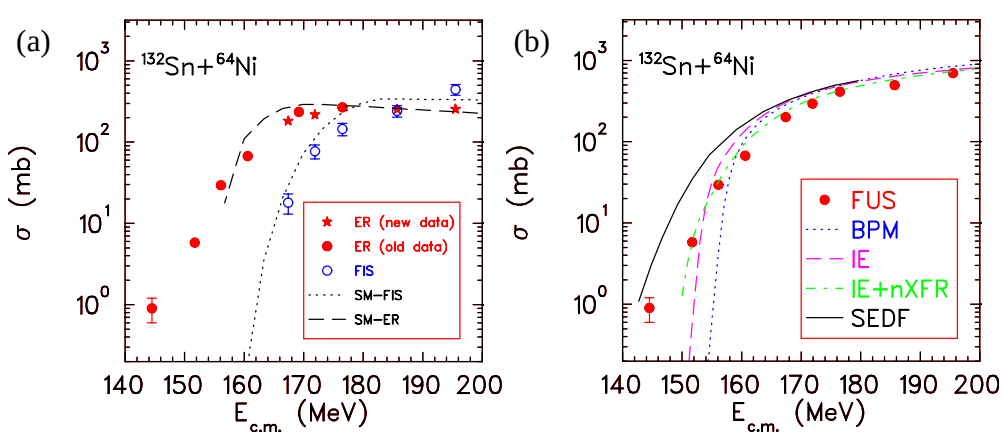

FIG. 1: (a)Comparison of measured ER and fission cross sections to statistical model predictions. (b)Comparison of measured fusion cross sections with coupled-channel calculations.

The structure of ^{8}B through measurement of ^{7}Be+p scattering

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PACS numbers: 27.20.+n, 25.40.Cm, 25.60.-t, 26.30.+k

We have measured ^{7}Be+p elastic and inelastic scattering cross sections at the Holifield Radioactive Ion Beam Facility (HRIBF) at ORNL. Beams of isotopically pure ^{7}Be bombarded thin (100 μg/cm^2) polypropylene targets; scattered protons were detected in an array of silicon strip detectors. Cross sections were measured at 17 bombarding energies ranging from E$_{cm}$=0.5 to 3.4 MeV. The data at each energy were normalized using ^{7}Be+Au elastic scattering from a combined target of polypropylene and gold.

The ^{1}H(^{7}Be,p')^{7}Be* reaction populating the 429-keV ($1/2^-$) first-excited state in ^{7}Be was distinguished from elastic scattering by kinematics and was clearly observed for $E_{cm} > 1$ MeV. This is the first measurement of ^{7}Be+p inelastic scattering and the measured excitation function shows clear evidence for a new positive parity state in ^{8}B. A multi-level R-matrix analysis of the combined elastic and inelastic scattering cross sections was performed and properties of levels in ^{8}B were determined. Results will be presented and compared to previous results from elastic scattering [1, 2] and theoretical expectations from both the shell model [3] and microscopic cluster models [4]. Differential cross sections for ^{7}Be+^{12}C elastic scattering were also determined and will be presented in comparison to optical model calculations.

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Overview of the Synthesis of the Heaviest Elements

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Understanding the synthesis of the heaviest nuclei is one of the most challenging issues in studies of nuclear dynamics and structure. The small cross sections (fb-pb), and the complex interplay between structure, excitation energy and macroscopic dynamics under the influence of large Coulomb forces pique interest and challenge our descriptive ability. In this overview, I shall summarize our current understanding of the synthesis of heavy nuclei using stable and radioactive beams.

Cold fusion reactions, i.e., reactions involving Pb or Bi target nuclei and excitation energies of ~ 13 MeV, have been used to synthesize elements 107-113. Hot fusion reactions, i.e., reactions involving actinide target nuclei and excitation energies of ~30-50 MeV, have been reported to lead to the successful synthesis of elements 113-116 and element 118. This situation is depicted in Figure 1, where the cross sections for these reactions are shown. I will discuss the leveling off of the hot fusion cross sections for the highest Z products and recent attempts to confirm these data in chemical experiments.

The cross section for producing a heavy evaporation residue, σ_{EVR}, can be written as the appropriate spin and excitation energy weighted product of three factors, the capture cross section, $\sigma_{capture}$, P_{CN}, the probability of the colliding nuclei to evolve from the contact configuration to inside the fission saddle point and W_{sur}, the survival probability of the fused system against decay by fission. Recent experiments on the fusion of neutron-rich radioactive nuclei have given us new insight into the isospin dependence of the capture cross sections and the barrier shifts seen with neutron rich projectiles.

The survival probabilities can be calculated using standard formulas for Γ_n/Γ_f, recent calculations of the liquid drop fission barriers and the appropriate shell corrections, and the widely used formalism for the excitation energy dependence of the shell corrections. Tests of these calculations for a large number of systems with low fissility show the survival probabilities can be calculated adequately.

The P_{CN} factors are evaluated using a semi-empirical representation of Armbruster. The predicted cross sections for the synthesis of heavy nuclei (Z=102-113) using cold fusion reactions are well represented over eight orders of magnitude. A similar statement applies to hot fusion reactions where the predictions and measurements agree within a factor of 10 over 9 orders of magnitude. This predictive framework is then used to evaluate the synthesis of new heavy nuclei using radioactive beams. Significant opportunities exist for making new n-rich nuclei that should have profound influence of future studies of the atomic physics and chemistry of the heaviest nuclei. Stable beams continue to be the preferred avenue for making new elements. The most effective reactions involve hot fusion of lighter radioactive projectiles rather than cold fusion reactions of n-rich fission fragments.

The role of transfer reactions in future synthesis reactions is also treated.

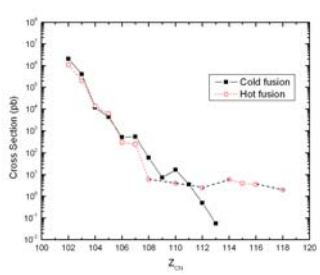

FIG. 1. A plot of the observed cross sections for the production of heavy elements by hot and cold fusion reactions.

Lifetime and g-factor measurements of isomeric states in Sn isotopes using relativistic fission fragments

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Recent experiments in the framework of the RISING campaign [1] at GSI allowed a detailed nuclear structure study such as magnetic moment measurements of isomeric states [2] from the very proton rich to the very neutron rich side of the valley of stability. One novel feature of these studies is the measurement of the spin-alignment of isomeric fragments produced by ^{238}U fission at relativistic energies and the use of this alignment for the g-factor determination of isomeric states in neutron rich nuclei near ^{132}Sn. These are impossible or very difficult to access by other methods. The selection of a cocktail of fission fragments with the FRS opened a possibility to investigate several isomeric decays in the vicinity of ^{132}Sn. Detailed spectroscopic information for many of these isomeric states has not been achieved yet.

The present work will report on recent microsecond lifetime measurements of isomeric states in Sn, Sb and In isotopes around A~130 based on event-by-event time correlation between the fragments and the delayed γ-rays de-exciting the isomers. The measured half-lives of the isomeric transitions allow the deduction of the electromagnetic transition rates which are a significant test for the theoretical models.

Additionally, first results from a g-factor measurement on isomeric states using the RISING detectors, based on measuring the perturbation of γ-anisotropy due to an externally applied magnetic field after implantation of the spin-oriented isomeric beam into a stopper, will be shown. Such investigations are of major importance for nuclear structure studies in the regions of the double magic nuclei far from stability.

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Puzzling New-Odd Parity Doublet Bands in ^{108,110,112}Ru

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The theory of chiral doubling of rotational bands in triaxial nuclei developed by Frauendorf and co-worker [see 1] has led to numbers of searches for such doublet bands, particularly in odd-odd triaxial nuclei. The best claim for chiral doublet bands were reported in ^{104}Rh [2]. In even-even ^{106}Mo, we observed doublet bands which tilted-axis cranking (TAC) calculations indicated could be chiral vibrational bands [3]. Recently one of the earlier proposals for chiral doublets in ^{134}Pr has been shown to not have all of the experimental properties of chiral bands [4]. With our high statistics data, we have carefully investigated levels in ^{108,110,112}Ru, populated in the spontaneous fission of ^{252}Cf. Their positive-parity bands are reported in another abstract. Negative-parity doublet bands are now seen in ^{108,110,112}Ru as shown in Fig. 1 for ^{110}Ru. The many decay-out transitions uniquely yield band-head spins and parities of 4^- and 5^-. Their odd-Z neighboring nuclei show evidence for a transition from symmetric shapes to maximum triaxiality in going from ^{99}Y to ^{113}Rh. The signature splittings of the quasi-γ vibrational bands in $^{108\text{-}112}$Ru are puzzling. The magnitude and direction of the signature splitting in ^{112}Ru are characteristic of a triaxial rotor. However, the smaller and opposite sign for the splitting in ^{108}Ru is puzzling. The odd-parity doublet bands seen in ^{108,110,112}Ru have some remarkable similarities in that their band head energies are close, 2111 keV (4^-); 2424 keV (5^-) in ^{108}Ru; 2016 keV (4^-) and 2243 keV (5^-) in ^{110}Ru; and 2003 keV (5^-) and 2334 (6^-) in ^{112}Ru and the branching ratios E2/(M1 + E2) ~ 6 are identical for the two bands in each nucleus and are nearly identical in all three nuclei. The moments of inertia for the doublet bands in ^{110,112}Ru are nearly equal and constant with spin as in chiral bands. The TAC calculations for ^{112}Ru provide some support for these bands being soft chiral vibrational bands but do not reproduce all the data. One of the real puzzles is seen in Fig. 2 where the energy differences for states of the same spin in the two bands are shown. For rigid chiral rotation, this difference approaches zero. In Fig. 2, one sees a very different pattern for each of ^{108,110,112}Rh. Why are these so different when their branching ratios and their band head energies are so close? The branching ratio agreements strongly indicate these doublet bands are not accidentally degenerate. These doublet bands have the characteristics of chiral bands; however, the TAC calculations do not reproduce all the features. If these are chiral doublets, the data are more complex than represented by present TAC calculations. On the other hand, the data may be pointing to some new symmetry we have not yet understood.

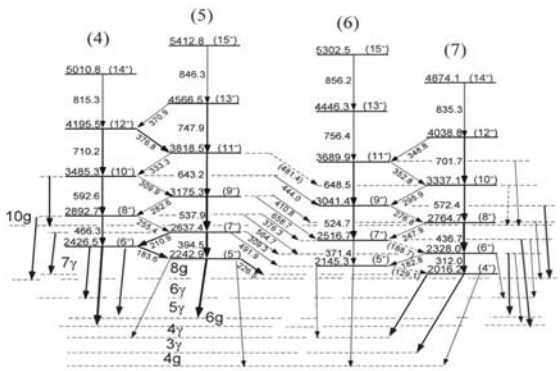

Fig. 1. Partial level scheme for ^{110}Ru

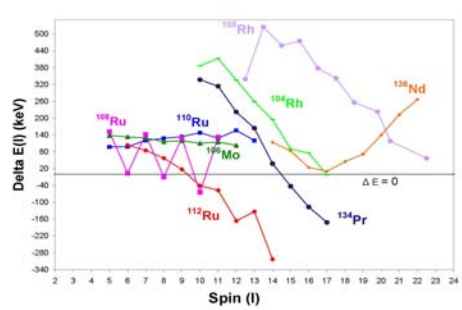

Fig. 2. $E(I)_a - E(I)_b$

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Shape Triaxiality in Neutron-Rich Odd-Mass Y, Nb, Tc and Rh

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Intensive investigations of shape transitions and coexistence in A ~ 100 neutron-rich nuclei have long been of importance [1]. Studies of Y, Nb, Tc and Rh neutron-rich nuclei with Z = 39 – 45, A ~ 100 provide insight into shape transitions with regard to triaxiality in this important odd-Z region. New level schemes of ^{99,101}Y (Z = 39) and ^{101,105}Nb (Z = 41) [2], ^{105,107,109,111}Tc [3] and ^{110,111,112,113}Rh [3] have been extracted from the measurements of prompt gamma rays from the fission of ^{252}Cf at Gammasphere. The data were interpreted by triaxial-rotor-plus-particle model calculations [3]. The model calculations were performed to reproduce the level excitations, signature splittings and branching ratios of the observed bands in these nuclei.

As seen in Fig. 1, the model calculations strongly support a pure axially-symmetric shape with large quadrupole deformation $\varepsilon_2 = 0.41$, $\gamma = 0^o$ and $\varepsilon_2 = 0.39$, $\gamma = 0^o$ in the $5/2^+$[422] ground-state bands of odd-Z, even N ^{99}Y and ^{101}Y

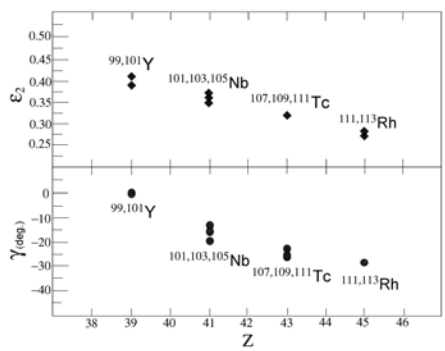

FIG. 1. Triaxial and quadrupole deformations

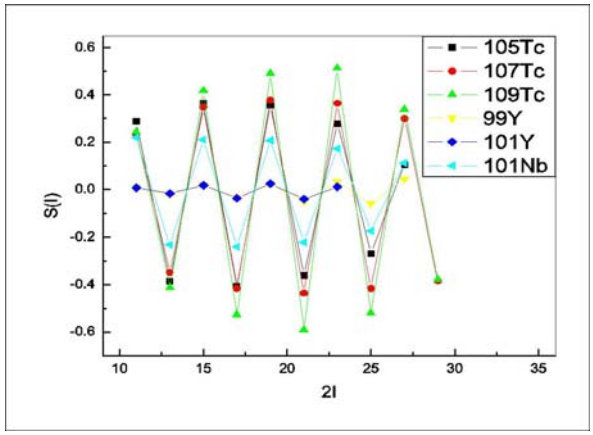

FIG. 2 Signature Splitting in Y, Nb and Tc

respectively. The calculations yielded γ values ranging from -13° to -19° for the $5/2^+$ ground-state bands of ^{101,103,105}Nb and a γ value of -5° for the two negative-parity bands $3/2^-$[301], and $5/2^-$[303] in ^{101}Nb. Here there is coexistence of symmetric and asymmetric shapes. In ^{107,109,111}Tc, the calculations yield for the $7/2^+$ bands, ε_2 of 0.32 in each case and γ = -22.5^o, -25°, -26°, respectively, (our new ^{109,111}Tc results are unpublished). In ^{111,113}Rh, the $\pi 7/2^+$ ground band has even larger signature splitting which is very nicely reproduced in the calculations for $\varepsilon_2 = 28$, γ = -28°, and 0.27, -28° respectively. The magnitude of the signature splitting in Fig. 2 tracks the increasing γ with increasing Z. The changes in quadrupole deformation and triaxiality are shown in Fig. 1 for these neutron-rich odd-Z nuclei with Z = 39 to 45. The deformed shell gaps for $\beta_2 \sim 0.45$ at Z = 38 and N = 60, 62 play an important role for Z = 39 [1]. When Z increases from 39 to 45, the nuclear shape changes from axial symmetry in Y isotopes to nearly maximum triaxiality in Tc and Rh nuclei.

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Astrophysically important ^{31}S states studied with the ^{32}S(p,d)^{31}S reaction

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The ^{30}P(p,γ)^{31}S reaction rate plays a crucial role in the synthesis of heavier nuclear species, from Si to Ca, in nova outbursts on ONe White Dwarfs [1–3]. However, its rate is very uncertain as a result of the lack of spectroscopic information on the levels above proton threshold in ^{31}S. The currently adopted rate of this reaction, based on a statistical Hauser-Feshbach calculation [4], could have an uncertainty as much as a factor of 100 higher or lower under nova conditions. To reduce these uncertainties, we have measured differential cross sections for the ^{32}S(p,d)^{31}S reaction and determined excitation energies for states in ^{31}S. A total of 26 states in ^{31}S were observed, including 17 above the proton threshold. Seven new states were observed. Uncertainties in the excitation energies of states in the high energy region were significantly reduced. Spins and parity values were determined or constrained for 15 of the observed levels through a distorted wave Born approximation (DWBA) analysis of the angular distributions, of which 6 were made for the first time. A new ^{30}P(p,γ)^{31}S reaction rate was calculated using the present experimental spectroscopic information. We confirmed the spin-parity assignment of $1/2^+$ for the ^{31}S state at 6267 keV which dominates the ^{30}P(p,γ)^{31}S reaction rate at lower temperatures in nova, while the ^{31}S state at 6546 keV dominates at temperatures above 0.2 GK. Our results indicate that the ^{30}P(p,γ)^{31}S rate is reduced by up to a factor of 10 at nova temperatures.

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Oak Ridge National Laboratory is managed by UT-Battele, LLC, for the U.S.Department of Energy under contract DE-AC05-00OR22725.

GAMMASPHERE: The First Decade*

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GAMMASPHERE, a gamma-ray spectrometer of unparalleled performance, is a National Facility funded by the DOE-Nuclear Physics Office that was designed and constructed by a collaboration of US National Laboratories and Universities led by LBNL. It consists of 110 modules (large volume HPGe Detectors and BGO Compton shields) covering a large solid angle approaching ~4π. With its unique characteristics - high energy resolution, large efficiency and granularity - enhanced by a suite of auxiliary devices, the array had a major impact in nuclear structure studies.

As we celebrate 10 years of successful operation, since its official dedication in December of 1995, we will review the rich and broad physics program carried out so far in two campaigns in Berkeley and two in Argonne. Examples in this talk will focus on applications in nuclear astrophysics and fundamental interactions.

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*This work was supported by the U.S. Department of Energy under contracts DE-AC02-05CH11231.

Nuclear Forces from Effective Field Theory: A New Era in Microscopic Nuclear Structure

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Realistic and accurate nuclear forces are a crucial prerequisite for meaningful microscopic nuclear structure calculations. Over the long history of the field, many such forces have been constructed. However, the models of the past are essentially phenomenology with no clear relation to the underlying theory of strong interactions, QCD. This theory gap is overcome when the scenario of low-energy QCD is described in terms of an effective field theory [1]. Based upon this concept, realistic and accurate two- and three-nucleon forces have been derived [2]. These recent developments set the stage for a new era in microscopic nuclear structure calculations.

This work is supported in part by the U.S. National Science Foundation under Grant No. PHY-0099444.

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Spin 1/2 Fermions in the Unitary Regime: A Superfluid of a New Type

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The unitary regime is commonly referred to as the situation in which the scattering length a greatly exceeds the average inter-particle separation, thus $n|a|^3 \gg 1$, where n is the particle number density. It is widely accepted by theorists that at $T = 0$ these systems are superfluid and that in the unitary regime the coherence length is comparable in magnitude with the average interparticle separation. At $T = 0$ this problem has been considered by a number of authors [1] and the most accurate results so far have been reported in Refs. [2-4]. In 2002 it was shown experimentally that such systems are (meta)stable, and they have been studied extensively experimentally ever since [5,6].
We have studied, in a fully non-perturbative calculation, a dilute system of spin 1/2 interacting fermions, characterized by an infinite scattering length at finite temperatures. Various thermodynamic properties and the condensate fraction were calculated and we have also determined the critical temperature for the superfluid-normal phase transition in this regime. The thermodynamic behavior appears as a rather surprising and unexpected mélange of fermionic and bosonic features. The thermal response of a fermion system at BCS-BEC crossover indicates that this is a new type of superfluid [7].

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Collective Excitations in the Strong Pairing Limit in Nuclei near the Neutron Drip Line

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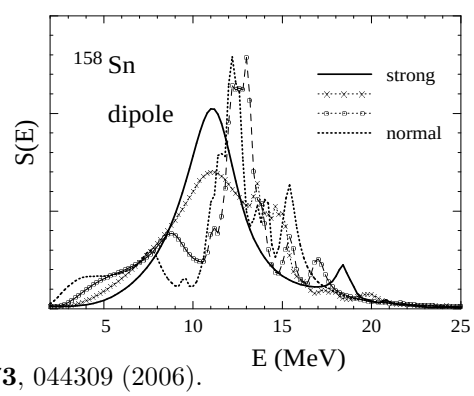
The nuclear pairing correlation depends very strongly on the nucleon density. It becomes stronger at lower densities around $(10^{-1} \quad 10^{3}) \times \rho_0$, reflecting the momentum dependence of the bare nucleon interaction in the ^1S channel. The pairing at such low density may be characterized as the one in a strong coupling regime, or more precisely the situation close to the border between the Bose-Einstein condensate of di-neutrons (strong coupling) and the conventional BCS pairing (weak coupling)[1]. If this is the case, the neutron rich nuclei may provide a unique opportunity to explore new features of the nuclear pair correlation. In fact, our previous study using the Hartree-Fock-Bogliubov mean-field plus the continuum QRPA technique have suggested that the low-lying dipole mode emerging in medium-mass nuclei near the neutron drip-line is affected strongly by the pair correlation in a peculiar manner not known in other modes in stable nuclei[2].

In the present work, we intend to clarify how the nature of collective excitations evolves if we vary the strength of pair correlation, focusing especially on the difference between stable and unstable nuclei. For this purpose, we adopt an artificially strong pairing force constrained only by the zero-energy scattering length $a = \quad 18$fm (this gives the pairing gap around $\Delta \sim 15$MeV), while a moderate and realistic density-dependent force produces gap around $\Delta \sim 1 \quad 2$ MeV. The Skyrme-HFB plus continuum QRPA formalism works fine even in such an enormously strong coupling case. We perform calculations for the dipole, quadrupole and octupole modes in ^{120}Sn and ^{158}Sn chosen as representatives of stable and near-drip-line nuclei, respectively.

In the strong pairing limit and in ^{120}Sn, we find a single mode of dipole collective excitation which has the character of the collective oscillation of a perfect superfluid (known as the Anderson-Bogliubov mode) with two different components (neutrons and protons). We see a very different situation in ^{158}Sn: there emerges an additional mode of excitation besides the AB mode. This mode has significant amplitude in the pair transition density around the nuclear surface and far outside, and hence clearly distinguishable from the AB mode of the volume type. It can be interpreted as a mode where neutron pairs or di-neutrons are leaking from the surface of nucleus, but decaying instantly just after the excitation. With decreasing the pairing strength toward the realistic value, the AB mode is resolved in the usual giant dipole resonance while the essential structure of the surface pair leaking mode remains. The situation for the quadrupole mode is different from the dipole case, and will be discussed also at NS06.



E1 strength function for ^{158}Sn calculated with the Skyrme Ly4 parameter and various strengths of the pairing interaction.

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A new look at the β-decay of ^{11}Li *

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The β-decay of halo nucleus ^{11}Li was investigated at ISAC-TRIUMF with the 8π spectrometer, an array of 20 Compton-suppressed high-purity Germanium detectors. In August 2002, a beam of about a thousand ^{11}Li atoms per second was delivered and implanted at the center of the 8π. The gamma spectrum resulting from the β-decay of ^{11}Li shows remarkable features, namely Doppler-broadened line shapes arising from the decay of the excited states of ^{10}Be, populated by β-delayed one-neutron emission. A Monte-Carlo simulation was developed to analyze these complex line shapes, from which it was possible to extract the lifetime of these excited states in ^{10}Be and some information about the neutron emitting states in ^{11}Be [1]. Disagreements were however observed with an experiment using a polarized ^{11}Li beam and time-of-flight neutron detectors [2]. Following the development of a more intense ^{11}Li beam at ISAC, the experiment was recently repeated with an enhanced experimental setup, comprising the 8π and Sceptar, a plastic scintillator array located in the inner volume of the 8π. The higher ^{11}Li yield and the capability of taking data in β-γ coincidences lead to higher quality line shapes, as seen in the figure below. The analysis of those line shapes should help resolve the discrepancies observed with [2] and possibly lead to new insights in the β-decay of ^{11}Li.

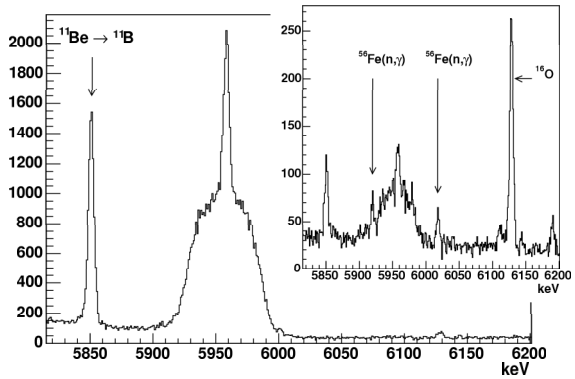

FIG. 1. Line shape of the ~5958keV transition as observed in the recent experiment compared to the first one (inset). The overall lineshape quality is improved both by the higher statistics obtained and by the removal of transitions uncorrelated with the beam implantation using β-γ coincidences.

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On the alpha decay of ^{109}I

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Alpha emission is a rich source for nuclear-structure information [1]. The alpha-particle energies E_α, corrected for the recoil effect, yield the difference between the ground-state masses of parent and daughter nuclides (Q_α). Far from stability the Q_α determination often represents the only way to determine the masses of ground and isomeric states. The Q_α values along an alpha-decay chain are also a probe for shell effects. In the region above ^{100}Sn an alpha-decay island occurs, which directly reflects the strong Z=50, N=50 shell-closure.
In an experiment performed at the Recoil Mass Separator of the HRIBF at Oak Ridge National Laboratory, the first evidence for the alpha-decay branch of the proton-emitter ^{109}I was obtained. The results and the consequences for nuclear masses in this region will be discussed.

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Structure of nuclei near the doubly magic ^{78}Ni from isomer- and beta-decay studies

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Nuclei with very large neutron-to-proton (N/Z) ratios have become available for experiments and are crucial to test the increasingly complex many body models. The half-century old nuclear shell model has been a very successful tool to describe the properties of nuclei closer to the stability valley and is undergoing a period of revival to describe the properties of more exotic isotopes [1] thanks to the increased computing capabilities. The predictive power of these calculations must be tested by experiments on nuclei with as large proton-neutron asymmetry as possible. Magic nuclei and their neighbors are the best candidates to perform these investigations.
Particularly interesting is the region close to the Z=28, N=50 nucleus ^{78}Ni. Different experimental approaches have been used to understand the evolution of magicity this far away from the beta-stability valley [2-11]. Detection systems sensitive to beta and gamma radiation enabled the spectroscopy of states populated in the deexcitation of short-lived isomers and following beta decay and a variety of other gamma-spectroscopy methods have also been applied to investigate the properties of these nuclei [12-14]. These sensitive measurements provided, among other results, the first observation of the energies of the lowest excited states in the magic nickel nuclei from ^{70}Ni to ^{76}Ni. The presence of $(\nu g_{9/2})^2$ $J^\pi=8^+$ microsecond isomers in the even-even Ni chain $^{70-76}$Ni was predicted as a consequence of the doubly-magic character of ^{78}Ni. Such isomers were observed in the valence-mirror N=50 nuclei close to ^{100}Sn. The shell-model framework successfully applied in the case of ^{68,70}Ni could not satisfactorily reproduce the measured properties of the more exotic nickel nuclei [15], such as the disappearance of $J^\pi=8^+$ seniority isomers in ^{72,74}Ni and their reappearance in ^{76}Ni [11]. This behavior of the even-even Ni isotopes found recently a possible explanation in new shell-model calculations with a semi-empirical interaction [16].
An overview of experiments performed recently to elucidate the structure of neutron rich nuclei close to ^{78}Ni, in an attempt to learn as much as possible on the magicity of ^{78}Ni itself, will be given in comparison with shell-model predictions.

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Nuclear Magnetic Moment of ^{57}Cu Ground State *

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The nuclear magnetic moment of the ground state of ^{57}Cu($I^\pi = 3/2^-$, $T_{1/2} = 196.3$ ms) was measured for the first time. Together with a known magnetic moment of the mirror partner, ^{57}Ni, the spin expectation value, which is a contribution of nucleon spins to the magnetic moment, was extracted from the isoscaler part of magnetic moments, taking advantage of their charge symmetry. In the *sd* shell, all of the ground state magnetic moments of isospin $T = 1/2$ mirror nuclei have been measured and a systematic trend of the spin expectation value depending on the shell structure has been observed. On the other hand, in the *fp* shell, only few mirror magnetic moments are known (^{41}Ca-^{41}Sc and ^{43}Sc-^{43}Ti pairs) and therefore it is essential to measure more magnetic moments in order to explore the evolution of shell structure. Because ^{57}Cu consists of the closed-shell ^{56}Ni core plus one proton, the single-particle contribution is expected to be strong and any deviation from the shell model is a direct proof of shell breaking at ^{56}Ni, which has been suggested [1] based on a systematic deviation between magnetic moments of odd-mass Cu isotopes and theoretical shell-model predictions.

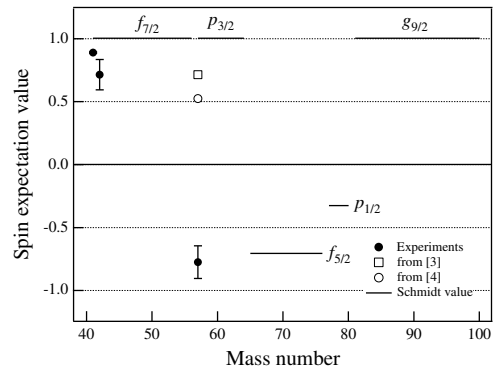

FIG. 1: Spin expectation values in the *fpg* shell.

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. The ^{57}Cu ions were produced from a primary beam of ^{58}Ni (140 MeV/nucleon) impinging on a ^{9}Be target. A charge pick-up reaction was employed for the production and nuclear polarization of ^{57}Cu. The ^{57}Cu ions were separated from other reaction products by the A1900 fragment separator, delivered to the β-NMR apparatus and implanted into a single-crystal NaCl under a strong external magnetic field.

From the resonance frequency, the magnetic moment was derived as $|\mu(^{57}\mathrm{Cu})| = (2.00 \pm 0.05)\mu_\mathrm{N}$ [2]. Together with the known magnetic moment of ^{57}Ni, the spin expectation value was extracted as $\langle \Sigma_z \rangle = 0.78 \pm 0.13$, which is shown in Figure 1. The small $\mu(^{57}\mathrm{Cu})$ results in a large deviation and opposite sign from the shell-model calculations. Considering the systematic behavior of the spin expectation value of $T = 1/2$ nuclei in the *sd* shell, where the spin expectation values are restored close to the single-particle values around the shell closures, the present result indicates a significant shell breaking at ^{56}Ni with the neutron number $N = 28$.

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*This work was supported in part by the National Science Foundation Grants No. PHY 01-10253 and No. PHY 99-83810.

Experiments on synthesis of super-heavy elements at RIKEN

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Abstract. In the Institute of Physical and Chemical Research (RIKEN), using high intensity heavy ion beams from the RIKEN Linear Accelerator, productions and decays of isotopes of the heaviest elements have been investigated by using the gas-filled recoil separator, GARIS. The isotopes studied were ^{265}Hs, ^{271}Ds, ^{272}Rg, ^{277}112, and ^{278}113, respectively. Based on the observed decay chains consisting of consecutive alpha decays connected to the previously known alpha decays or spontaneous fissions, assignments of the initially produced isotopes were done. Our data with the atomic number from 108 to 112, agree well with the data previously reported taken by a group at Gesellschaft für Schwerionenforschung (GSI), Germany. The production cross section of the isotope ^{278}113 of the 113th element have reached around 32 fb which shows the simple decrease of the cross section with the increase of the atomic number. The isotopes were produced, for the first time in the 1n evaporation channel from heavy-ion induced fusion reaction.

RI Beam Factory at RIKEN

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At RIKEN, RI (Radioactive Isotope) Beam Factory (RIBF) is under construction. It is upgrade of the present cyclotron complex, which provides high-intensity beams of light unstable nuclei by the projectile fragment at ion scheme, as well as polarized deuteron beams, intense heavy-ion beams in the 5 MeV/nucleon region used for super-heavy element search, low-energy (~5 MeV/nucleon) RI beams, and so on. By building three new cyclotrons, which will be coupled with the present accelerators, the beam energy will be boosted to 350 MeV/nucleon with high intensity up to 1 p micro A for hydrogen to uranium. Using projectile fragmentation or uranium induced in-flight fission, intense RI beams of around 200-300 MeV/nucleon will be produced. The limit of production with 1 particle/day yield covers almost the expected r-process path for heavy element synthesis. The RIBF is the first realization of the "next generation" RI beam facilities. We expect the first beam during the year 2006, and first experiments will start in 2007.

One-Proton and Two-Proton Radioactivity of the (21^+) Isomer in ^{94}Ag

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The (21^+) isomer occurring in the lightest known isotope of silver, ^{94}Ag, has properties that are unmatched in the entire nuclear chart. It is characterised by a long half-life of 0.39(4) s [1], a high spin [2] and, although its dominant disintegration modes are β-delayed γ-ray [2] or proton [1] emission, the excitation energy of 6.7(5) MeV [3] makes direct one-proton (1p) and two-proton (2p) radioactivity possible. The experimental results on the latter two decay modes [3,4] will be summarised here.

The decay properties of the (21^+) isomer were studied at the GSI on-line mass separator by using a ^{58}Ni(^{40}Ca,p3n) fusion-evaporation reaction. After ionisation and acceleration to 55 keV, the A=94 ions were mass separated and implanted into a tape positioned in the centre of an array of segmented silicon and composite germanium detectors. The tape was periodically removed from the implantation position in order to reduce the build-up of long-lived daughter activity. While the silicon detectors were used to record protons the germanium crystals served to 'tag' on known γ-ray transitions in the 1p daughter, ^{93}Pd, and the 2p daughter, ^{92}Rh, respectively. In this way the 1p and 2p radioactivity was identified, the decay energies and decay probabilities amounting to 0.79 MeV, 1.01 MeV and 1.9(5) %, 2.2(4) % in the former and 1.9(1) MeV and 0.5(3) % in the latter case. The cross-section for producing the 2p radioactivity in the fusion-evaporation reaction was found to be about 350 pb [5].

By comparing the experimental partial half-lives of the two 1p-decay modes with WKB estimates, very small spectroscopic factors of 1×10^{-6} and 3×10^{-7} were deduced [3]. The experimental proton-proton correlation data are displayed in Fig. 1 together with predictions obtained from the break-up model ([4] and references therein). The spectra displayed in Fig. 1 were derived out of the Si_1-Si_2-γ-γ coincidence matrix, with a total of 19 events fulfilling the triple condition set on two ^{92}Rh γtransitions and on the 2p sum-energy in the range of 1.8 – 1.95 MeV.

In general, 2p decay can proceed through sequential proton emission involving intermediate ^{93}Pd states, or through a simultaneous three-particle decay mechanism. The former decay should result in narrow peaks in the spectrum shown in Fig. 1b whose energies depend on the (unknown) energy of the ^{92}Rh state involved and should add up to a total of 1.9(1) MeV. As there is no evidence for such peaks (see Fig. 1b), the observed proton-proton correlations seem to be consistent only with ^{94}Ag decaying through a simultaneous 2p emission process. For ^{94}Ag such a 'true' 2p-decay is expected to be much slower than the sequential decay mode: However; the 2p-decay half-life estimated by using the 'simultaneous emission' model exceeds the experimentally determined half-life by a factor of $10^3 – 10^6$. Finally, the experimental results on the 2p half-life and on the proton-proton energy correlation are interpreted, on the basis of a comparison with predictions from the breakup model, as indicating a very large, prolate deformation of the parent nucleus, with the emission of protons occurring either from the same or from opposite ends of the 'cigar' [4].

All in all, it is the first time that 1p and 2p radioactivity has been identified to occur from one and the same nuclear state and that proton-proton correlations have been observed in 2p radioactivity. The interpretation of the strong deformation of the (21^+) isomer in ^{94}Ag is indeed a challenge for future experimental and theoretical work.

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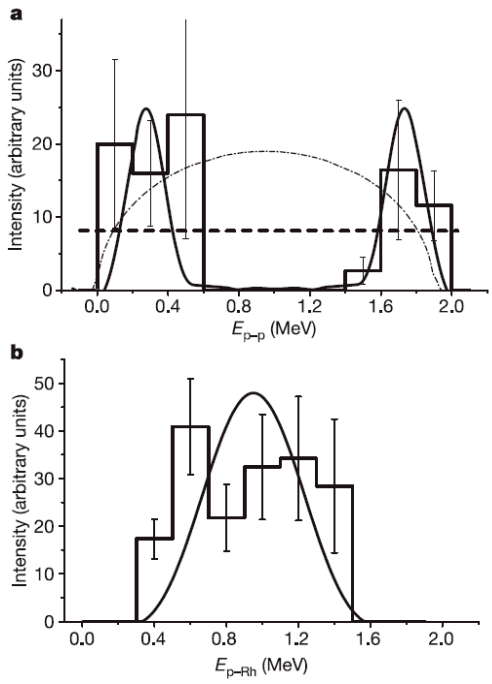

Figure 1: Correlations observed in the 2p decay of the (21^+) isomer of ^{94}Ag. Relative-energy spectra for proton-proton (E_{p-p}) and proton-^{92}Rh (E_{p-Rh}) correlations are shown by histograms in **a** and **b**, respectively. Solid curves are predictions of our model of simultaneous proton emission from a deformed nucleus convoluted with an experimental uncertainty of 200 keV. The dashed line represents the fit obtained with a sequential emission mechanism. The dashed-dotted curve shows the calculated distribution when the 2p decay is isotropic in the absence of the mentioned decay mechanisms [4].

Static and Dynamic Approaches to Collective Excitations in Nuclei Far From Stability Line

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An atomic nucleus exhibits a variety of collective modes of excitation associated with nuclear deformation, and responds to many kinds of experimental probes; Coulomb and nuclear excitations, spin- and isospin-dependent probes, high- and low-energy reactions. In order to investigate properties of these nuclear excitations, we have been developing static (time-independent) and dynamic (time-dependent) methods using the Skyrme energy functional. The static methods are based on the variation after projection (VAP) method and the con guration mixing calculation diagonalizing the Hamiltonian matrices in a certain set of basis states. The dynamic methods are based on the time-dependent Hartree-Fock (TDHF) theory.

The static methods are similar to the generator coordinate method (GCM) with the angular momentum projection. However, the basis states (Slater determinants) are generated either by variation after parity projection [1] or by a stochastic procedure [2]. These calculations can be regarded as an extension of the GCM, in the sense that the generator coordinate is not assumed *a priori*, and also as an extension of the shell model calculation, in the sense that the model space is extensively large. These static methods are useful for explicitly obtaining wave functions, and spectroscopic quantities, and the ground-state correlations.

As a kind of complementary method to the static approaches, we have proposed a method of the small-amplitude TDHF in real time [3]. Utilizing the absorbing-boundary condition, this is an alternative and an extension of the continuum RPA. The TDHF is known to be able to describe nuclear dynamics with a proper inertial parameter and determine its collective path for itself. The method has following advantages over the conventional continuum RPA method: (1) It is easy to carry out the fully self-consistent calculations including the spin-orbit, Coulomb, and time-odd residual interactions. (2) It is able to calculate response in deformed systems. (3) Nuclear dynamics of giant resonances can be visualized with the TDHF wave packet. (4) A single time evolution provides information in a wide range of energy.

In this talk, we will present our recent results with the full Skyrme functional for stable and unstable nuclei. We will show that the new static approaches can properly take into account long-range correlations described by the Skyrme interaction. The small-amplitude TDHF dynamics suggest an interesting behavior of weakly-bound neutrons at the drip line. An example is shown in Fig. 1 for the $E1$ giant resonances in ^{14}Be. The TDHF simulation seems to indicate a strong screening e ect caused by these weakly bound neutrons.

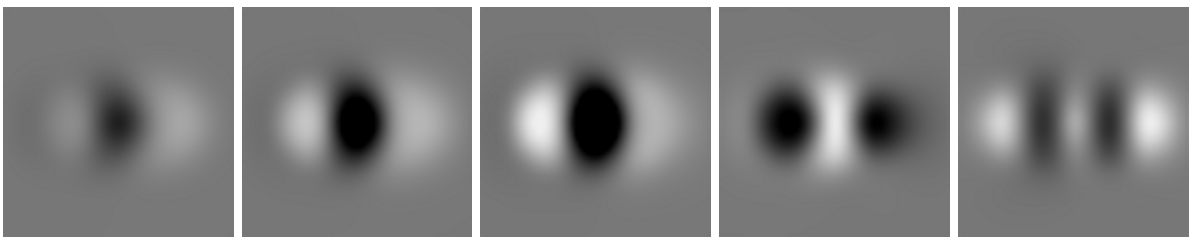

FIG. 1. TDHF simulation of $E1$ giant resonance in ^{14}Be. The figure indicates the time-dependent neutron density variation, $\delta\rho(\mathbf{r},t) \equiv \rho(\mathbf{r},t) - \rho_0(\mathbf{r})$, where $\rho_0(\mathbf{r})$ is the ground-state density. White (black) parts show $\delta\rho > 0$ ($\delta\rho < 0$)

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Nuclear Structure with Correlated Realistic Interactions *

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The Unitary Correlation Operator Method (UCOM) has been developed to explicitly introduce short-range central and tensor correlations into the nuclear many-body wave function. A realistic nucleon-nucleon force is transformed into a phase-shift equivalent correlated interaction $V_{\rm UCOM}$. This is achieved by a unitary transformation of the Hamiltonian involving kinetic energy T and bare two-body potential V using unitary correlation operators C_r and C_Ω that describe the short-range central and tensor correlations respectively.

$$C_r^\dagger C_\Omega^\dagger (T+V) C_\Omega C_r = T + V_{\rm UCOM} + V_{\rm UCOM}^{[3]} + \ldots$$

Details on the construction of the correlation operators are given in [1,2]. The tensor correlator C_Ω has one parameter I_ϑ which controls the range of the tensor correlations included via the transformation. In addition to the correlated two-body interaction $V_{\rm UCOM}$ the transformation generates a three-body interaction $V_{\rm UCOM}^{[3]}$ as well as higher-order terms. The effect of omitting these higher order terms is studied in exact no-core shell model calculations for ^{3}H and ^{4}He [2]. The results in Fig. 1 show that we can cover with the two-body $V_{\rm UCOM}$ the Tjon line as a function of the tensor correlation range. By choosing the tensor correlation range such that the experimental binding energies are best reproduced we achieve effectively a cancellation between three-body terms in the cluster expansion and genuine three-body forces.

With this particular choice for the tensor correlation range we study heavier nuclei with Hartree-Fock and many-body perturbation theory [3]. These results as well as first no-core shell model calculations in the p-shell (see Fig. 1) indicate that $V_{\rm UCOM}$ provides good results without the need for explicit three-body forces.

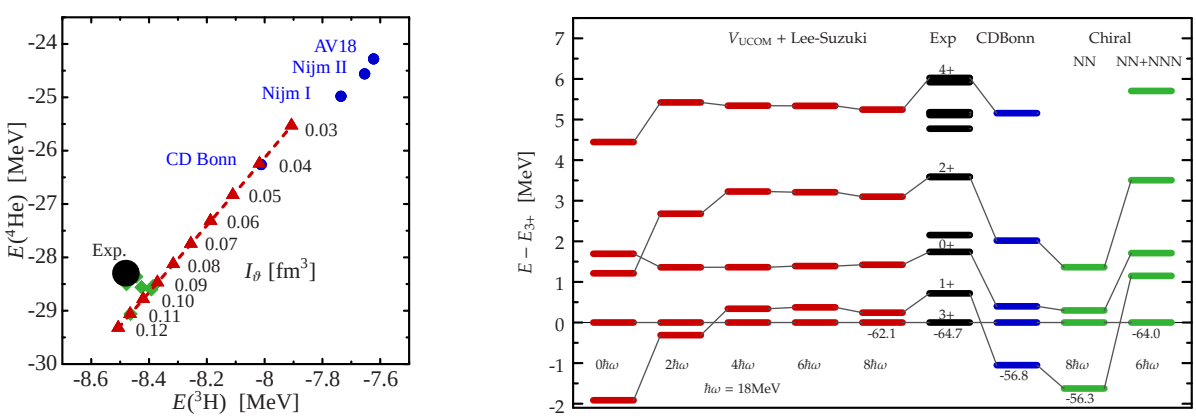

FIG. 1. (Left) ^{3}H versus ^{4}He binding energies with $V_{\rm UCOM}$ as a function of tensor correlation range I_ϑ. Results with bare NN forces and bare NN+NNN forces. (Right) Spectrum for ^{10}B calculated in the NCSM with $V_{\rm UCOM}$ and other forces.

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*This work was supported by NSF grant PHY-024445.

Scanning AGATA prototype detectors and the first in-beam experiment using an AGATA triple cluster*

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It is expected that the next generation of gamma spectrometer for nuclear structure studies will consist of a large array of highly segmented HP-Ge detectors, utilizing the techniques of Pulse Shape Analysis [1] and Gamma Ray Tracking [2]. The photon interaction positions will be determined to within a few millimeters and scattered events can be added-back to comprise a full energy event. This will allow for greatly improved efficiency as well as excellent angular resolution. Prototype detectors for the Advanced GAmma Tracking Array (AGATA) have been constructed with 36-fold segmentation and scans have been performed in order to characterize the detectors' response and position sensitivity. Some results of these scans will be presented.

When completed, the functional array, consisting of 180 of these large volume detectors, will make use of electric field simulation software to calculate theoretical pulse shapes for every position within the detector volume. These will be compared to the pulse shapes obtained experimentally in real time in order to assign a position to an interaction. Results of a comparison between the pulse shapes calculated using such software and those determined from a detector scan will be presented.

A description of an in-beam experiment using three of the prototype detectors in the reaction d(^{48}Ti,p)^{49}Ti will also be presented. The three detectors, 108 detecting elements in total, were in a single cryostat creating a modular AGATA triple cluster unit at 90° to the beam line. An annular silicon detector was used to determine the energy and the angle of the recoiling proton. It is hoped that data from this experiment along with scan results can be used to show the detectors' ability to reduce Doppler broadening and improve position resolution beyond that which can be achieved by segmentation of the crystal alone. Thus the results of this analysis will provide a means to assess the efficacy of the concept of a tracking array and is therefore of great consequence to the nuclear structure community.

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*This work was supported by the EPSRC

Quantum Monte Carlo studies of bound and unbound nuclear states *

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The last fifteen years have seen tremendous advances toward an understanding of nuclei in terms of the bare nucleon-nucleon interaction. These advances include both improved descriptions of the interaction itself and improved theoretical methods to compute wave functions and energies of light nuclei using the interaction as input. Over the next several years, these advances will improve our understanding of how nuclear properties arise from the interactions that give rise to them. They also offer the prospect of reliable absolute cross sections for astrophysical processes involving the light nuclei.

I will describe work by myself and my collaborators, based on the Argonne v_{18} two-nucleon interaction [1] and (mostly) the Illinois-2 three-nucleon interaction [2]. We compute wave functions using two quantum Monte Carlo (QMC) methods: variational Monte Carlo (VMC) and Green's function Monte Carlo (GFMC). VMC is a variational method based on adjusting parameters in a sophisticated guess wave function to minimize the energy for given spin, isospin, and parity. The GFMC method takes the VMC wave function as an initial guess and projects out the true ground state for the given quantum numbers and boundary conditions. I will describe the application and results of these methods. Wave functions for several nuclear systems have been computed using the QMC methods, with GFMC energies computed for some sixty bound and narrow states in light ($A \leq 12$) nuclei [2,3]. Both absolute energies and the ordering of states are good matches to experimentally-measured energy levels.

The QMC methods do not use basis functions, but the wave function at each point in configuration space is a vector in the possible particle spins and isospins. Because of the tensor interaction, there is strong coupling between all subspaces in this basis. The size of our isospin-conserving basis grows approximately as the factorial of particle number; this gives us a practical limit of $A \leq 12$ for GFMC calculations as presently implemented. However, much remains to be done because calculations to date have emphasized energies of bound and narrow states. There are many other quantities that can be computed with these methods. In particular, the lack of a spatial basis function expansion makes QMC particularly suited to computations of weakly-bound or unbound nuclei.

Work on properties beyond energies is advancing on several fronts. In the past, we computed off-diagonal matrix elements (*e.g.*, electroweak transition strengths) using VMC. We are now developing methods to compute such quantities using GFMC. Recently, GFMC has also been used to compute nuclear charge radii for heavy He and Li isotopes. In addition, spectroscopic factors and their associated overlap functions are being computed from VMC and used to interpret pickup and stripping reactions in radioactive-beam experiments [4].

The most important advance occurring now is the extension of QMC to scattering and reactions. We have extended the VMC and GFMC codes to address scattering with a single open channel. The first application of this method is to neutron scattering on ^{4}He below 5 MeV. We find that the Argonne v_{18} + Illinois-2 interaction reproduces the ^{4}He+n cross sections extremely well. This development opens the door to the study of many broad resonances, as well as scattering and electroweak capture reactions away from resonance. Over the longer term, it should be possible to address problems in more than one open channel using essentially the same method. I will conclude by discussing unbound-state problems we plan to tackle in the near future, and in particular the utility to astrophysics of *ab initio* predictions of absolute cross sections.

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*This work was supported by the U. S. Department of Energy under contract No. W-31-109-ENG-38.

Direct mechanisms in multi-nucleon removal reactions at intermediate energy: from knockout to fragmentation.

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Beams of exotic nuclei provide a key tool to study nuclear structure far from stability. At intermediate energies (∼100 MeV/nucleon), exotic beams can be produced via in-flight fragmentation, where the nucleus of interest is obtained by removing nucleons from an incident primary beam. One-nucleon removal reactions from projectiles at intermediate energies have been shown to be direct processes [1] with the resulting cross sections to different excited states sensitive to the quantum numbers of the removed nucleon. We discuss here the properties of multi-nucleon removal reactions.

We present new results from two-nucleon knockout and few-nucleon removal reactions from experiments performed at the National Superconducting Cyclotron Laboratory at Michigan State University. Several incident secondary beams at ∼100 MeV/nucleon on the proton-rich side of the *sd*-shell were used. Ejectiles from two-nucleon knockout and multi-nucleon removal were identified and detected in the S800 magnetic spectrograph [2]. Both inclusive cross sections and cross sections for the population of individual states were determined. Cross sections to excited states were obtained by measuring deexcitation γ-rays with the SeGA HPGe segmented array [3] in coincidence with reaction products.

Two-neutron knockout reactions performed on ^{34}Ar, ^{30}S and ^{26}Si in the proximity of the proton dripline [4] are discussed. Two-proton removal has recently been shown to be direct for neutron-rich nuclei [5-7]. The present results show that two-neutron knockout on proton-rich nuclei is a direct mechanism as well. The comparison of measured cross sections with state-of-the-art calculations [7] indicates a strong sensitivity to the correlations in the initial nucleus between the two removed nucleons.

We further examine the transition between direct reactions to statistical processes by correlating the relative population of excited states in several *sd*-shell nuclei with the number of removed nucleons [8].

The authors acknowledge support from the U.S. National Science Foundation under Grants No. PHY-0110253 and No. PHY-0244453, and the United Kingdom Engineering and Physical Sciences Research Council (EPSRC) under Grant No. EP/D003628.

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Applications of the ab initio No-core Shell Model for Nuclear Structure and Reactions*

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A long-standing goal in nuclear physics is to arrive at a first-principles description nuclear properties (both structure and reactions) with the fundamental interactions between the constituent nucleons. Because of recent advances in both computational capability and theoretical methods, this goal appears to be now within reach. Three methods can address this critical question and can be benchmarked against one another. These are: 1) Green's Function Monte Carlo (GFMC), 2) No-core, Shell Model (NCSM), and 3) Coupled clusters. In this work, we present the latest developments with applications of the NCSM with realistic two- and three-body interactions.

By definition, ab initio methods begin with a proper representation of the fundamental interaction. In recent applications of the NCSM, we explore the utility of potentials derived with effective-field theory (EFT). EFT offers an elegant and consistent framework to determine the fundamental inter-nucleon interactions at a given order in the expansion parameter. Here, we show recent results where both the two- and three-nucleon interaction are determined from EFT. We show that a unique potential can be derived by requiring that the binding energies of ^{3}H, ^{3}He, and ^{4}He be reproduced as well as the rms radius of ^{4}He. Our ultimate goal is to arrive a consistent two-, three-, and four-nucleon interaction at the level of N^{3}LO in effective field theory.

With the two- and three-nucleon EFT potentials, we show the results of large-basis shell-model calculations for p-shell nuclei up to ^{16}O. These ab initio calculations are performed within the framework of the no-core shell model, namely with an effective interaction derived from the Okubo-Lee-Suzuki transformation, which offers a mechanism to attain converged results for the full interaction within a computationally tractable model space. Calculations were performed with three-body interactions including up to 6 oscillator quanta in excitation. The dimensions involved in these calculations are of the order 30×10^6, and were performed on massively parallel computers at LLNL, in particular THUNDER, with CPU requirements in excess of 6000 hours. We show that even at the simplest level, with only two free parameters determined only from three- and four body nuclei, the three-body EFT potential gives a good overall description of nuclear structure; correctly predicting the ground-state spin for A > 10 nuclei, i.e., 3^+ for ^{10}B.

In addition to structure, we have extended the NCSM to describe dynamic processes, such as radiative capture, light-ion fusion, and neutron-induced reactions. We outline the developments of the formalism and recent applications. In particular, we show applications for ^{7}Be(p,γ)^{8}B and binary fusion reactions.

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*This work was perfomed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48

Core Excited Fano-Resonances in Exotic Nuclei

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Over the last few years various unexpected phenomena have been observed in the study of light exotic nuclei, indicating a shift away from mean-field dynamics towards a new type of correlation dynamics [1]. Here, we consider a particular class of states above the neutron emission threshold, the so-called Fano-resonances, which are investigated as a new continuum excitation mode in exotic nuclei [2]. By theoretical model calculations we show that the coupling of a single particle elastic channel to closed core-excited channels leads to sharp resonances in the low-energy continuum of the [n + (A – 1)] system [2].

These states are known as Bound States Embedded in the Continuum (BSEC) [3, 4, 5], which, for example, we have observed in ^{11}Be [6, 7] and ^{15}C [8, 9]. A signature for such BSEC are characteristic interference effects leading to asymmetric line shapes. We have observed a such interference in the ^{15}C spectra [8, 9]. Fano interference [10] consists of the quantum-mechanical interaction between discrete and continuous configurations, leading to characteristically asymmetric peaks in the spectra. The first model for auto-ionizing atomic states was developed by Fano in the 1960's [10].

Following the Quasiparticle-Core Coupling model [11] we consider the coupling of 1-QP (one-quasiparticle) and 3-QP components and find a number of long-living resonance structures close to the particle threshold [2]. The approach described here also extends the QPC model into the continuum. Results of the theoretical calculations for the ^{15}C nucleus are compared with the experimental data. The experimentally observed spectral distribution (both the narrow resonances and the interference pattern) are reproduced in a qualitative way, showing an agreement with a BSEC interpretation [2].

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*This work was supported in part by the MCTS program of the European Community, contract No. HPMT-CT-200100223, and GSI Darmstadt.
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Shell Evolution and Nuclear Forces

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I will discuss how the nuclear shells evolve as N and/or Z changes, due to the spin-isospin components of the nucleon-nucleon interaction. Some examples will be taken from stable and exotic nuclei in comparison to experimental data. The calculated results are obtained not only from shell-model calculations but also from mean-field calculations with the tensor force.

Nuclear properties of neutron-rich Ge isotopes

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Besides the interest *per se* of studying the evolution of the shell structure in transitional nuclei with a complex structure, the study of germanium (Ge) isotopes around N=50 also supplies information about the correspondence between waiting points in the astrophysical r-process and localized peaks in the abundance of stable nuclei around $A \sim 80$.

As we try to study nuclei farther from stability, the determination of experimental observables becomes increasingly challenging with low intensity beams, short lived species and high background experiments. Our recently reported measurement for the B(E2; $0^+ \rightarrow 2_1^+$) values of the radioactive germanium isotopes $^{78,\,80}$Ge and the closed shell nucleus ^{82}Ge [1] constitute an excellent example of how the combination of novel techniques, powerful detection systems and good quality Radioactive Ion Beams (RIBs) can help to overcome these problems.

With only four protons outside the closed shell Z=28, Ge nuclei are currently the lightest isotopic chain that allows the study of B(E2)↑ values between the sub-shell closure at N=40 and the major shell N=50. While the availability of this experimental data constitutes a challenging test for theoretical models it would be highly desirable to measure other nuclear properties such as quadrupole moments, g-factors and masses. We will present the status of our program towards studying nuclear properties of germanium isotopes at the ORNL's Holifield Radioactive Ion Beam Facility.

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Measurement of Transfer Reactions on Fission Fragments in Inverse Kinematics

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The measurement of (d,p) reactions on fission fragments yields information on the development of single-particle structure in neutron-rich nuclei. The data provided by such experiments are a crucial test of nuclear structure models away from stability. High quality beams of fission fragments around the $N = 50$ and $N = 82$ shell closures are available at the Holifield Radioactive Ion Bean Facility (HRIBF) at Oak Ridge National Laboratory. These can be accelerated to sufficient energy to perform (d,p) reactions around the Coulomb barrier.

Experimentally, measuring (d,p) reactions on fission fragments is complicated by the effects of strongly inverse kinematics, and the relatively low intensities currently obtainable with rare isotope beams. Ejectile detection with high resolution in position and angle, a high dynamic range and with a large solid-angular coverage is required. The Oak Ridge Rutgers University Barrel Array (ORRUBA) is an array of silicon strip detectors that is under development to meet these requirements.

The resolution in excitation energy obtainable in such an experiment by measurement of reaction ejectiles alone is fundamentally limited by the effects of target thickness. In cases where the resolution that can be achieved by charged particle detection alone is insufficient to resolve populated states, de-excitation γ rays emitted in-flight by the final nucleus can be measured in coincidence. A test measurement has been performed with stable beams to determine the feasibility of measuring de-excitation γ rays in a (d,p) reaction on light ($N \approx 50$) fission fragments at ~ 4 MeV/A. The current status of the development of ORRUBA, and results from the feasibility measurement will be discussed, along with results of recent measurements on $N = 50$ and $Z = 50$ species.

*This work is supported in part by the U.S. Department of Energy under contract numbers DE-FC03-03NA00143 (Rutgers), DE-AC05-00OR22725 (ORNL), DE-FG02-96-ER40955 (TTU), the National Science Foundation, and the LDRD program of ORNL.

Competing structures in ^{186}Pb

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In very neutron deficient Pb isotopes, both experimental and theoretical evidence for shape coexisting configurations has been achieved [1,2]. This phenomenon becomes transparent particularly at the neutron midshell, where the competing structures intrude down to energies close to the spherical ground state. These structures can be associated with proton 2p-2h and 4p-4h configurations across the Z=82 shell gap. Together with the spherical ground state, they form a unique triplet of 0^+ states in ^{186}Pb, each of which can be associated with a different shape [3].

In our recent in-beam experiment we were able to collect $\gamma\gamma$-coincidence data for ^{186}Pb by employing the recoil-decay tagging method. The data allowed us to construct a level scheme which has more than 20 new states, including three collective non-yrast bands and several inter-band transitions [4]. Results have been compared with known bands in neighbouring nuclei and with theoretical calculations carried out within the framework of Interacting Boson Model. The interpretation of these new bands and future prospects to further investigate this nucleus in more detail will be discussed.

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The two-body random ensemble in nuclei

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We investigate properties of the two-body random ensemble (TBRE), and obtain semi-analytical results for the fluctuations of and the correlations between the spin-dependent spectral widths. Our results explain the preponderance of spin-0 ground states in the TBRE and the difficulties in fitting the effective nuclear interaction. For geometrical reasons, the monopole operators are dominant, while several two-body operators have very small norms and are therefore difficult to determine from a fit to spectral data.

Strongly Deformed Bands in ^{163}Tm: Particle Excitation *vs.* Wobbling?

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In a Gammasphere experiment, using the ^{130}Te(^{37}Cl,4n)^{163}Tm reaction at a bombarding energy of 170 MeV, we have observed two interacting strongly-deformed triaxial (TSD) bands in the Z=69 nucleus ^{163}Tm. This is the first observation of interacting TSD bands in an element other than Lu where wobbling bands have been identified in this mass region. The observed TSD bands in ^{163}Tm appear to indicate particle excitations, rather than wobbling. TAC calculations reproduce all experimental observables for these bands reasonably well. The calculations also provide a plausible explanation of why wobbling bands are observed in the Lu(Z=71) nuclei, but not in the Tm(Z=69) nuclei.

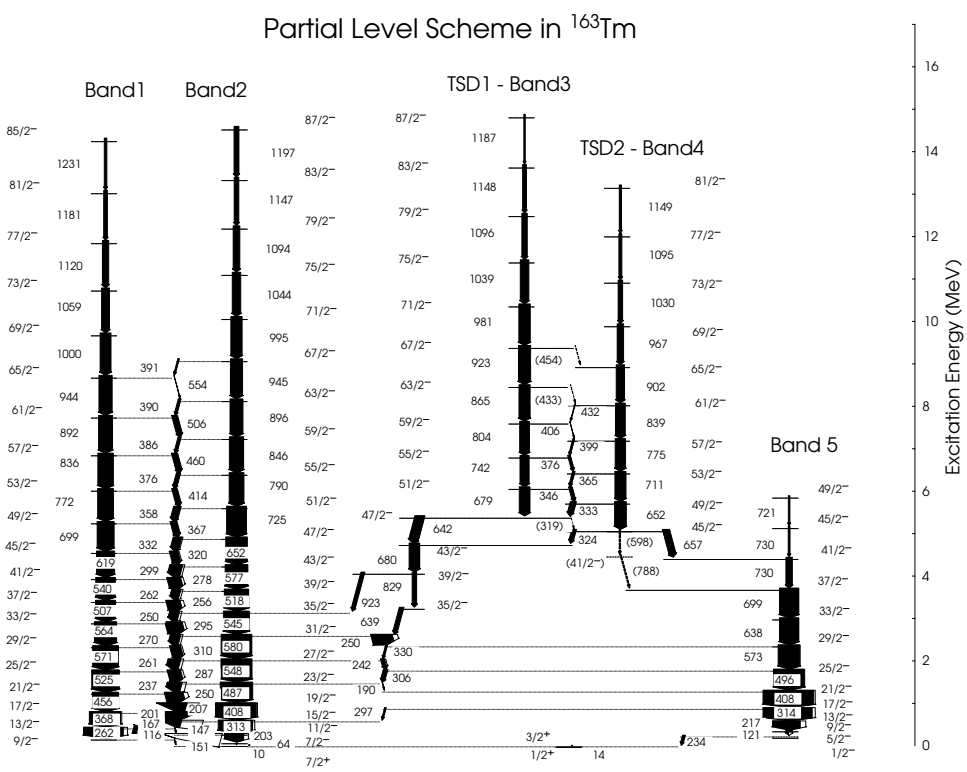

FIG. 1: Partial level scheme of ^{163}Tm showing the TSD bands and their feeding into the normal-deformed bands.

This work was supported in part by the U.S. National Science Foundation (grants no. PHY04-57120 and INT-0111536), the Department of Science and Technology, Government of India (grant no. DST-NSF/RPO-017/98), the U. S. Department of Energy Nuclear Physics Division, under contracts no. W-31-109-ENG-38 and DE-FG02-95ER40934, and the U.K. Science and Engineering Research Council.

Lifetime measurements in ^{110,112}Te: particle-hole induced collectivity *

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Lifetime measurements have been performed for smooth terminating bands in ^{110,112}Te using the Doppler-shift attenuation method. The Gammasphere spectrometer, in conjunction with the Microball charged-particle array, was used to investigate high-spin states in neutron-deficient ^{110,112}Te following a ^{58}Ni + ^{58}Ni fusion-evaporation reaction at 240 MeV. The Microball was used to select γ-ray coincidence events in ^{110}Te (α2p evaporation) and ^{112}Te (4p).

For a $\Delta I = 2$ intruder band in ^{112}Te, a centroid-shift analysis yielded a transition quadrupole moment of 4.0 ± 0.5 *eb*, in the spin range $18 - 32\hbar$. This translates to a quadrupole deformation $\varepsilon_2 = 0.26 \pm 0.03$, which is significantly larger than the ground-state deformation of tellurium isotopes ($\varepsilon_2 \approx 0.13$). For a $\Delta I = 1$ band in ^{110}Te, a Doppler-broadened lineshape analysis yielded information on both B(M1) and B(E2) strengths. A transition quadrupole moment of $Q_t \approx 2.8$ *eb* was found in the spin range $21 - 23\hbar$, which translates to a quadrupole deformation $\varepsilon_2 \approx 0.18$.

Cranked Nilsson-Strutinsky calculations are used to interpret the results and emphasise the importance of particle-hole (p-h) excitations across the proton shell gap at $Z = 50$ in inducing nuclear deformation. The $\Delta I = 1$ band in ^{110}Te is based on a 1p-1h excitation ($\pi g_{9/2}^{-1} h_{11/2}^{1}$), while the $\Delta I = 2$ band in ^{112}Te is based on a 2p-2h excitation ($\pi g_{9/2}^{-2} h_{11/2}^{2}$). The latter 2p-2h proton excitation is also involved in the high-spin superdeformed bands in the cerium isotopes ($Z = 58$).

*This work was supported in part by the DOE grant DE-F05-96ER-40983, the US National Science Foundation, the UK Engineering, the Physical Sciences Research Council, the US National Research Council under the Collaboration in Basic Science and Engineering Program, and by the Swedish Science Research Council.

New Superderformed Bands in ^{131,132}Ce *

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A high-statistics, high-fold experiment has been performed with the Gammasphere spectrometer, containing 100 HPGe detectors, in order to study the high-spin structure of ^{131,132}Ce. The ^{100}Mo(^{36}S,xn)$^{136-x}$Ce reaction was used at a bombarding energy of 165 MeV, with the beam provided by the ATLAS facility of the Argonne National Laboratory. With a trigger condition of at least seven Compton-suppressed HPGe's firing, 1.4×10^9 events were recorded in seven days of beam time. In the preliminary analysis of the data, a Radware 4-D hypercube was constructed which contained 10^{11} unfolded γ^4 coincidence events. Following a band search in the hypercube, two new superdeformed (SD) bands have been found in ^{131}Ce, making a total of four such bands in this nucleus. In the case of ^{132}Ce, at least two new SD bands have been found in addition to several shorter rotational sequences with lower moments of inertia.

Cranked Nilsson-Strutinsky calculations have been performed to assign configurations to some of the bands; the four SD bands in ^{131}Ce and the yrast (strongest) SD band in ^{132}Ce are fairly straightforward to interpret, while without neither definite spin nor parity values, the other, excited SD bands in ^{132}Ce cannot be assigned to specific structures. The main ingredients of the theoretical configurations are deformation-driving holes in the upsloping (with respect to ε_2) $\pi g_{9/2}$ orbital and particles in the downsloping $\nu i_{13/2}$ orbital. In the cerium isotopes, superdeformation occurs at $\varepsilon_2 \sim 0.35$, which is close to a prolate shape with a 3:2:2 axes ratio.

So far, it has not been possible to link any of the SD bands unambiguously into the low-spin level schemes of ^{131,132}Ce. This is particularly puzzling for the strong yrast SD band in ^{132}Ce, which carries 5% of the channel strength, and may indicate that the decay out of the SD minimum is fragmentary in the cerium isotopes. Several new, non-yrast structures have however been identified in ^{132}Ce through which the yrast SD band decays.

*This work was supported in part by the United Kingdom Engineering and Physical Sciences Research Council, the State of Florida, the National Science Foundation, the US Department of Energy under Contract No. AC03-76SF00098, and the Swedish Science Research Council.

Misinterpretation of near-degenerate bands as chiral partners

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The experimental information on the observed nearly degenerate bands in the *N=75* isotones, in particular ^{134}Pr and ^{136}Pm, which are often considered as the best candidates for chiral bands, is critically analyzed. The apparent near degeneracy of the two bands, the energy signature staggering, the particle alignments for the two bands, the crossing frequencies and branching ratios in the crossing region are discussed for the two nuclei [1]. Most properties of the bands in ^{134}Pr, in particular the recently measured branching ratios [2] and lifetimes [3], are in clear disagreement with the interpretation of the two bands as chiral bands. For *I = 14-18* in ^{134}Pr, where the energies are almost degenerate, we have analyzed the measured energy differences and out-of-band to in-band branching ratios of stretched quadrupole transitions assuming that the states are mixed, caused by a 2-state interaction with no off-diagonal E2 matrix elements. Thereby one can determine correlated values of the interaction strength, |V| and the ratio of intrinsic E2 transition moments of the two unperturbed bands. We have obtained a value of $Q_1/Q_2 = 2.0(4)$ for the ratio of the transition quadrupole moments of the two bands, and an interaction strength |V| of ~13 keV and ~17 keV for odd and even spins, respectively (see Fig. 1).

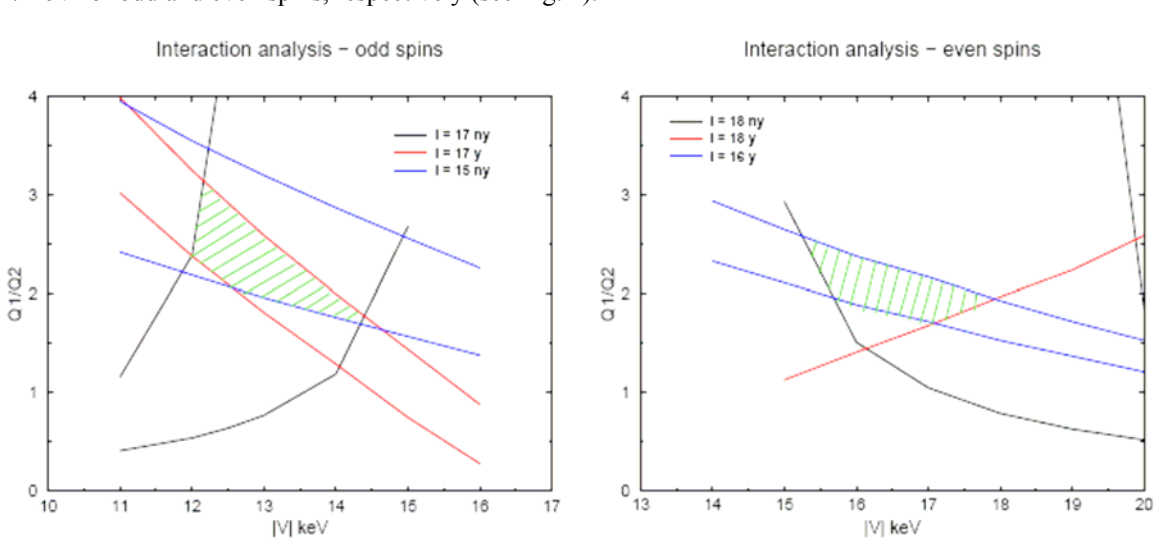

FIG. 1. Ratio of unperturbed E2 transition moments Q_1/Q_2 vs interaction strength |V| in the crossing region. Data for yrast and non-yrast initial states are denoted by y and ny, respectively. The shaded area shows the values allowed by the experimental data.

We note that the quantities used in our analysis are not based on the assumption of a rigid shape. Thus, there must be a significant difference in the shapes associated with the two bands and it is therefore questionable if and to what extent a reminiscence of the chiral geometry is present in the ^{134}Pr data. Though chiral twin bands are theoretically expected to appear under specific circumstances, the present type of critical analysis should be applied also to other cases of many available publications in which the chiral interpretation is claimed. The insufficiency of the near-degeneracy criterion to trace nuclear chirality is clearly demonstrated.

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A six-quasiparticle isomer in ^{140}Nd

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The nuclei around the N = 82 shell closure are a fertile field of spectroscopic investigations both at low and high spins: At low spins the presence of isomers based on simple particle-hole confgurations helps to establish the active quasiparticle confiurations in a specifc nucleus and test the suitability of various nuclear potentials [1], whereas at high spins the combined contribution of neutron holes and proton particles drive the nuclear shape towards a stable triaxial shape with $\gamma \approx +30°$ [2, 3]. At very high spins superdeformation is observed [4]. To give a realistic interpretation of the observed bands at high spins one needs to know the linking transitions of the bands to low-lying structures and their characteristics, and of course, the spins and parities of the low-lying states. In all high-spin experiments, the detailed study of the low-spin structure of the nuclei is a prerequisite for the understanding of the high-spin structures, whose excitation energy, spin and parity depend on the low-spin states.

The task of determining the characteristics of the low-lying states in the nearly spherical nuclei close to the shell closures is more difficult than in the well deformed nuclei due to the presence of isomeric states, which often stops and fragments the decay flux. The analysis of the data coming from large γ-arrays like GASP, Euroball and Gammasphere is made diffcult by the presence of low-energy γ–rays and isomeric states, which often are not measured in the performed experiments. Such a situation is encountered in the weakly-deformed Nd nuclei with neutron numbers close to the N=82 shell closure, with irregular sequences of transitions and possible yrast traps. In fact, isomeric states were observed in ^{138}Nd ($I^{\pi} = 10^{+}$, $T_{1/2}$= 410 ns) [5] and ^{140}Nd ($I^{\pi} = 10^{+}$, $T_{1/2}$= 32 ns and $I^{\pi} = 7^{-}$, $T_{1/2}$= 600 μs) [6]. In the odd-even Nd nuclei the information about the isomeric states is much more limited.

The study of the isomeric decay in these nuclei is very important for the understanding of the quasiparticle excitations into the orbitals closest to the Fermi surface, while the search for high-spin isomers in needed to test the theoretical model predictions of multi-quasiparticle configurations, as for example the recent CNS predictions of the favored high-spin configurations in ^{140}Nd [3, 7].

In this work we report results on isomeric states in ^{140}Nd obtained from prompt and delayed $\gamma\gamma$ coincidences measured in a pulsed beam experiment. We have identified a new high-spin isomer at $I^{\pi} = 20^{+}$ in ^{140}Nd. Its properties are interpreted using configuration dependent cranked Nilsson-Strutinsky (CNS) calculations as the maximum-spin state which can be formed from the six holes in a ^{146}Gd core. It is thus built from four protons in the ($d_{5/2}$,$g_{7/2}$) orbitals and two neutrons in the $h_{11/2}$ orbitals. The lifetime of the isomer is estimated to be larger than the acquisition time gate of ~ 400 ns.

We show how the general evolution with spin of the ^{140}Nd level scheme is well understood in the CNS formalism, starting from the shell-model states for $I \leq 20$, with a transition to well-developed triaxial bands in the I = 20 - 40 spin range and finally superdeformed bands at the highest spin values. The general features of the shell-model states fed by the 20^{+} isomer are well understood as built from the subshells below Z = 64 and = 82. We believe that these states would be an ideal laboratory for full shell model alculations, to learn more about the details and also to get a better understanding of the fftive interactions appropriate in this region of nuclei. For spin values just above I = 20, we predict close-to-spherical yrast states with for example an especially favoured 27^{-} state built as the maximum spin state with one proton excited across the Z = 64 gap. These states have not been observed in experiment and it would be interesting to perform some educated experiment to learn more about the possible evolution of these close-to-spherical states beyond I = 20.

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Diffusion and Transport of ^{120}Xe: Towards Rn Electric Dipole Moment Measurements at ISAC*

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The existence of permanent electric dipole moments (EDMs) would reveal time reversal violation and that the Standard Model is incomplete. An atomic EDM search is beginning at TRIUMF involving odd-A Rn isotopes predicted to have enhanced EDMs from collective octupole deformations. In anticipation of Rn beams in 2006-2007, techniques to transport radioactive gas from a collection foil to a measurement cell were developed using ^{120}Xe.

The ^{120}Xe half life was measured to be 46.0 ± 0.6 min. Diffusion coefficients were calculated for Ta, Pt, and Zr foils. Zr had the highest diffusion rate, but Ta may be more reliable due to Zr reactivity. ^{120}Xe gas was transferred from the target chamber to the cell using cryopumping and gas-pushing techniques. The pushing efficiency was determined to be 44% with an upper limit on the overall transfer efficiency of 26% depending on the foil release and cryopumping efficiencies under different conditions.

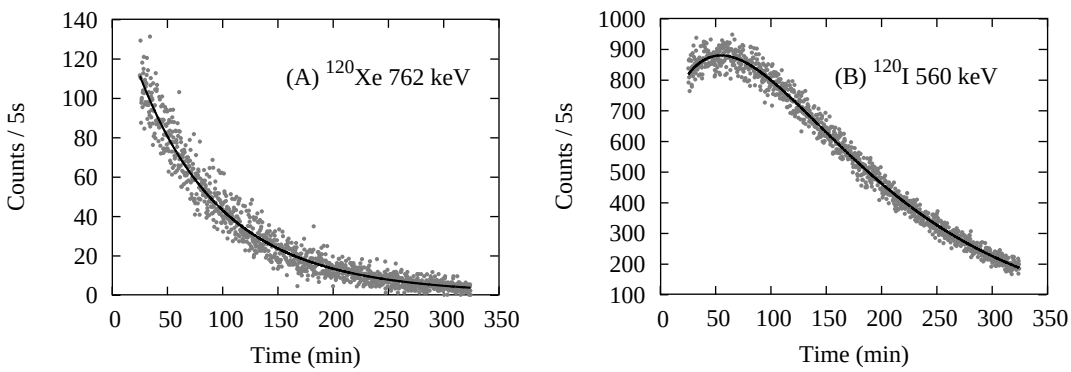

FIG. 1: Fits of activity decay data generated from (A) ^{120}Xe 762 keV and (B) ^{120}I 560 keV γ-ray peaks. The points represent the rate-corrected counts as a function of time in 5 s bins. The solid line represents the region over which the data were fit. For display purposes, only every third data point is shown. The best fit half lives are 46.0 ± 0.6 min and 82.1 ± 0.6 min for ^{120}Xe and ^{120}I respectively.

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*This work was partially supported by the Natural Sciences and Engineering Research Council of Canada and the United States National Science Foundation. TRIUMF receives federal funding through a contribution from the National Research Council of Canada.
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Structure of off-stability line Rhenium nuclei

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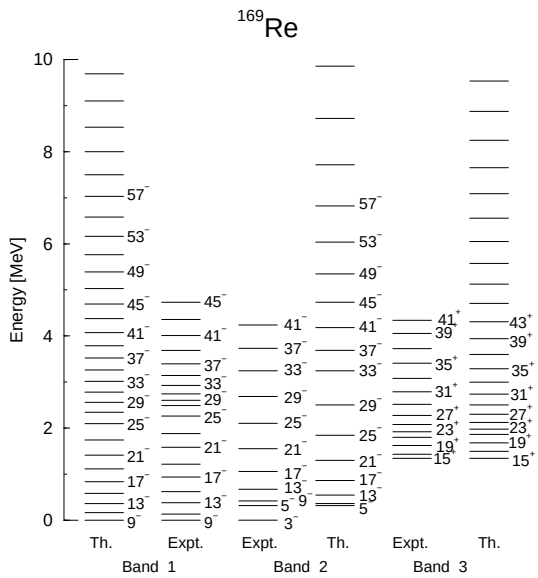
With the coming of new generation of accelerators, study of nuclei away from the valley of stability is possible. At the same time nuclei can be populated at very high spins and energies and band structures can be studied with large gamma arrays, such as the GAMMASPHERE. Multi-quasi-particle (MQP) bands have been seen experimentally in many cases [1]. In this context, we have done microscopic study of the structure of some of off-stability-line nuclei ^{165,167,169}Re using deformed Hartree-Fock and Angular momentum projection (PHF) model [2, 3].



Very little is experimentally known about the spectra of these neutron deficient Re nuclei such as ^{165}Re. In fact, experimentally only two rotational states have been known for ^{165}Re isotope so far. In this work we have tried to explain all the known one and three quasi particle (QP) bands for ^{167,169}Re. At the same time we predict some more bands for these as well as ^{165}Re nucleus. Comparison of theoretical and experimental spectrum of ground state band (K=9/2$^-$) of ^{169}Re and band crossing due to intruder orbits ($i_{13/2}$) are shown in the Fig. (2J are indicated near the energy levels). Signature effect of one quasiparticle K=1/2$^-$ band is explained. B(M1), B(E2) values are predicted upto very high spin states for all bands; at the same time B(M1)/B(E2) ratios are compared for experimentally known cases. Five and seven quasiparticle bands are also studied upto high spins. Thus these nuclei are likely to have very interesting spectroscopic properties and can be studied with large Gamma arrays.

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Alpha decay of ^{257}Rf*

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^{257}Rf is known to have a complex alpha decay spectrum [1]. The weakest lines lack sufficient intensity to allow the technique of decay-decay correlations – the standard approach for unambiguous identification of the mother nucleus if the decay energies to the daughter are known – to be used. In this work, we studied ^{257}Rf using the Fragment Mass Analyzer (FMA) at Argonne National Laboratory to provide the mass/charge (A/Q) ratio as an additional parameter for the interpretation of the decay spectrum and the origin of weak alpha lines. Fig. 1 compares the A/Q spectrum obtained in a setup reaction producing Th nuclei with the spectrum from ^{257}Rf events.

The Rf nuclei were produced by impinging a ^{50}Ti beam, accelerated by the Argonne Tandem LINAC Accelerator System (ATLAS) with a middle-of-target energy of 233 MeV and an average intensity of 115 pnA, on a ^{208}Pb target mounted on a rotating wheel to prevent melting as a result of beam energy loss in the target. The recoil position at the FMA focal plane, which allow the measurement of the A/Q ratio, was obtained with a Parallel Grid Avalanche Counter (PGAC) and subsequently implanted into a Double-sided Silicon Strip Detector (DSSD) with 1600 pixels, each with an area of 1 mm^2. Scattered and non-reacted beam was suppressed by the FMA and recoils were identified by their energy deposition in the DSSD as well as by their time-of-flight between the PGAC and the DSSD. Position and time of implant and subsequent alpha decay were measured and correlated. Amplifiers with different gains allowed summed conversion-electron energy to also be recorded simultaneously with the alpha data.

Decay spectroscopy of heavy nuclei is of great interest for an understanding of the structure of heavy nuclei in the absence of a liquid-drop fission barrier and gives insight into the evolution of single-particle energies. These data are important for testing model calculations and their predictions concerning the next proton shell closures in super heavy nuclei.

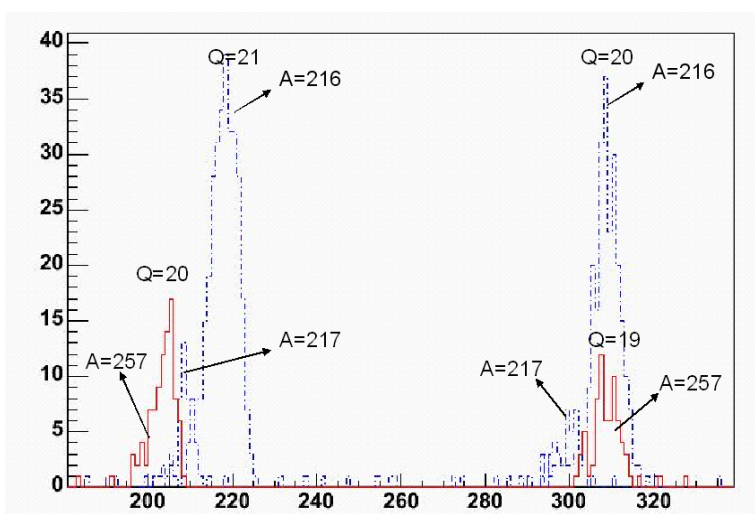

Figure 1. PGAC x position (in channels) indicates the recoil mass to charge ratio. Solid lines: charge states q=19 and 20. Dashed lines: data from a setup reaction ^{50}Ti + ^{170}Er, two masses (A = 216, 217) are marked. (Preliminary!)

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* This work was supported by the U.S.Department of Energy, Office of Nuclear Physics, under contract No. W-31-109-ENG-38 (ANL) and DE-FG02-91ER-40609 (Yale)
+ ABG would also like to acknowledge financial support from Nexia Solutions Limited, s subsidiary of BNFL.

Favoured high-spin states in $N \approx Z$ nuclei close to ^{100}Sn.

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The recently observed $I = 21$ isomer in the $N = Z$ nucleus ^{94}Ag [1] is naturally understood as as the fully aligned configuration of the six $g_{9/2}$ holes relative to ^{100}Sn. This is also how it is described in shell model calculations although some configuration mixing appears important [2]. Even so, it has been argued [3] from two-proton decay data that this state is strongly deformed with the longer axis at least twice as long as the shorter axis. In the cranked Nilsson-Strutinsky formalism [4], this state is calculated at a small prolate deformation with an axis ratio smaller than 1.1:1 ($\varepsilon_2 \approx 0.06, \gamma = -120°$, see Fig. 1). It is also interesting to consider the total energy of this state which is very low, i.e. it has a shell energy of approximately -6 MeV [5]. This shell energy is calculated relative to a rotating liquid drop energy based on the Lublin-Strasbourg drop (LSD) model with moments of inertia calculated from a diffuse matter distribution. Indeed this 21^+ state and related 20^+ and $37/2^+$ states in the neighbour nuclei ^{94}Pd and ^{95}Ag appear to have 'larger negative shell energies' than any other high-spin states in the nuclear chart (they might be referred to as magic high spin states). The total energies are reproduced by the calculations with the expected accuracy of 1-2 MeV. For deformations with an axis ratio larger than 2:1 on the other hand, the calculated energy for the $I^\pi = 21^+$ in ^{94}Ag is much higher ($\sim$ 15 MeV or more) than experiment (see Fig. 1), which indicates that effects other than deformation must be invoked to explain the two-proton decay data.

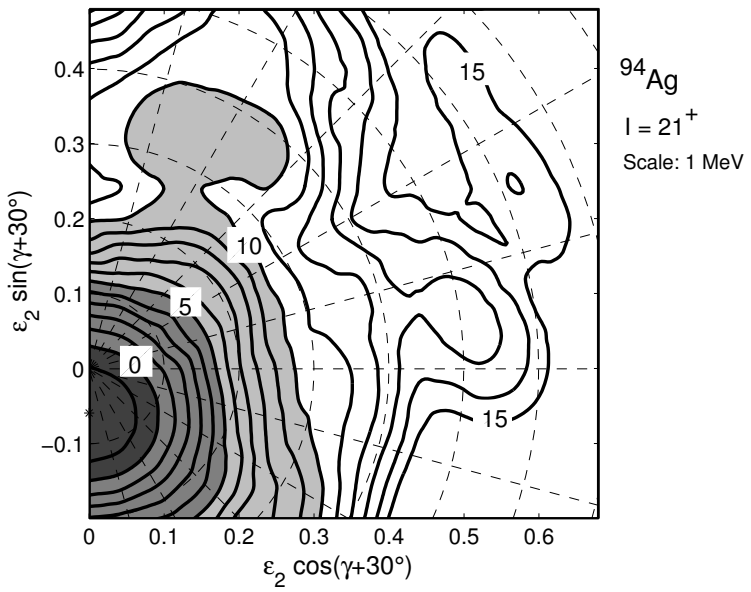

FIG. 1: Calculated potential energy surface for ^{94}Ag at $I^\pi = 21^+$. The contour line separation is 1 MeV. The minimum is calculated at a small prolate deformation with rotation around the symmetry axis, $\varepsilon_2 \approx 0.06, \gamma = -120°$. The energy at the contour line marked by zero is in approximate agreement with the observed binding energy but the discrepancy increases rapidly with increasing deformation reaching approximately 15 MeV at 2:1 deformation ($\varepsilon_2 \approx 0.6$).

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Valleys of favoured deformation in the shell energy landscape

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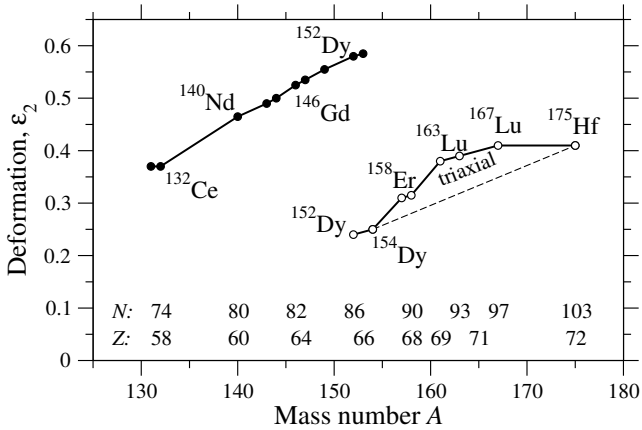
The variation of the shell energy as a function of particle number and deformation is a decisive factor concerning which nuclear shapes are realized in nuclei. Long ago it was pointed out that if the shell energy is plotted as a function of particle number and quadrupole deformation, valleys of favoured energy will intersect this landscape in such a way that increasing particle number leads to increasing deformation [1]. It now seems well established, see e.g. [2] and references therein, that the evolution of deformations for the superdeformed bands in the $A = 140 \quad 150$ region can be understood from such a valley and that this valley can be followed down to ^{132}Ce, as illustrated in the figure, and possibly also down to the smooth terminating bands in the $A = 110$ region.



Here we suggest that a similar valley can be defined starting from the collective bands in ^{152,154}Dy, passing through the newly discovered collective bands in ^{157,158}Er and ^{161}Tm (preliminary assignment), continuing over the TSD bands in $^{163-167}$Lu and reaching the strongly deformed Hf isotopes.

In a Nilsson diagram, these valleys are located between regions of upsloping orbitals, so that essentially down-sloping deformation driving orbitals are being filled with increasing particle number. A common feature of the configurations in the ^{132}Ce - ^{152}Dy valley is two proton holes in the upsloping [404 9/2] orbital emerging from the $g_{9/2}$ shell, located below the spherical $Z = 50$ gap, and in a similar way, two neutron holes in the [505 11/2] orbital emerging from the $h_{11/2}$ shell below the spherical $N = 82$ gap is a common feature of the ^{152}Dy - ^{175}Hf valley. With such holes also in the ^{175}Hf high spin band, the calculated quadrupole moment comes close to the experimental value [3]. A new feature in the ^{152}Dy - ^{175}Hf valley is the large triaxial deformation, which is well established [4] in the Lu isotopes and clearly important also in several of the other nuclei. The configurations with large triaxiality are characterized by two holes in an upsloping $N = 4$, $n_z = 0$ orbital, which will drive them away from $\gamma = 0$, according to the mechanism discussed in Ref. [5].

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Test of nuclear chirality in ^{104}Rh by study of the electromagnetic transitions properties *

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Chirality is a recently recognized form of spontaneous symmetry breaking in nuclear rotations [1,2]. This phenomenon is related to time reversal and can occur if the valence protons, valence neutrons and the core couple their angular momenta in a mutually perpendicular way. Such geometry can be realized in odd-odd nuclei at intermediate spins when the Fermi level is located in the lower high-j subshell for protons (neutrons) and in the upper subshell for neutrons (protons) and the core is sufficiently triaxially polarized. The spontaneous breaking of chirality in the body-fixed system results in $\Delta I = 1$ degenerate doublet bands in the laboratory reference system. Since the first interpretation of a side partner of the yrast positive parity band in ^{134}Pr as it's chiral partner, extensive experimental and theoretical efforts have been devoted to the mass $A \sim 130$ and $A \sim 100$ regions.

The experimental features of chiral bands have been investigated in several works and it was concluded that these band should exhibit the following features [3]:

1. Existence of a doublet of $\Delta I = 1$ bands of the same parity which are approximately degenerate for a range of spins I
2. The function $S(I) = E(I) - [E(I+1) - E(I-1)]/2$ is independent of spin I in chiral region
3. The chiral geometry imposes strong restrictions on the wave functions leading to characteristic behavior of $M1$ and $E2$ strength of chiral partners: $B(E2)$ values for the in-band $E2$ cross-over transitions are nearly constant as a function of spin while $B(M1)$ values of in-band and inter-band $M1$ transitions exhibit pronounced staggering between odd and even spin.

The chiral interpretation should be valid only if all the fingerprints are fulfilled. However, due to the lack of experimental information on transition strengths in the chiral bands the third fingerprint has been only partially tested. It was a disturbing surprise when the first measurements of the lifetimes in the chiral band in ^{134}Pr [4] have shown complete disagreement with the expectations of chiral geometry. This has triggered a discussion as the opinions range from complete repudiation of chirality to arguments that ^{134}Pr is not an ideal chiral rotor. Therefore the very recent measurement of the lifetimes in the chiral band in ^{104}Rh is considered as a decisive experiment which is expected to provide an answer whether the nuclear chirality exists in $A \sim 100$ region. This experiment will be presented in details and some preliminary results will be discussed.

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Reaching new frontiers with deep inelastic reactions at GANIL

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The quest to produce and study nuclei with extreme values of isospin has been one of the foremost goals using radioactive ion beams. The use of high intensity stable beams is an alternative way of achieving the same goal. In this talk we will discuss in particular the use of deep inelastic transfer reactions at energies near the Coulomb barrier to populate neutron rich nuclei. Results of using ^{238}U beam on a thin ^{48}Ca target, at GANIL, to populate very neutron rich isotopes around Z=20 will be presented. The uniqueness of the experimental setup which used the direct detection of the target like nuclei in the VAMOS spectrometer and gamma rays in the EXOGAM array will be discussed. These results will be used to address a problem of current interest namely the existence of new neutron shell closures in this region

The "octupole transitional" nuclei ^{219,220}Th*

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In the actinide region, two distinct modes for octupole collectivity have been established so far. In nuclei around ^{236}U, sequences built on octupole surface vibrations are observed [1,2]. In nuclei around ^{224}Th on the other hand, the rotational mode is observed, implying a nuclear shape with stable octupole and quadrupole deformations [1,2]. Departing from the center of stable deformation around ^{224}Th (N=134) towards N=126, a transitional region is crossed. Here only the octupole deformation may remain competitive with the trend towards a spherical shape, giving rise to a new type of high-spin behavior.

The data presented are from a recent experiment to study the ^{219,220}Th nuclei via the ^{198}Pt(^{26}Mg,xn)^{219,220}Th reactions at 128 MeV. The evaporation-residue nuclei from this very fissile system have been selected with the HERCULES detector and residue gated γ rays have been measured with GAMMASPHERE. A new detailed level scheme for ^{220}Th and, for the first time, a level scheme for ^{219}Th has been established.

The ^{220}Th nucleus exhibits the simplex feature (alternating-parity levels) up to the highest spins observed (23 $\hbar$) but it behaves less rotational-like than its heavier isotopes and rather resembles the vibrational-like isotone ^{218}Ra [3]. Unlike in the latter case, two negative-parity odd-spin sequences are observed and distinct staggerings between even and odd spins are established not only for the transition energies but also for the *E1/E2* branching ratios.

The ^{219}Th nucleus exhibits also a structure of alternating-parity levels. However, this structure is rather short (observed over a spin range of 6 $\hbar$), is off-yrast, and coexists with other structures of single-particle-like behavior.

For ^{220}Th, a discussion will be presented based on the picture of tidal waves traveling on a reflection asymmetric nuclear surface. The shape in the rotating frame is a combination of quadrupole and octupole deformations, both increasing with spin. This ensures that the level spacing of the "tidal" yrast band is vibrational-like, as observed in experiment, and allows for the staggering effects reported. In contrast to the "standard" surface vibrations, the tidal waves are non-adiabatic. The presence of a second negative-parity odd-spin sequence is consistent with a shape with only one reflection plane ("non-axial").

The tidal-wave picture has been also applied to a vibrational-like band structure in ^{182}Os, built on a high-K isomer and associated with a triaxial reflection symmetric shape [4]. Tidal waves appear to be a common high-spin phenomenon in the transitional regions between different symmetries (axial and triaxial, spherical and reflection asymmetrically deformed, etc.) where the symmetries are weakly broken.

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*This work was supported by the U.S. Department of Energy under contracts DE-FG02-88ER-40406 and W-31-109-ENG-38.

The Return of Significant Collectivity Beyond Band Termination in N~90 Erbium Nuclei at Ultra-High Spin

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The response of the atomic nucleus to increasing angular momentum values or rotational stress continues to be a fundamental and fascinating field of study. In the light rare-earth region some recent central themes have included, (i) the study of superdeformed (SD) nuclei around ^{152}Dy, (ii) the study of stable triaxial strongly deformed (TSD) nuclei around ^{163}Lu, and (iii) the study of finite-particle effects manifest as band termination in N=88-90 nuclei. The nuclei ^{157,158}Er have featured heavily in the storied history of the latter [1]. Now we can add a new chapter in the evolution with spin of these nuclei with the discovery of high moment of inertia rotational sequences (see Fig. 1) indicating the re-emergence of significant collectivity in both ^{157,158}Er above the energetically favored "valence-space" terminating states near I = 45-50. Cranked Nilsson-Strutinsky calculations indicate that the configurations of these bands involve high-j orbitals normally associated with super or strongly deformed shapes and that the bands observed cover the spin range of I = 25 to 65. The present sequences therefore may be viewed as having physics connections to both the traditional SD and TSD regions.

In the present study of ^{157,158}Er a 215-MeV ^{48}Ca beam, provided by the 88 Inch Cyclotron accelerator at the Lawrence Berkeley National Laboratory, was used to bombard two stacked thin self-supporting foils of ^{114}Cd of total thickness 1.1 mg/cm^2. A total of 1.2x10^9 events were collected using the magnificent Gammasphere spectrometer when at least seven of the 102 Compton-suppressed Ge detectors fired in prompt coincidence.

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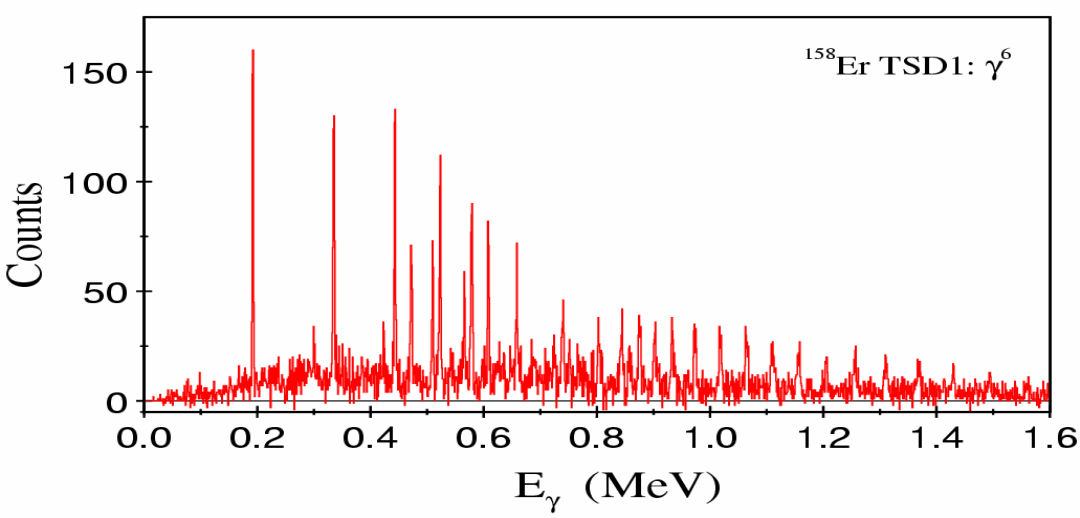

Fig. 1. Coincident gamma-ray spectra of a new high spin sequence observed in ^{158}Er.

Ground State Proton Radioactivity from ^{121}Pr*

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Proton radioactivity has proved to be an ideal tool for studying nuclear structure far from stability [1]. The phenomenon of proton decay has been studied extensively since it was first discovered. The first example of proton decay from an isomeric state was discovered in 1970 [2] and in the same year inconclusive evidence of proton decay from the ground state of ^{121}Pr was observed [3]. The first conclusive evidence of ground state proton radioactivity was not found until 1981 [4]. Since late 1990s proton emitters were found for all odd-Z elements Z=50 and Z=84 except Pr and Pm. The observed proton emitters span a variety of shapes from spherical to highly deformed.

In a recent experiment performed at Argonne National Laboratory evidence of ground state proton radioactivity from ^{121}Pr was observed. This is the first time that the historic claim of ground state proton radioactivity from ^{121}Pr has been tested. ^{121}Pr was produced via the p6n fusion-evaporation channel using a 240-MeV ^{36}Ar beam to bombard a ^{92}Mo target. The recoiling ions were implanted into an 80 X 80 double sided strip detector where subsequent decays were observed.

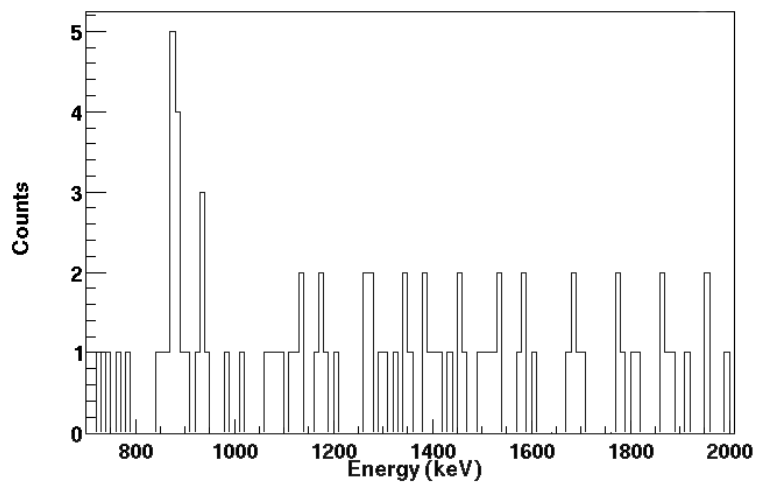

FIG. 1. Decays in the DSSD within 30 ms of implantation of an A = 121 residue into a DSSD quasipixel, showing the ground-state proton decay peak of ^{121}Pr.

Evidence of proton radioactivity from ^{121}Pr will be presented (see Fig. 1) and confronted with earlier work [5] which may have been the first observation of ground state proton radioactivity. The ^{121}Pr decay properties will be also compared with theoretical predictions [6] and properties of other proton emitters.

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*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W-31-109-ENG-38.

Studying the Transition to the Island of Inversion*

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The existence of deformed (2p2h) intruder ground states in A~30 N~20 nuclei ("island of inversion" [1]) provides (a) one of the most dramatic and clear manifestations of the modification of conventional shell structure in neutron-rich nuclei, and (b) a measure of the valence nucleon interactions away from beta stability. The inversion can be associated with a reduction in the N=20 shell gap from ~6 MeV in ^{40}Ca to the ~3 MeV in ^{32}Mg, due to the strong T=0 monopole interaction between valence $d_{3/2}$ neutrons and $d_{5/2}$ protons [2]. While the evidence for intruder ground states is well established, the questions remain; where does the transition from normal to deformed intruder ground states occur, and what is the nature of the observed collectivity? Information on excited states is needed to understand both these questions.

An experiment to study N~20 neutron-rich nuclei was carried out at the NSCL. A 140 MeV/A ^{48}Ca primary beam produced a "cocktail" of secondary beams (^{29}Na/^{30}Mg/^{32}Al and ^{32}Mg/^{33}Al/^{35}Si), which underwent secondary knockout/fragmentation reactions to produce n-rich isotopes of N, F, Ne, and Na; gamma-ray decays were detected by the segmented germanium array, SeGA. The experiment provided a rich data set on nuclei in the vicinity and throughout the island of inversion providing the first data on excited states in several nuclei and greatly extending the known states for many more. Having multiple secondary beams led to the same nucleus being produced in different reactions, and it was possible to compare the population of excited states as a function of the reaction. In several cases (^{28}Ne, ^{30}Na) the spectra showed a clear reaction dependence; in addition, the high quality of the data enabled a gamma-gamma coincidence analysis, which proved to be essential to establish the correct level scheme in, for example, ^{28}Ne.

In this talk I will compare the measured excitation spectra to shell-model predictions using USD and SDPF interactions, and discuss the role of the cross-shell (sd-pf) intruder configurations through the transition to the island of inversion. Furthermore, the experimental cross sections for two-nucleon knockout reactions (from both "normal" and "intruder" beams) are compared to recent calculations to extract information on two-nucleon correlations. I will focus on the neon chain ^{28,29,30}Ne, which spans the transition to the island of inversion. The ground state configuration of ^{28}Ne is calculated [3] to be ~50% 0p0h and ~50% 2p2h, and a low-lying 0_2^+ is also predicted with a 50-50 mixture of 0p0h-2p2h. Our data on ^{28}Ne rule out the recently reported [4] candidate for the excited 0^+ state, and therefore the predicted 0_2^+ level remains unobserved in ^{28}Ne. Identifying excited 0^+ states is an important test of the shell-model interaction (e.g. SDPF-M) and I will discuss the impact of our result on shell-model calculations and the structure of ^{28}Ne (e.g. intruder mixing). In ^{30}Ne, a low-energy $2_1^+ \rightarrow 0_1^+$ transition is confirmed and a new transition, tentatively assigned to be the $4_1^+ \rightarrow 2_1^+$, is identified. The observed level energies are consistent with a highly deformed ^{30}Ne 2p2h ground state and may even suggest a larger moment of inertia than calculated [3].

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*This work was supported by the U.S. Department of Energy, Lawrence Berkeley National Laboratory, under contract No. DE-AC02-05CH11231, and by the National Science Foundation, under Grants No. PHY-110253 and PHY-0244453

Density Matrix Renormalization Group approach for Many-Body Open Quantum Systems

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We have applied the DMRG method in the context of the Gamow Shell Model (GSM). In this model, which describes the configuration mixing in open quantum many-body system, the completness relation is resolved in the Berggren ensemble consisting of bound states, resonant states (Gamow states) and complex energy continuum states. The eigenvalue problem is inherently non-hermitian and given by complex-symmetric matrix with complex eigenvalues. Inclusion of resonances and associated continuum states leads to an explosive growth of the size of the multiconfigurational space and the standard diagonalization methods cannot be applied. To deal with this difficulty, we have solved the GSM problem using the DMRG technique in the J-scheme. This choice ensures the total angular momentum conservation at each step in the iterative procedure. The GSM+DMRG model has then been applied for the description of weakly bound or unbound states (multi-nucleon resonance) in He isotopes.

Microscopic theory of the two-proton radioactivity

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Nuclear decays with three fragments in the final state are very exotic processes.
The two-proton radioactivity is an example of such decay which can occur for even-Z nuclei in the vicinity of the proton drip-line. In the case where pairing correlations are strong enough to prevent one proton decay, the two protons are emitted simultaneously by a *direct* mechanism from the initial nucleus. In the other situation where one proton emission channel is opened, two-proton decay could also occur by an *indirect (sequential)* mechanism via states of the intermediate nucleus.
In order to have a microscopic description of the two-proton radioactivity, we have extended the formalism of the Shell Model Embedded in the Continuum (SMEC) for the two-particle continuum.
During this talk, I will first present the theoretical limiting cases corresponding to the different mechanisms of two-proton decays in the SMEC formalism, and I will discuss results we have obtained for the two-proton radioactivity in $^{18}\mathrm{Ne}$, $^{45}\mathrm{Fe}$, $^{48}\mathrm{Ni}$ and $^{54}\mathrm{Zn}$ nuclei.

Hypernuclei beyond the normal drip lines

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Current nuclear physics is focused on exploring fundamental interaction between nucleon (N) and hyperon (Y) and basic properties of the hadronic many body system. The strong attractive N-Y and Y-Y interactions are useful to explain the phase transition in interior of the compact stars like strange quark stars, hybrid stars and hyper-compact hyperon stars. Strange hadronic matter [1] is composed of hypernuclei, the first kind of flavored nuclei, with hyperon(s) inside normal nuclei. By studying their binding properties one hopes to learn more about the weak force, one of nature's four fundamental forces.

Since the mean field gets modified according to the type (i.e., mass, charge and strangeness) of hyperon inside the normal nuclear core, the values of nucleon binding are different for different hypernuclei. Some hyperons are strongly bound inside a nucleus and it is important to know the limits of binding of such hyperons. We have addressed this many body problem using a recently developed mass formula, called BWMH [2], which is a generalized version of the modified- Bethe-Weizsäcker mass formula (BWM) [3]. BWMH is applicable to both strange and non-strange nuclei. Its predictions on hyperon separation energies were found to be in close agreement with the available experimental data and with relativistic (RMF) [4] and quark- mean field (QMF) [5] calculations as well [2]. Using this mass formula the neutron- and proton-separation energies of all normal nuclei and hypernuclei (containing Λ^0, $\Lambda^0\Lambda^0$, Ξ^-, and Θ^+ hyperons) have been calculated to predict and compare the driplines of both the normal [6,7] and hypernuclei.

Addition of a single charged-hyperon in normal nucleus is found to affect the entire proton drip line more prominently than that by neutral hyperon. The neutral hyperonic effect on proton dripline is significant for lighter nuclei than for heavier ones. Both charged as well as neutral hyperons are found to affect almost the entire neutron dripline. The separation distance between the hyperonic drip lines and the stability line is found to vary depending on the hyperon charge and strangeness. Some hyperon(s) can form neutron-rich or, proton-rich (neutron-deficient) bound nuclei beyond the normal neutron and proton drip lines. Existence of such exotic bound nuclei could have significant effect on formation, evolution or phase transition of strange stellar objects. It might be possible to produce some of these light metastable exotic nuclei in the laboratory.

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Enhancing Gammasphere with some Auxilliary Detectors and vice versa

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The new physics that were done and/or can be done with Gammasphere augmented by auxiliary detectors will be reviewed. Only experiments that could not be done without The Microball, The Neutron Shell, The Si Wall and Box, and HERCULES will be highlighted. Future advances in measurements with these and some new auxiliary devices will be discussed in the conjunction with Gammashere, Gretina and possibly GRETA.

First excited state of doubly-magic ^{24}O*

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Magic nuclei have played a pivotal role in understanding nuclear structure in the past. For example, the magicity of nucleon numbers such as 28, 50, and 82 made us realize the importance of spin-orbit coupling in atomic nuclei. Magic numbers appear when gaps between the highest completely filled and the lowest empty single-particle orbitals become large such that two-body interactions such as pairing or quadrupole-quadrupole forces are comparably too weak to induce significant correlations or collectivity. For heavy oxygen isotopes, neutron effective single-particle energies have been predicted to form a significant gap between the occupied $0d_{5/2}$ and $1s_{1/2}$ orbitals on the one hand and the empty $0d_{3/2}$ orbital on the other hand, the latter one being a resonance in ^{17}O [1]. However, this result changes dramatically with increasing occupation of the proton $0d_{5/2}$ orbital which helps explain the existence of fluorine isotopes with $N > 16$ [2].

Phenomenologically, magic nuclei can be identified by their increased binding energy, by their high-lying first excited state, and by a rather small transition matrix elements for exciting the first excited state from the ground state. For heavy oxygen isotopes, neutron separation energy systematics indicate the formation of the new magic number $N = 16$ [3], while the search for excited states in ^{23,24}O using γ spectroscopy has yielded no results [4]. In order to unambiguously identify ^{24}O as a doubly magic nucleus, we therefore have resorted to neutron decay spectroscopy. Experimentally, the two-proton-knockout reaction of a 86 MeV/u ^{26}Ne beam on a Be target at the fast-fragmentation radioactive beam facility of the National Superconductive Cyclotron Laboratory was investigated and ∼500 neutron-^{23}O coincidences were recorded using the Sweeper/MoNA setup. From these events, a decay-energy spectrum was reconstructed which combined with the neutron separation energy of ^{24}O yields an excitation energy of the first excited state of ^{24}O in the order of 3.6 MeV, in agreement with new USD shell-model calculations [5].

Moreover, we found tantalizing hints in the decay-energy spectrum from neutron-^{22}O coincidences for a first excited state in ^{23}O at $\sim$ 75 keV above the 2.7 MeV neutron separation energy of ^{23}O. The excitation spectrum of ^{23}O is of importance for the evolution of neutron effective single-particle energies. Modern theory [5] predicts a sizable gap between the occupied $0d_{5/3}$ and the empty $1s_{1/2}$ orbitals in the neighboring ^{22}O nucleus, making it another candidate for a doubly magic nucleus. The decay-energy spectra of n+^{22,23}O represent one of the first major results of the MoNA collaboration which employed several undergraduate institutions in the construction of a state-of-the-art detector for neutron decay spectroscopy using fast fragmentation beams.

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*This work was supported by the National Science Foundation Grant No. PHY-01-10253.
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First high-precision Penning trap mass measurements of short-lived isotopes from fast-beam fragmentation

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The Low-Energy Beam and Ion Trap facility LEBIT at the NSCL at MSU was used for the first time to demonstrate that rare isotopes produced by fast-beam fragmentation can be slowed down and prepared for precision mass measurements. The system employs a high-pressure gas-stopping concept [1] combined with advanced ion manipulation techniques. The first Penning trap mass measurements on short-lived rare isotopes have been performed with a 9.4 Tesla Penning trap mass spectrometer. Example nuclides are ^{66}As, with a half-live of only 96 ms, and ^{38}Ca, for which a mass accuracy of 8 ppb (280 eV) has been achieved [1]. ^{38}Ca is a particularly interesting case as it is a super-allowed Fermi-emitter and the high accuracy of its new mass value makes it a new candidate for the test of the Conserved Vector Current hypothesis. In addition, other measurements using LEBIT have drastically improved the mass values for ^{37}Ca, ^{40,42}S, ^{67}As and ^{65}Ge and the capability to resolve isomers was demonstrated by the observation of $^{81m+g}$Se. The LEBIT system and its first results will be presented.

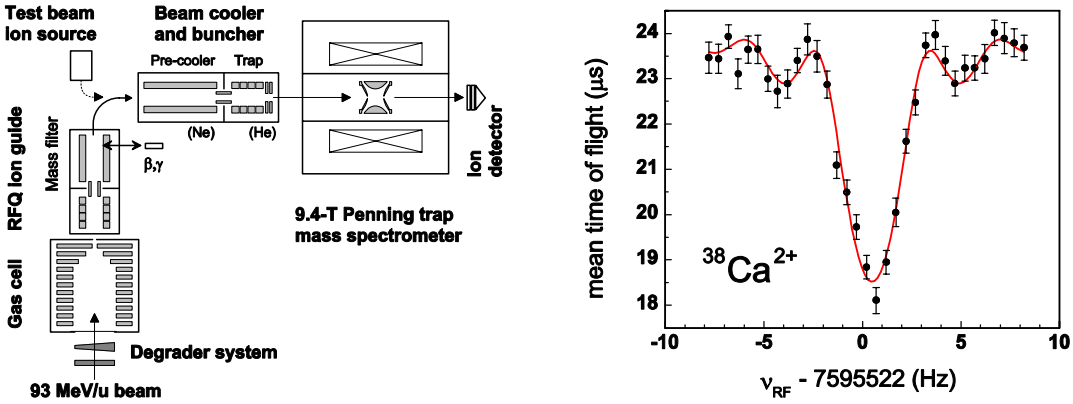

Figure 1*: Schematic of LEBIT at NSCL/MSU (left) and cyclotron resonance curve obtained for ^{38}Ca ($T_{1/2}$=440 ms) (right).*

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Nuclear Structure with Low-Momentum Interactions *

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We discuss how the renormalization group can be used to construct low-momentum interactions, called $V_{\text{low}\,k}$, by integrating out high-momentum modes larger than a cutoff Λ [1]. The resulting $V_{\text{low}\,k}(\Lambda)$ is phase-shift equivalent for all energies $E_{\text{lab}} < 2\Lambda^2/m$, and thus $V_{\text{low}\,k}(\Lambda)$ defines a class of new nucleon-nucleon potentials. In addition, we present first results for smooth cutoffs [2].

Exact calculations of many-body observables have to be cutoff-independent. This can be used to adjust chiral three-nucleon (3N) interactions $V_{3\text{N}}(\Lambda)$ to $V_{\text{low}\,k}(\Lambda)$ over a range of cutoffs. For cutoffs $\Lambda \lesssim 2\,\text{fm}^{-1}$, we have found that the resulting low-momentum 3N interactions are perturbative in light nuclei and thus tractable, and scale as expected from chiral power-counting estimates [3]. Therefore, we will be able to perform the first calculations of intermediate-mass nuclei including microscopic 3N interactions.

In contrast to traditional interactions, the theoretical error due to neglected many-body interactions can be estimated by varying the cutoff in calculations with $V_{\text{low}\,k}(\Lambda)$ and $V_{3\text{N}}(\Lambda)$. The first checks of this sort are very promising: The radii of light nuclei are cutoff-independent over a wide range, and an approximate second-oder calculation of nuclear matter binding becomes more cutoff-independent when 3N interactions are included [4].

We then give an update on applications of low-momentum interactions to many-body systems. We report on progress towards a benchmark calculation of the binding energy of ^{16}O using the Coupled-Cluster method, the No-Core Shell Model and a perturbative approach [5]. This benchmark is based only on $V_{\text{low}\,k}$, and serves as a study of the improved convergence of low-momentum interactions and the performance of these many-body methods. Our results show that low-momentum interactions offer the unique possibility to advance ab-initio calculations to intermediate mass nuclei, into an overlap region with microscopic many-body methods for heavier nuclei.

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[5] The Coupled-Cluster calculations are performed in collaboration with D. Dean, the No-Core Shell Model calculations are in collaboration with P. Navratil, and the perturbative calculations are in collaboration with R. Roth.

*This work is supported by the U.S. Department of Energy under Grant DE-FG02-97ER41014.

Neutron transfer and flow in reactions between heavy neutron-rich nuclei.

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Fusion reactions are used to synthesize heavy elements and a great deal of effort has been put into finding optimal conditions for the production reactions. We have measured the formation of Evaporation Residues (ER) at near and sub-barrier energies in collisions between several Te and Sn beams on ^{58}Ni and ^{64}Ni targets. The measured excitation functions are sparse but by measuring several systems we try to explore systematic trends in the sub-barrier cross section for ER formation. The data obtained show the obvious enhancement of ER production (survival) with the addition of neutrons to the fused system. An analysis of these data in a WKB formalism incorporating neutron transfer channels in a two step process (see Denisov[1] and Zagrebaev[2]) will be presented. Only global potentials are used in our analysis, resulting in poorer fits to individual data sets but hopefully more predictive power.

Figure 1 shows a comparison of ER cross section data to capture cross sections predicted with a WKB + neutron transfer two step calculation. The calculated capture cross sections should be compared only at sub-barrier energies where expected fission competition is small. Oviously for the four cases shown here sub-barrier cross sections are under predicted. The only system having neutron transfer channels with positive Q values is ^{132}Sn+^{64}Ni but the predicted sub-barrier enhancement is minimal there. Note that the same model also predicts a suppression of the cross section above the barrier when neutron transfer channels with negative q-value are included.

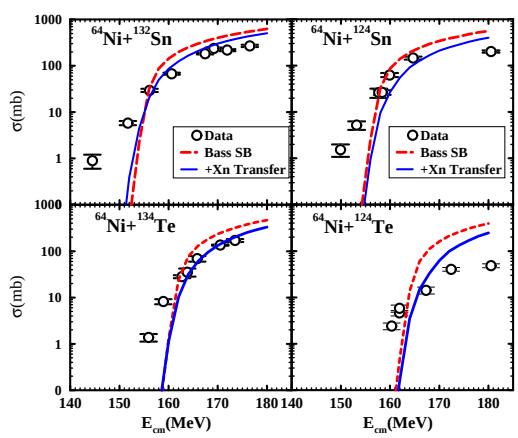

FIG. 1: Comparison of measured ER cross sections to two step WKB calculations.

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Level densities and gamma-ray strength functions in Sm isotopes

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The Oslo group has developed a technique[1,2] to measure with high precission the level density from the ground state up to the neutron binding energy. The method provides simultaneously the level density and gamma-ray strength function in one and the same experiment. After establishing the level density as a function of excitation energy, $\rho(E)$, the entropy is known by $S(E) = k_B \ln \rho(E)$ and we can explore various thermodynamical parameters of the nucleus. The caloric curve $T(E)$, derived within the framework of the micro-canonical ensemble, shows structures, which we associate with the break up of nucleon pairs. The nuclear heat capacity is deduced within the framework of the canonical ensemble and exhibits an S-shape as function of temperature, indicating a pairing transition.

Important applications of nuclear level densities are the determination of nuclear cross sections from Hauser-Feshbach type calculations. These cross sections are used as input parameters in large network calculations of stellar evolution, and in the simulation of accelerator-driven transmutation of nuclear waste. Unfortunately, the predictions of such calculations suffer from the lack of experimentally determined level densities. To day our knowledge is mainly based on the counting of discrete levels in the vicinity of the ground state and neutron resonance spacings at 6-8 MeV of excitation energy.

I will discuss the evolution of the level density and radiative strength function as one moves from the well deformed ^{161,162}Dy, ^{166,167}Er and ^{171,172}Yb nuclei to the close to spherical ^{148}Sm and ^{149}Sm nuclei[3]. A pygmy resonance at around 3 MeV has been observed in several deformed rare earth nuclei and vanishes for the spherical nuclei. This is as expected for a scissors mode (M1 multipolarity) pygmy resonance. Results from Oslo combined with a thermal neutron capture experiment analysing two-step cascades finally establish the M1 multipolarity of this pygmy resonance[4]. Preliminary result for ^{143,144,146,147}Sm will also be shown and a discussion of what happens to the level density and the radiative strength function of samarium isotopes as one approaches and crosses the N=82 closed shell. This work was supported by the Norweigian Research Council.

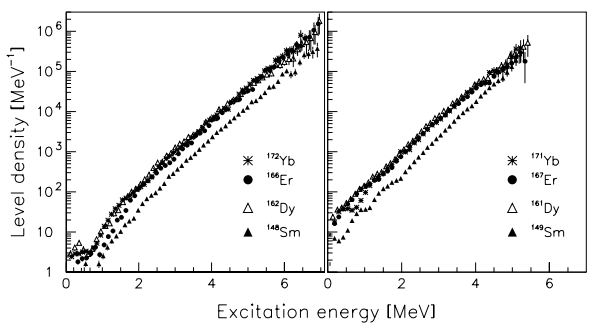

Figure 1: *The level density is clearly lower for the spherical Sm isotopes as compared to the deformed Dy, Er and Yb isotopes.*

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Lifetime Measurement in ^{81}Rb

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The region of nuclei with A $\sim$ 80 is very rich in nuclear phenomena. It contains nuclei having large deformation with very interesting features. These nuclei have low density of single particle levels and large shell gaps of 2 MeV at oblate ($\beta_2 \approx$ -0.3, N or Z = 34,36) and prolate ($\beta_2 \approx$ +0.4, N or Z = 38,40) shapes, exhibiting the dependence of nuclear shapes on proton number, neutron number and on their configuration as well as on spin and lead to shape-coexistence effects. This has, therefore, generated a lot of interest to study nuclear shapes in nuclei in this mass region [1, 2].

An experiment was performed to deduce the lifetimes of the high spin states of ^{81}Rb through Doppler shift Attenuation Method (DSAM). ^{81}Rb is populated through the reaction $^{55}Mn(^{29}Si, 2pn)^{81}Rb$ at 95 MeV of beam energy delivered by the 15 UD Pelletron facility at Inter University Accelerator Centre (IUAC), New Delhi. The target used was the ^{55}Mn of thickness 690 μg/cm^2 with a backing of Au of thickness 8.6 mg /cm^2. The γ-rays were detected using the Gamma Detector Array (GDA) setup in IUAC consisting of 10 Compton Supressed HPGe detectors relative efficiencies of 25% with 14 BGO element multiplicity filters, seven were placed on the top and the seven were on the bottom position of target position at 90^0 w.r.t the beam direction. The detectors were arranged in three different rings making an angle of 50^0, 98^0 and 143^0 with the direction of beam. One clover detector was also used at the angle of 98^0 w.r.t the beam direction. Total 350 million $\gamma \quad \gamma$ events were collected during the experiment. The data was sorted out offline using the INGASORT [3] programme. For the lifetime measurement asymmetric matrices were formed with all detectors versus the detectors at backward angle of 143^0 and forward angle of 50^0. For the lifetime measurement LINESHAPE programme [4] is being used.

Analysis of the data is underway to determine the level lifetimes for investigating shape change at high spins.

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The monopole shift in nuclei and properties of the effective nuclear force

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Some of the intriguing questions related to the physics of exotic nuclei are how their shell structure changes with respect to that of nuclei close to the line of β-stability and what mechanisms are responsible for that.

We have performed systematic studies of the nuclear mean-field variations in series of isotopes or isotones, adjacent to semi-magic nuclei, using a monopole plus pairing shell-model Hamiltonian. The self-energy correction for a single nucleon is calculated in the lowest order, incorporating the residual proton-neutron interaction and nucleon occupation probabilities, obtained from solution of the BCS equations. This approach represents an accurate approximation to the full shell-model centroids of the single-particle states in these nuclei [1]. In this way we are able to treat nuclei which require large model spaces and at present cannot be studied by exact diagonalization.

The approach is applied to explore the evolution of the mean field in a series of F, Cu, Sb and Bi isotopes, as well as $N = 29$ and $N = 51$ isotones from neutron-deficient to very neutron-rich nuclei [2]. The changes of the single-particle energies are shown to be mainly due to the monopole part of the effective two-body interaction. The comparison between realistic and different schematic interactions (finite-range central force, tensor and two-body spin-orbit forces) is performed in an attempt to understand the role of specific terms acting within the effective interaction [2,3,4].

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Visualizing Nuclear Mass Models with the Computational Infrastructure for Nuclear Astrophysics

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In addition to playing a crucial role in our understanding of the nucleus, theoretical models of nuclear masses are absolutely essential to simulating stellar explosions and other astrophysical phenomena. Research in nuclear mass models requires the ability to compare a variety of predicted parameters with experimental values, as well as to compare the predictions of different mass models. This visualization is now facilitated by a Mass Model Evaluator software tool that is freely-available online at **nucastrodata.org.** The tool is part of the **Computational Infrastructure for Nuclear Astrophysics,** a suite of computer codes that streamlines the incorporation of recent nuclear physics results into astrophysical simulations and enables users to run and visualize these simulations. Current capabilities of the Mass Model Evaluator include 1d plots of mass difference and RMS mass difference as functions of Z, N, or A, as well as tables of points of the mass models. Additionally, 2-d nuclide charts of mass excess, Q-values, and separation energies are quickly available for a single model, for differences between two models, or for differences between a theoretical model and experimental data. The 2d plots are customizable, with color mapping, parameter range, isotope labels, and zoom factor all adjustable. Furthermore, magic numbers, stable isotopes, and an r-process path can be toggled on or off. Users can quickly upload their own mass model, visualize its predictions, and compare it with other mass models or with experimental values. Future developments include enhanced interactivity, display of additional information, and utilization of mass models for other calculations (e.g., cross section calculations).

* Managed by UT-Battelle, LLC, for the U.S.D.O.E. under contract DE-AC05-00OR22725

The g-factor of the 10^+ isomer in ^{128}Sn using the g-RISING setup

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We report the results of an experiment to measure the g-factor of the 10^+ ($t_{1/2} = 2.69[1]/3.4[2]$ μs) isomer in ^{128}Sn. This measurement will shed light on the nature of suggested configuration mixing to explain the B(E2) ratio of isomers in ^{128,130}Sn nuclei, which deviates from the value 4/8 expected for a pure $h^n_{11/2}$ $\nu = 2$ system. The ^{128}Sn nuclei were produced by the fragmentation of a ^{136}Xe beam at 600MeV/u, provided by the SIS synchrotron at GSI. The orientation of the nuclear spin ensemble obtained from the fragmentation reaction was preserved by separating the fully stripped fragments using the fragment separator (FRS) and stopping in a perturbation free Cu foil placed between the poles of an electromagnet. The nuclei of interest were identified on an event-by-event basis and fragment-γ coincidences were recorded. The γ decay was detected using eight cluster Ge detectors mounted in the horizontal plane. The delayed γ-ray spectrum obtained (part of the data) by gating on ^{128}Sn reaction products is shown in Fig. 1(a). A total number of $\approx$ 14000 counts was obtained for the 321 keV transition, which is placed in the cascade below the 10^+ isomer (see Fig. 1(b)). This allows to construct the time-dependent ratio functions to determine the Larmor precession frequency. Preliminary results from this analysis will be reported.

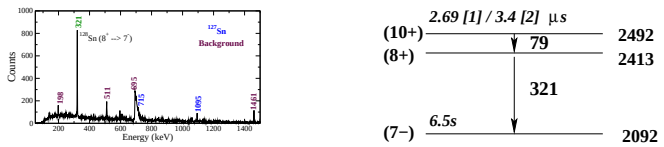

FIG. 1. (a) The delayed γ-ray spectrum showing the 321 keV line from ^{128}Sn. (b) Partial level scheme of ^{128}Sn.

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Heavy-ion Coulomb excitations as a comprehensive test of microscopic quadrupole collective models

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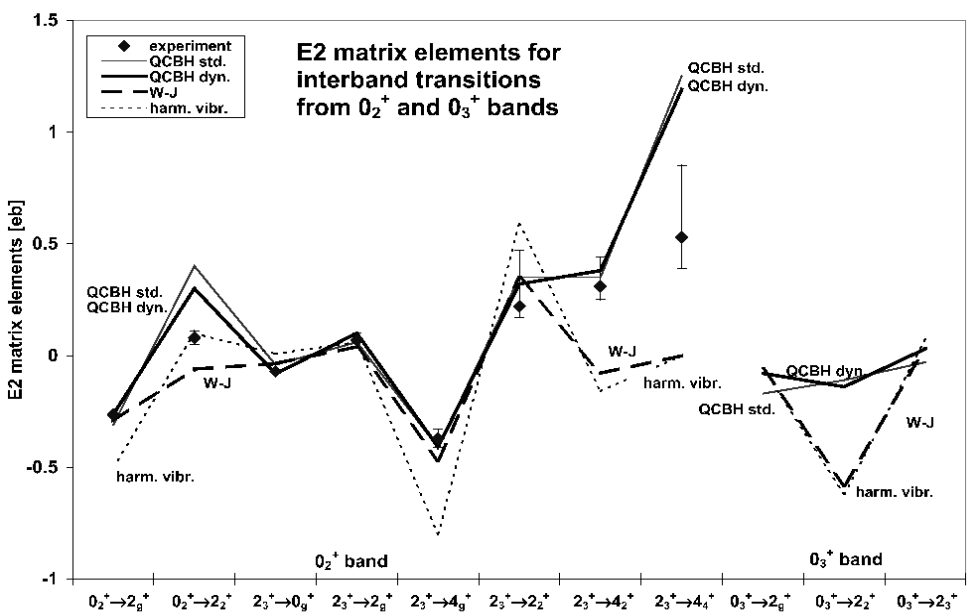
Heavy-ion induced Coulomb excitations make possible to excite states up to high spin and to measure both the signs and magnitudes of the practically complete set of E2 matrix elements for the low laying collective states in the stable even-even nuclei. Sets of data from the Coulomb excitation experiments having a wide range of projectile Z values and scattering angles made it possible to obtain a model independent set transitional and diagonal E2 matrix elements. Here we present results of ^{104}Ru target excitation using ^{58}Ni, ^{136}Xe and ^{208}Pb projectiles [1]. The entire data are confronted to calculations preformed in a frame of the Bohr Generalized Collective Hamiltonian. This Hamiltonian is obtained from a more general "quadrupole plus pairing" collective model trough the Born-Oppenheimer approximation that takes into account the effect of the pairing dynamics [2]. All six inertial functions and the potential were determined from a microscopic theory. Without any parameters fitted to ^{104}Ru experimental data, a very good agreement was obtained between the experimental and theoretical results for absolute energy levels as well as for the rich set (about 30) of E2 matrix elements. As an example of E2 matrix elements experimental and theoretical comparison interband transition matrix elements of γ–transitions from bands based on 0_2^+ and 0_3^+ levels are presented below. The comparison with the prediction of the following models are shown:

(1) the microscopic quadrupole collective Bohr Hamiltonian with standard BCS pairing – $QCBH_{std}$,
(2) the microscopic quadrupole collective Bohr Hamiltonian with the effect of the dynamical pairing – $QCBH_{dyn}$,
(3) the phenomenological rigid triaxial rotor – D-F,
(4) the phenomenological γ-unstable β-vibrator in the version of ref. [3] – W-J ,
(5) the phenomenological standard quadrupole harmonic vibrations – harm. vibr.

Such comprehensive test of microscopic quadrupole collective models was not possible by any other experimental methods but heavy-ion induced Coulomb excitations.



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New structure information on ^{93}Ru near ^{100}Sn

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Properties of excited states in the doubly magic nucleus of ^{100}Sn are not known from direct measurements. Thus there is a strong interest in nuclei in close vicinity to ^{100}Sn as they provide indirect evidence on the structure properties of the doubly magic system. Of particular importance are excitations of the core, which in principle should reflect the stability of the shell closures. The nuclei along N=50 below ^{100}Sn, have protons in the $g_{9/2}$ shell, and thus states at low excitation energy should be easily calculated as multiproton systems with several protons in the high-j orbit. The transition matrix elements are very sensitive probes of the admixtures to the wave functions. Our recent lifetime results for the 6^+, 4^+ and 2^+ states in ^{94}Ru and ^{96}Pd have shown strong departure from the simple picture mentioned above. These deviations can be explained only by admixtures of neutron excitations to the low-lying states in these N=50 nuclei. Our lifetime measurements in the subnanosecond region (ps to ns) were performed at the LISE facility at GANIL via isomer-delayed gamma-gamma time-delayed coincidences. The nuclei in the region of N=Z close to ^{100}Sn were produced in the fragmentation reaction of ^{112}Sn. They were identified on an event-by-event basis and implanted into a Si detector at the point of measurement. Using the array of Studsvik-designed BaF_2 detectors we have obtained high quality results even for very weakly produced exotic nuclei at the rate of 1 decay per second. The new results include the lifetime of the 1936 keV level in ^{93}Ru, which shows a very slow B(E2) value for the $17/2^+$ to $13/2^+$ transition, which is related to the B(E2) pattern observed for ^{94}Ru and ^{96}Pd. Results of shell model calculations will be presented.

Pioneering the Time of Flight Technique for Lifetime Measurements with Intermediate-Energy Beams of Heavy Nuclei *

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The plunger method for picosecond lifetime measurements of excited γ-ray emitting nuclear states has been adopted to the specific requirements originating from the use of fast beams of heavy ions from fragmentation reactions [1]. A test measurement was carried out with a beam of ^{124}Xe at an energy of $\sim$55 MeV/u. The beam ions were Coulomb excited to the 2_1^+ state on a movable target. Excited nuclei emerged from the target and decayed in flight after a distance related to the lifetime. A stationary degrader positioned downstream with respect to the target was used to reduce the velocity of the excited nuclei. As a consequence, the γ-ray decays from the 2_1^+ excited state that occurred before or after traversing the degrader were measured at a different Doppler shift as shown in Fig. 1. The γ-ray spectra were analyzed from the forward ring of the Segmented Germanium Array (SeGA); this ring positioned at 37° simultaneously provides the largest sensitivity to changes in β and the best energy resolution. The ratio of intensities in the peaks at different Doppler shifts gives information about the lifetime if the velocity β is measured. The τ=64^{+10}_{-8} ps lifetime for the first excited 2_1^+ state in ^{124}Xe measured with the above method is in excellent agreement with the most accurately known value of τ=67.5(1.7) ps from Ref.[2].

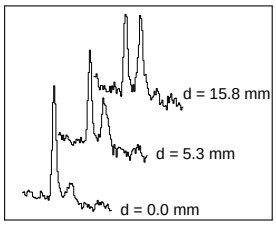

FIG. 1. Spectra showing change of intensity as a function of the target-degrader distance for the two components of a Doppler-shifted γ-ray peak corresponding to the 354 keV transition from the first excited 2_1^+ state in ^{124}Xe. The higher(right)- and lower(left)-energy components of the peak correspond to the decays upstream and downstream with respect to the plunger degrader foil, respectively. From the intensities of these two components as a function of the target-degrader separation and the velocity of nuclei between the target and the degrader the lifetime of the excited state which is depopulated by the observed gamma-ray transition can be determined.

Subsequently the method has been applied to study lifetimes of N=Z nuclei in the mass A$\sim$60 region produced in knock-out and fragmentation reactions at energies $E \sim 90$ MeV/u and for neutron-rich, collective Z=46 Pd nuclei excited using intermediate-energy Coulex. First results of these measurements, which will be presented and discussed, give evidence for the very high potential of the employed method for lifetime measurements after reactions with intermediate-energy beams of rare isotopes.

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*This work has been partially supported by the (US) National Science Foundation Grant No. PHY01-10253 and by the BMBF (GERMANY) under contract No. 06K167.

No-core shell model: theory and applications

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The no-core shell model (NCSM) is a powerful many-body method that provides the solution to the Schrodinger equation for A-interacting nucleons in a restricted space [1]. Starting from realistic nucleon-nucleon interactions that accurately fit the experimental phaseshifts, and theoretical three-body forces, one usually uses a unitary transformation approach to obtain an effective interaction in a restricted model space, where an exact diagonalization in a many-body basis can be performed. This approach has been very successfully applied to the description of energy spectra of light nuclei, from ^{3}H to ^{16}O and even beyond. We will discuss recent developments in the NCSM, including the unitary transformation approach to the theory of effective long- and short-range operators [2] and the Lorentz integral transform application to the total photodisintegration cross section [3]. In general, it is difficult to obtain the long-range observables using effective operators consistent with the interaction [2]. The description of long-range observables requires large model spaces, which make the application of the method to masses larger than 16 very challenging. This motivates us to search for new approaches that would provide a consistent treatment of effective interactions and operators in smaller model spaces.
Even in the absence of exact solutions from QCD, effective filed theories (EFT) provide a modern understanding of the nuclear forces at low energies [4]. Chiral perturbation theory is based on a power organization of the interaction for momenta of the order of the pion mass, taking into account the separation of scales involved in the problem. It allows a consistent and improvable description of the experimental data in the low energy region of interest for nuclear structure.
A simpler EFT, which involves momenta smaller than the pion mass, is the pionless EFT. I will present a novel approach to the derivation of effective interactions for NCSM calculations, based on the pionless EFT. Such an approach can provide a consistent, order-by-order improvable method to obtain interactions tailored for the model spaces used in the many-body calculations, as well as the corresponding electromagnetic and weak operators. Moreover, one obtains model-independent results, as well as theoretical estimation of the errors for the results obtained in a certain order. This also makes possible obtaining a reliable effective interaction for heavier nuclei, relevant to the proposed rare isotope accelerator, in a model space that should be still numerically tractable. We have to point out that in the heavy-nuclei region one has to expect that the theory without pions used in this work will break down. However, the same techniques can be employed in the theory with pions, making this investigation relevant. The first task is to obtain an effective two-body interaction, based on a truncation in the harmonic oscillator basis, and which keeps the the connection with the nucleon-nucleon phaseshifts. Application to nuclei in the p-shell using the effective interactions obtained by means of this new approach will be presented.

This investigation was supported in part by NSF grant numbers PHY0070858 and PHY0244389.

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Symmetry violation and restoration schemes at band termination

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A comparative study between state of the art shell-model (SM) and self-consistent Skyrme-Hartree-Fock (SHF) mean-field has been performed for the maximum-spin I_{max} (favored signature) as well as for $I_{max}-1$ (unfavored signature) terminating states within $f^n_{7/2}$ and $d^{-1}_{3/2}f^{n+1}_{7/2}$ configurations in the $N \geq Z$ $A{\sim}44$ nuclei. The aim is to explore the structural simplicity of these states for identification, quantitative evaluation and subsequent phenomenological restoration (correction) of the broken symmetries inherently obscuring the SHF treatment. Two examples of such phenomena are briefly discussed below.

Figure 1a shows the energy difference between the I_{max} states $\Delta E = E(d^{-1}_{3/2}f^{n+1}_{7/2}) - E(f^n_{7/2})$ calculated in SM and SHF relative to experiment. Difference between SM and SHF results for $N = Z$ nuclei nicely illustrates the isospin symmetry violation in SHF at high-spins. This is because SHF states correspond either to single neutron $|\nu_{ph}\rangle$ or single proton $|\pi_{ph}\rangle$ $1p$-$1h$ excitations but not to mixtures of thereof. While the corresponding energy correction can be easily evaluated, the discrepancy between the description of $N > Z$ and $N = Z$ nuclei remains in both approaches signaling, most likely, missing isoscalar pairing type correlations at band termination [1].

Figure 1b shows the energy difference $\Delta E = E([f^n_{7/2}]_{I_{max}}) - E([f^n_{7/2}]_{I_{max}-1})$ calculated in SM and SHF. Within SHF, the $[f^n_{7/2}]_{I_{max}-1}$ configuration can be generated from the $[f^n_{7/2}]_{I_{max}}$ state by changing either the neutron or proton signature; hence, admitting two independent solutions. Closer examination shows, however, that these solutions are mixtures of spurious $|I_{max}, I_{max}-1\rangle$ and physical $|I_{max}-1, I_{max}-1\rangle$ states, thus constituting an example of rotational symmetry violation at an almost spherical shape. A simple alghoritm can be devised that allows for evaluation of broken symmetry effects.

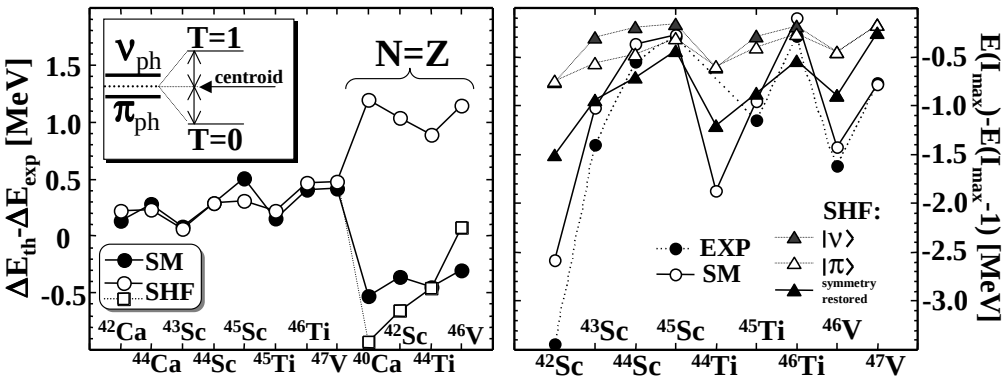

FIG. 1: **a)** Difference between theoretical and experimental excitation energies of the fully-stretched terminating states. Dots (circles) mark the SM (SHF) solutions, respectively. Squares denote the isospin-corrected SHF results. **b)** Difference between excitation energies of I_{max} and $I_{max}-1$ terminating states within the $f^n_{7/2}$ configuration. Dots (circles) mark experimental data and SM results, respectively. SHF results are marked by triangles.

[1] G. Stoitcheva *et al.*, nucl-th/0509059

Probing shell-model matrix elements at band termination

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The systematic study of the energy difference, ΔE, between the fully-aligned, high-spin $f^n_{7/2}$ seniority isomers and the $d^{-1}_{3/2}f^{n+1}_{7/2}$ intruder states in the $N \geq Z$ $A{\sim}44$ nuclei from the lower-fp shell has been performed using the nuclear shell model (SM) in the full $sdfp$ configuration space limited to 1p-1h cross-shell excitations. The calculations [1] show clear discrepancy between the description of $N > Z$ and $N = Z$ nuclei and the characteristic seesaw pattern of $\Delta E_{SM} - \Delta E_{exp}$ what signals (i) missing isoscalar pairing type correlations at band termination or/and (ii) incorrect isospin dependence of SM matrix elements. The latter possibility emerges from the Bansal-French-Zamick (BFZ) mechanism [2] where the isospin-dependent contribution to the excitation energy can be easily evaluated to be $\Delta E^T_{N>Z} = b(T-1/2)/2$ and $\Delta E^T_{N=Z} = -3b/4$ in $N > Z$ and $N = Z$ nuclei, respectively, with b denoting the symmetry energy strength. Indeed, the reduction of b by $\delta b \sim 700$keV leads to an almost perfect agreement with the experiment.

To verify the BFZ prediction we have performed preliminary calculations using SM interaction with diagonal $p-h$ matrix elements modified in the following way: $V_{phph}(JT=0) \rightarrow V_{phph}(JT=0)+3d$ and $V_{phph}(JT=1) \rightarrow V_{phph}(JT=1)-d$ where d=175keV. Such a shift should, at least according to a simple single-j J–T SM phenomenology [3], reduce b by $\delta b \sim 4d \sim 700$keV. Although the use of modified SM clearly improves the agreement with experimenatal values of ΔE, the effect appears to be much smaller than anticipated from the BFZ mechanism alone. As shown in Fig. 1b, the modified interaction significantly improves an overall agreement with the data for low-spin 1p-1h intruder states, Unfortunately, at the same time it spoils the agreement with experimental nuclear binding energies. Hence, an intriguing question is whether the systematic refinement of isotopic dependence of SM interaction can lead to a global improvement of different observables.

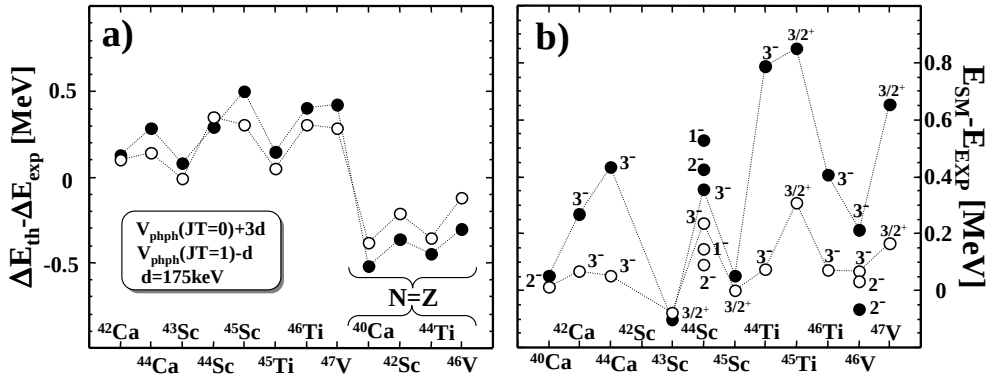

FIG. 1: Difference between SM and experimental excitation energies of the terminating states **a)** and low-spin 1p-1h intruder states **b)**. Calculations done using original (modified) SM interaction are marked by dots (circles) respectively.

Parity Non-Conservation in ^{180m}Hf revisited*

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Measurements of Parity Non-Conservation (PNC) in bound nuclear states aim to establish the magnitude of parity violating terms in the nuclear potential. The 5.5h 8^- K-isomer in ^{180}Hf has stood since the 1970's as the only bound state in which PNC is clearly observed [1]. It was studied by observing the forward-backward asymmetry with respect to the polarization axis of the 501 keV $8^- - 6^+$ gamma transition from a source polarized at milliKelvin temperatures in the intermetallic compound $ZrFe_2$ [2,3] which gave an effect of ~ 10 standard deviations: 1.66 +/- 0.18%. Investigations by circular polarization gave compatible results [4].

Renewed interest in this result arises from its continued uniqueness, combined with the availability of improved experimental techniques for its measurement. In a new experiment, a ^{180m}Hf beam developed at ISOLDE, CERN was implanted into a pure Fe foil cooled to milliKelvin temperatures in the NICOLE on-line nuclear orientation facility. This system allows continuous implantation, giving steady state, rather than decaying sample, measuring conditions and gives access to both higher degrees of nuclear polarization and to lower temperatures than was possible in the earlier work.

The temperature of the sample was measured using a ^{57}Co nuclear orientation thermometer and gamma rays were detected in HPGe detectors placed at 0, 90 and 180 degrees with respect to a field of 0.5 T which served to polarize the Fe foil and establish the axis of orientation. The direction of the magnetic field was reversed periodically, reversing the sense of polarization and effectively interchanging the 0 and 180 degree detectors.

The results show excellent overall agreement with the earlier results on the asymmetry of the 501 keV, with the improvement that they cover a wider range of temperature, from 60 mK to 7 mK. Asymmetries of the successive band cascade transitions of 444 keV ($8^+ - 6^+$), 332 keV ($6^+ - 4^+$) and 215 keV ($4^+ - 2^+$) transitions are zero within experimental errors (0.1%).

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[4] T.S.Chou, K.S. Krane and D.A. Shirley, Phys. Rev. **C12**, 286 (1975).

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*This work was supported by U.S. DoE Grants DE-FG02-96ER40983 (N.J.S.) and DE-FG02-94ER40834 (J.R.S.).

Nuclear structure of neutron-rich nuclei from excited-state g-factor measurements on radioactive beams

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Successful measurements of the g factors of picosecond-lived excited states, which have recently been performed on radioactive beams produced both by the ISOL method [1] and by fast fragmentation [2], will be reviewed. It will be shown that in both cases a precision approaching that of near-by stable-beam measurements has been achieved, which is enabling critical studies of nuclear structure near closed shells.

The Recoil In Vacuum (RIV) technique is being used at the Holifield Radioactive Ion Beam Facility (HRIBF), Oak Ridge, USA, to study radioactive nuclei near ^{132}Sn re-accelerated to ~ 3 MeV/nucleon. When the data from [1]are combined with new calibration data on the stable Te isotopes obtained at ANU (see Fig. 1) we obtain $g(2^+)$ in ^{132}Te with a precision of about 10%. Extension of the technique to more exotic isotopes such as ^{134,136}Te is underway.

The measurements on fragment beams at the National Superconducting Cyclotron Laboratory (NSCL), Michigan State University, USA, focused on neutron-rich isotopes of sulfur between $N = 20$ and $N = 28$, which are believed to undergo a transition from spherical at $^{36}_{16}S_{20}$, to prolate deformed in $^{40}_{16}S_{24}$ and $^{42}_{16}S_{26}$. A novel application of the transient field technique was used to measure the first-excited state g factors in ^{38}S and ^{40}S and hence study the shell structure underlying the quadrupole collectivity in these nuclei [2]. In combination with shell model calculations, the measured g factors indicate strong coupling between protons and neutrons, and that there is a fine balance between the proton and neutron contributions to the magnetic moments in both sulfur isotopes. It will be shown that the g factor of 'deformed' ^{40}S does not resemble that of a conventional collective nucleus because spin contributions are more important than usual. Shell model predictions and possibilities for future measurements on nuclei near $N = 28$ will be discussed.

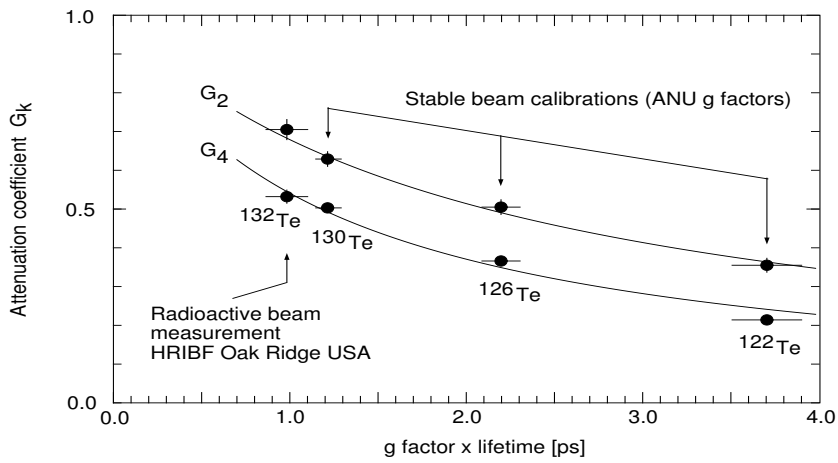

FIG. 1. Attenuation coefficients, G_k, for Te ions recoiling in vacuum.

[1] N.J. Stone, A.E. Stuchbery, M. Danchev, J. Pavan *et al.*, Phys. Rev. Lett. **94**, 192502 (2005).

[2] A.D. Davies, A.E. Stuchbery, P.F. Mantica, P.M. Davidson, A.N. Wilson *et al.*, Phys. Rev. Lett. **96**, 112503 (2006).

Study of the tensor correlation in oxygen isotopes using mean-field-type and shell-model methods

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The correlation induced by the tensor force plays important roles in nuclear structure. The recent exact-type calculations, for example, the Green's function Monte Carlo calculation and the no-core shell model calculation, show the large attractive energy comes from the tensor force in light nuclei. There still remains many problems on the effect of the tensor correlation to be studied. The effect of the tensor correlation in neutron-rich nuclei is one of such problems. Recently, the tensor correlation in neutron-rich nuclei has been widely discussed. The relation between the shell evolution in neutron-rich nuclei and the tensor force was discussed by Otsuka and his collaborators, and the effect of the tensor correlation on the breakdown of the magic number 8 in ^{11}Li was discussed by Myo and his collaborators. These studies indicate the importance of the tensor correlation in neutron-rich nuclei.

Recently, we have developed a mean-field-type framework which can treat the tensor correlation directly. The one of the most important correlations induced by the tensor force is a 2p–2h-type correlation which is hard to be treated in a simple mean-field framework. To exploit the 2p–2h correlation in a mean-field-type framework we introduce single-particle states with the parity and charge mixing [1]. For the total wave function, the parity and charge projections before variation are performed and a Hartree-Fock-type equation is obtained. We solve the equation (the charge- and parity-projected Hartree-Fock equation) selfconsistently. We applied the CPPHF equation to sub-closed oxygen isotopes and found that relatively large attractive energy comes from the tensor force as shown in Fig. 1. We also found that the importance of the blocking effect for j=1/2 orbits on the tensor correlation. To study the correlation which cannot be treated in the present mean-field-type method, we performed a shell model calculation with 2p–2h configurations and found that the large attractive energy comparable to the binding energy comes from the tensor force in ^{16}O.

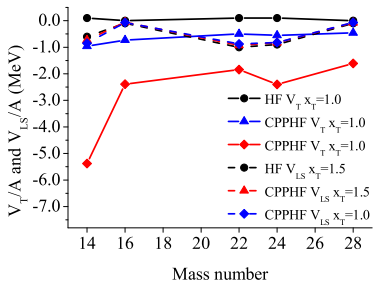

FIG. 1: The potential energies from the tensor and LS forces divided by mass numbers. HF and CPPHF stand for the simple Hartree-Fock calculation and the charge- and parity-projected Hartree-Fock calculation. x_{T} is a numerical factor multiplied to the $\tau_1 \cdot \tau_2$ part of the tensor force.

[1] S. Sugimoto, *et al.*, Nucl. Phys. A **740**, 77 (2004).

*This work is supported by the Grant-in-Aid for the 21st Century COE "Center for Diversity and Universality in Physics" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

Shell model method for Gamow-Teller Transition rates in heavy, deformed nuclei

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The weak interaction rates are important for understanding of the late stages of stellar evolution. Under the stellar conditions, most nuclei of interest lie outside the stability valley, for which experimental studies in laboratory are not feasible. It has been shown that the shell-model calculation with a full diagonalization of an effective Hamiltonian in a chosen model space is the preferable method for such calculations. Wildenthal and Brown [1] obtained the Gamow-Teller (GT) rates in the sd shell nuclei and Langanke and Martinez-Pinedo [2] made the shell-model GT rates available also for the pf shell nuclei. Still, these sophisticated calculations are tractable only for nuclei up to the mass-60 region, and cannot be applied to heavier nuclei which play important roles in the nuclear processes in massive stars.

For nuclei in medium and heavy mass regions, new shell model methods must be developed. The central theme has been how to carry out a shell model truncation. One of the choices is to use the Projected Shell Model (PSM) [3] wavefunctions to calculate the nuclear matrix elements. We report on the recent development for Gamow-Teller transition calculations in the PSM framework. The advantage of using the PSM wavefunction and the technical development will be illustrated. Possible applications to the current research fields such as nucleosynthesis, supernova mechanism, and double β-decay will be discussed. Our first example below indicates that, while experimental Gamow-Teller transitions from the ground-state of ^{164}Ho are reproduced, stronger Gamow-Teller transitions from some low-lying excited states are predicted to occur. These transitions are very difficult to measure in the laboratory. However, contribution from these transitions can substantially modify the decay rates in stellar environments when the excited states are thermally populated.

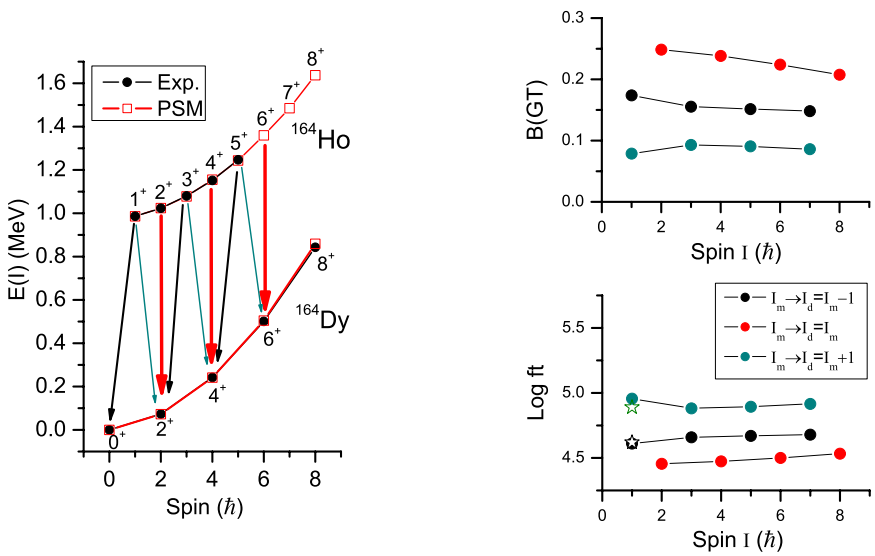

FIG. 1. Possible GT transitions from ^{164}Ho to ^{164}Dy and the predicted B(GT) and Log*ft* values.

[1] B.A. Brown, B.H. Wildenthal, At. Data Nucl. Data Tables 33 (1985) 347.
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[3] K. Hara, Y. Sun, Int. J. Mod. Phys. E 4 (1995) 637.

Gamma-Ray Spectroscopy with TIGRESS and the 8π Spectrometer at TRIUMF-ISAC

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The Isotope Separator and Accelerator (ISAC) facility located at TRIUMF is one of the world's most advanced ISOL-type radioactive ion beam facilities. An extensive gamma-ray spectroscopy program at ISAC is centered around two major research facilities, the 8π Gamma-Ray Spectrometer for beta-delayed gamma-ray spectroscopy experiments with the low-energy beams from ISAC-I, and the TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) for in-beam experiments with the accelerated radioactive ion beams to be provided by the new ISAC-II facility beginning in 2006. An overview of these facilities and recent highlights from the diverse program of nuclear structure, nuclear astrophysics, and fundamental interaction studies they support will be presented.

The 8π Spectrometer, comprised of 20 Compton-suppressed HPGe detectors, has recently been augmented by the SCEPTAR array of 20 thin plastic scintillators for β-particle tagging, the PACES array of 5 Si(Li) conversion electron detectors, the DANTE array of 10 BaF_2 detectors for fast-lifetime measurements, an in-vacuum tape transport system, and an upgraded data acquisition system, making it a world-unique facility for β-γ-electron coincidence decay studies with short-lived radioactive ion beams. Highlights from recent experiments with the 8π Spectrometer, including a measurement of the ^{62}Ga superallowed Fermi β decay branching ratio to a precision better than 0.02%, will be discussed.

TIGRESS is a next-generation γ ray spectrometer which has been designed for in-beam experiments with the accelerated beams to be provided by ISAC-II. TIGRESS will be comprised of 12 clover-type HPGe detectors, each equipped with a composite BGO-CsI Compton Suppression shield. Sensitivity to the locations of γ-ray interactions within the HPGe clover is achieved through 32-fold segmentation of its outer electrical contacts, and through pulse-shape analysis following flash digitization of the signal waveforms from each contact. This position sensitivity allows the detectors to be placed close to the target location without sacrificing angular resolution, leading to large gains in γ-ray detection efficiency while retaining the high intrinsic resolution of HPGe. Progress to date in the installation and commissioning of TIGRESS and an overview of the scientific opportunities for nuclear structure, nuclear astrophysics, nuclear reactions, and fundamental symmetries research at various stages of TIGRESS implementation will be presented.

Nuclear Level Densities and Extracted Entropies in Lead Isotopes.

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Information on nuclear level densities is of fundamental importance in nuclear structure and reaction theory. It finds its applications in calculating astrophysical models of stellar evolution and models of accelerator driven transmutation of nuclear waste. The γ-strength function is another important parameter for understanding the nuclear structure and decay properties. The present talk will focus on the energy dependent nuclear level densities and γ-strength functions of $^{205-208}$Pb nuclei below the nuclear separation energies.

The Oslo Cyclotron Group has developed an experimental method [1] that extracts nuclear level densities and γ strength functions simultaneously from primary γ-rays in light-ion reactions. The experimental primary γ-ray spectra per excitation energy bin, $P(E_i,E_\gamma)$, have been extracted for the (^{3}He, α) and (^{3}He, ^{3}He') reactions. The Axel-Brink hypothesis [2,3] has been employed to separate out level density and γ-strength function from the primary γ spectra by

$$P(E_i, E_\gamma) \propto \mathcal{T}(E_\gamma)\rho(E_i - E_\gamma),$$

where $\mathcal{T}$ is the γ-ray transmission coefficient and ρ is the level density.

The nuclear thermodynamical properties are extracted from the experimental nuclear level density within the microcanonical and canonical ensemble. The Boltzmann's postulate for *entropy* can be employed, stated under as

$$S(E, N) = k_B \ln \Omega(E, N),$$

where Ω is the number of microstates derived from experimentally found level densities, and k_B is the Boltzmann's constant. The experimentally determined radiative decay for the present isotopes will also be discussed.

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Variational calculations for asymmetric nuclear matter and a new term in the mass formula

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Asymmetric nuclear matter at zero temperature is studied by a variational method in which the energy per nucleon is expressed as an explicit functional of spin-isospin-dependent radial distribution functions, tensor distribution functions, and spin-orbit distribution functions. In this method, the expectation values of the central, tensor, and spin-orbit potential energies per nucleon are expressed exactly. On the other hand, the kinetic energy caused by correlations between nucleons is expressed only approximately; if the wave function is assumed to be of the Jastrow-type, the one-body, two-body, and the main part of the three-body cluster terms as well as a part of higher-order cluster terms are included in the kinetic energy expression. A notable feature of this method is that the necessary conditions on spin-isospin-dependent structure functions (Fourier transforms of the spin-isospin-dependent radial distribution functions) are automatically guaranteed. The distribution functions in the energy expression are regarded as variational functions, and the Euler-Lagrange equations are derived. Then, the fully minimized energies are obtained by numerical calculations with the AV18 two-body nuclear potential. The full minimization of the energies as mentioned above will be difficult to perform by other variational methods such as the Fermi Hypernetted Chain calculations. In the present study, the contribution of the three-body nuclear forces is also taken into account phenomenologically so as to reproduce the saturation density $\rho_{\rm sat}$ and the saturation energy together with reasonable values for the incompressibility and the symmetry energy. Numerical results were obtained for various nucleon number density ρ and various degrees of asymmetry $\zeta = (\rho_{\rm n} - \rho_{\rm p})/\rho$, where $\rho_{\rm n}$ ($\rho_{\rm p}$) is the neutron (proton) number density. When the results for the energy per nucleon, $E(\rho, \zeta)/N$, were inspected closely, a peculiar behavior was found as explained in the following.

It has been widely believed that $E(\rho, \zeta)/N$ of the infinite nuclear matter at a fixed ρ can be expanded into a power series in ζ^2, and accordingly $E(\rho, \zeta)/N$ can be well approximated as

$$E(\rho, \zeta)/N \approx E(\rho, \zeta = 0)/N + e_{\rm s}\zeta^2 , \tag{1}$$

in the neighborhood of $\zeta^2 = 0$, say $|\zeta| \leq 0.3$. However, the results of the above variational calculation deviate from the relation Eq. (1) significantly, and it has turned out that, the energies cannot be represented by a power series in ζ^2 in the physically interesting range of ζ. Then, in this study, a new term $e_1 (\zeta^2 + \zeta_0^2)^{1/2}$, where ζ_0 is a small number and e_1 (> 0) is a coefficient, is proposed; if the power series is supplemented with this new term, it reproduces the energies obtained by variational calculations very accurately. The main cause of the new term is strongly suspected to be the partial cluster formation in nuclear matter.

The finding of a new term in $E(\rho, \zeta)/N$ for nuclear matter suggests that a corresponding term is necessary in the mass formula of finite nuclei. In the case of finite nuclei, we should treat the energy at the saturation density $\rho_{\rm sat}(\zeta)$ for each value of ζ. Then, we express $E(\rho_{\rm sat}(\zeta), \zeta)/N$ as

$$E(\rho_{\rm sat}(\zeta), \zeta)/N = e_{0\rm s} + e_{1\rm s} [(\zeta^2 + \zeta_{0\rm s}^2)^{1/2} - \zeta_{0\rm s}] + e_{2\rm s}\, \zeta^2. \tag{2}$$

By comparison with the results of the variational calculations for $|\zeta| \leq 0.3$, the parameters in Eq. (2) are determined as follows:

$$e_{0\rm s} = -15.80 \text{ MeV},\ e_{1\rm s} = 2.88 \text{ MeV},\ \zeta_{0\rm s} = 0.058,\ e_{2\rm s} = 26.50 \text{ MeV}. \tag{3}$$

In the mass formula of finite nuclei, the second term on the right side of Eq. (2) multiplied by the mass number A should be included. Since the values of the parameters $e_{1\rm s}$ and $\zeta_{0\rm s}$ are expected to be sensitive to the nuclear forces, they should be treated as adjustable parameters in the mass formula. The new term has a considerable resemblance to the Wigner term, but its importance does not diminish in heavy nuclei.

Top-on-top mechanism in the triaxially deformed rotational bands in odd mass nuclei

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By applying Holstein-Primakoff transformation to both single-particle angular momentum $\vec{j}$ and total angular momentum $\vec{I}$, we obtained an algebraic solution for the particle-rotor model with one high-j nucleon coupled to a triaxially deformed core [1]. We have proved that Bohr's symmetry is recovered up to the second order expansion of two kinds of bosons a and b for $\vec{I}$ and $\vec{j}$, and the energy levels are classified in terms of a pair of quantum numbers n_α and n_β coming from the diagonalization of the Hamiltonian by new bosons α and β. At the symmetric limit and without the single-particle potential, the algebraic solution reduces to a well-known expression. Thus, n_α can be interpreted as the precession of $\vec{R} = \vec{I} - \vec{j}$ and n_β as the precession of $\vec{j}$, and Bohr's symmetry imposes the restriction on these quantum numbers depending on I. In this scheme, both angular momenta interact each other on an equal footing, and the precession of $\vec{R}$ correlates with that of $\vec{j}$. Such an interplay between $\vec{R}$ and $\vec{j}$ is called the "top-on-top mechanism". Moreover, we can infer the selection rules for the interband and intraband electromagnetic transitions with the help of these quantum numbers. As a test, we applied our method to odd mass Lu isotopes, and got a reasonable fit to the experimental data both for energy levels and the transition rates [1].

Although the deformation parameter is large (β =0.38), experimental data shows there still remains a gradual increase of the neutron core moments of inertia. We include the Coriolis anti-pairing effect on the neutron moments of inertia phenomenologically. The following figure shows the comparison between the experimental and the theoretical energy levels of three bands in ^{163}Lu with A=0.0075. Theory predicts TSD1 band has quantum numbers $n_\alpha = 0$ and $n_\beta = 0$, TSD2 band $n_\alpha = 1$ and $n_\beta = 0$ and TSD3 $n_\alpha = 2$ and $n_\beta = 0$. With the same parameter set, the absolute values of $B(E2)_{in}$, $B(E2)_{out}$ and $B(M1)_{out}$ are well explained.

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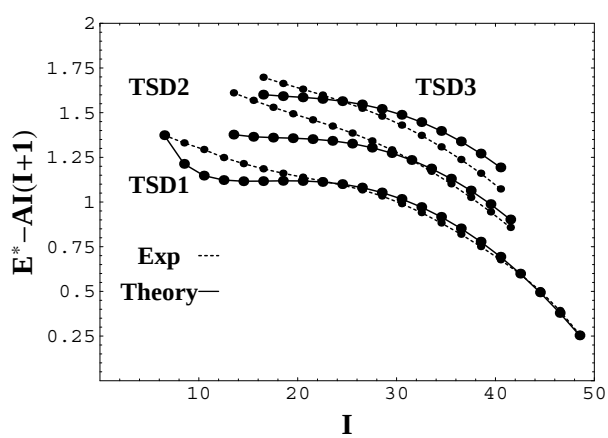

Multi-quasiparticle states in ^{254}No: K-conservation, single particle energies and pairing strengths

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Spectroscopic studies of the heaviest nuclei are challenging due to their sub-microbarn cross-sections and overwhelming fission competition. The investigation of K-isomers in these nuclei reveal the extent of robustness of axial symmetry for nuclear shapes in a regime characterized by a delicate balance between nuclear attraction and Coulomb repulsion. Experimental information regarding energies and nucleonic configurations of multi-quasiparticle states provide an insight into single particle energies and in even-even nuclei, also the pairing strength. These are important new inputs for model predictions of superheavy nuclei and can also provide discriminating tests of the models and, indirectly, of their predictions of magic gaps for superheavy nuclei.

Two experiments were performed to identify the γ rays and conversion electrons emitted in the decay of isomers in ^{254}No, which was formed with the ^{208}Pb(^{48}Ca,2n) reaction, using a 217 MeV (at mid-target) beam of ^{48}Ca from the ATLAS accelerator at Argonne. Evaporation residues of ^{254}No were transported and identified by their mass/charge ratio with the Fragment Mass Analyzer (FMA), then implanted into a 140 μm thick double-sided Si strip detector (DSSD) with 40x40 pixels, each with 1 mm^2 area. An isomeric decay in ^{254}No was identified by time and spatial correlations, namely an electron signal within 1 s of an evaporation residue in the same pixel as the implanted nucleus. The γ rays from the decay of an isomer were also detected, in prompt coincidence with an isomeric electron signal, in three large clover Ge detectors.

Two isomers, built on two and four-quasiparticle excitations, with $K^\pi = 8^-$ and (14^+) and half-lives of 266(10) ms and 171(9) μs have been identified in ^{254}No [1]. The 266 ms isomer had been found earlier, but its quantum numbers had not been determined [2]. In addition, a low-energy two-quasiparticle $K^\pi = 3^+$ state has also been established. The observed large decay hindrances provide a quantitative indication that K is a good quantum number and therefore the nucleus has an axially symmetric shape. Calculations of two-quasiparticle energies in ^{254}No have been performed with single particle energies given by the universal parameters of the Woods-Saxon potential and a Lipkin-Nogami formalism for pairing, which accounts for reduced pairing due to orbit blocking. These calculations show better agreement (within 150 keV) with experiment than those obtained from self-consistent mean-field Skyrme-Hartree-Fock-Bogolyubov and Relativistic Mean Field models. This extends the validity of Woods-Saxon single-particle energies for nuclei with Z up to at least 102. These results suggest a need for improved interactions for self-consistent mean-field models, which can more accurately describe single-particle energies.

This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W-31-109-ENG-38, DE-FG02-94ER40848 and DE-FG02-91ER-40609.

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Delayed Alignments and Search for Oblate Rotation in Neutron-rich Hf Nuclei*

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High spin states in neutron-rich hafnium nuclei exhibit a healthy competition for yrast status between single-particle excitations and collective rotation, where well-deformed axially-symmetric prolate shapes couple with valence nucleon orbitals with large angular momentum projections on the symmetry axis. Theoretical predictions at high angular momentum in these nuclei, that have remained untested for decades due to experimental limitations, include very long-lived yrast isomers [1], as well as oblate collective rotation being energetically favored [2,3]. While the evolution of the quantum number K as a function of spin and isospin has been a key motivation for our studies in the A~180 region for a number of years [4,5], the search for signatures of the predicted oblate collectivity at high spin near the yrast line constitute our present research thrust.

With fusion-evaporation reactions ruled out due to a lack of stable beam-target combinations, the nuclei of interest were populated to high spins via deep-inelastic and transfer reactions with heavy beams. Our most recent experiment focused on prompt spectroscopy of ^{180}Hf nuclei utilizing particle-gamma coincidence techniques to extend the yrast band structure beyond the first nucleon alignment. A 1.3 GeV ^{180}Hf beam from the ATLAS accelerator at Argonne was incident on a ^{232}Th target (~25% above the Coulomb barrier). The Gammasphere array was used in conjunction with CHICO, a parallel-plate, gas-filled compact heavy-ion counter [6], to distinguish between beam-like and target-like fragments recoiling out of the thin target. The gamma-ray spectra can be Doppler corrected event-by-event for either beam-like or target-like fragments through measurements of the time of flight of the recoiling ions. The yrast band of ^{180}Hf is extended to $20\hbar$, where a band crossing is evident from the observation of two parallel gamma rays feeding the 18^+ state. Our earlier work on this nucleus, utilizing a ^{136}Xe beam at ~15% above the Coulomb barrier on an enriched ^{180}Hf target stopped short of reaching the alignment frequency [7]. In addition to defining the alignment frequency, the observation of the two branches feeding the 18^+ state provides information on the interaction matrix element between the crossing bands.

The results of this recent experiment will be presented and compared with the systematics of first nucleon alignments as a function of neutron number in Hf, W and Os isotopes. The nature of the band crossing will be discussed in the context of competing theoretical scenarios, which include the occurrence of a sub-shell closure at N=108, oscillations in g-s band interaction strengths as a function of neutron shell filling in this region, as well as the possible effects of near-yrast oblate potential minima at these spins.

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*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contracts DE-FG02-94ER40848, W-31-109-ENG-38 and the National Science Foundation.

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Configurations and decay hindrances of high-K states in ^{180}Hf*

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Deformed, mid-shell nuclei in the A≈180 region are characterized by the presence of both proton and neutron high-Ω orbitals near the Fermi surface. A natural consequence is the realization of intrinsic high-K states which can favorably compete with collective excitations. The observation of intrinsic states, especially K-isomers, and the associated rotational bands can provide an insight into the relative positions of the underlying single-particle orbitals about which there is limited information in neutron-rich territory. Isotopes of Hf are particularly suited for such studies since they are some of the best examples of rigid, axially symmetric, prolate rotors and therefore K is a conserved quantum number in these nuclei. This work focuses on the structure of intrinsic two- and four-quasiparticle states in ^{180}Hf, the heaviest stable Hf isotope.

Excited states in ^{180}Hf were studied using deep-inelastic reactions, with a 1.4 GeV ^{207}Pb beam from the ATLAS accelerator at Argonne National Laboratory, incident on an isotopically enriched, 250 mg/cm^2 ^{180}Hf target. The Gammasphere array was used to record coincidence events in two time regimes viz. *prompt* and *pulsed*, where all and 1 in 10 beam pulses respectively, with the natural 82.5 ns pulsing from ATLAS, were made incident on the target. This data complements earlier out-of-beam studies focused on μs isomers [1,2] and the prompt spectroscopy of ^{180}Hf [3,4] using Gammasphere in conjunction with the auxiliary heavy ion counter CHICO.

The data reveal the presence of a rotational band built upon the previously determined two-quasiparticle, $K^\pi=10^+$ state in ^{180}Hf which helped in establishing the nucleonic configuration from the deduced g-factors. A rotational band built upon a four-quasiparticle state reported in the previous work [1] has also been identified. The lifetimes determined for the $K^\pi=10^+$ and 12^+ states are found to be substantially different from those reported in the previous work [1], where the experimental parameters had been optimized for isomers with $t_{1/2} \gg 1$ μs. A new four-quasiparticle state and the associated rotational band have been identified. The lifetime of the $K^\pi=6^+$ state has been measured using the centroid-shift technique and is found to be $t_{1/2}=2.8(3)$ ns. The decay hindrances for the various isomers have been analyzed in detail. Multi-quasiparticle calculations to determine the excitation energies of high-K states have been performed and compared with experiment.

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*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-FG02-94ER40848 and W-31-109-ENG-38.

Multi-quasiparticle states in ^{254}No: K-conservation, single particle energies and pairing strengths*

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Spectroscopic studies of the heaviest nuclei are challenging due to their sub-microbarn cross-sections and overwhelming fission competition. The investigation of K-isomers in these nuclei reveal the extent of robustness of axial symmetry for nuclear shapes in a regime characterized by a delicate balance between nuclear attraction and Coulomb repulsion. Experimental information regarding energies and nucleonic configurations of multi-quasiparticle states provide an insight into single particle energies and in even-even nuclei, also the pairing strength. These are important new inputs for model predictions of superheavy nuclei and can also provide discriminating tests of the models and, indirectly, of their predictions of magic gaps for superheavy nuclei.

Two experiments were performed to identify the γ rays and conversion electrons emitted in the decay of isomers in ^{254}No, which was formed with the ^{208}Pb(^{48}Ca,2n) reaction, using a 217 MeV (at mid-target) beam of ^{48}Ca from the ATLAS accelerator at Argonne. Evaporation residues of ^{254}No were transported and identified by their mass/charge ratio with the Fragment Mass Analyzer (FMA), then implanted into a 140 μm thick double-sided Si strip detector (DSSD) with 40x40 pixels, each with 1 mm^2 area. An isomeric decay in ^{254}No was identified by time and spatial correlations, namely an electron signal within 1 s of an evaporation residue in the same pixel as the implanted nucleus. The γ rays from the decay of an isomer were also detected, in prompt coincidence with an isomeric electron signal, in three large clover Ge detectors.

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Coexistence of cluster structure and mean-field-type structure in medium-weight nuclei

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We have studied the coexistence of cluster structure and mean-field-type structure in medium-weight nuclei using Antisymmetrized Molecular Dynamics (AMD) with a new type of constraint. We found that normal deformed and superdeformed bands of ^{40}Ca have non-small amount of -^{36}Ar and ^{12}C-^{28}Si cluster structures, respectively. Furthermore, we found -^{36}Ar higher-nodal band.

The dynamics of nuclear structure has many degrees of freedom. As well known, relative motion between clusters is an important degree of freedom at least in light nuclei. It is usually considered that deformation of mean-field (for example, prolate shape, oblate shape and so on) is more important in heavier nuclei. But it is an open problem whether cluster structure is important in medium- and heavy-weight nuclei or not. Recently, many superdeformed states are found experimentally in medium-weight nuclei. The relation between clustering and superdeformation is also important problem.

Our interest in the coexistence of cluster structure and mean-field-type structure is in medium and heavy-weight nucleus, especially in $N \quad Z \gtrsim 20$ nucleus. We consider that cluster structure can be developed well due to proton-neutron correlation and Coulomb interaction in this region. Furthermore, those nucleus are important as the path of rp-process.

In ^{40}Ca, it was suggested that $K = 0_2^+$ band has -^{36}Ar cluster structure theoretically,[1] and the suggestion was supported by the experiment of ^{36}Ar(^{6}Li, d)^{40}Ca reaction.[2] Furthermore, it was suggested that superdeformed band has ^{12}C-^{28}Si cluster structure.[3]

For studying coexistence of cluster structure and mean-field-type structure, we proposed a new constraint of clustering for AMD, namely d-constraint.[4] By energy variation with d-constraint and quadrupole deformation constraint, we calculated wave functions of -^{36}Ar cluster structure, ^{12}C-^{28}Si cluster structure and mean-field-type structure. Superposing these wave functions with various types of structures, we performed GCM calculation. We found that -^{36}Ar cluster structure and ^{12}C-^{28}Si cluster structure were important components of normal deformed and superdeformed bands of ^{40}Ca, respectively. Furthermore, we found -^{36}Ar higher-nodal band.

We will discuss effective interaction dependence between Gogny D1S and Skyrme (SLy7) force.

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Properties of ^{9}B* and ^{12}C* determined in β-decay and in the ^{10}B(^{3}He, pααα) reaction

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Somewhat surprisingly, the properties of the excited states in ^{12}C above the triple-*α* particle threshold are not well established [1]. The interest in this region comes both from *α*-cluster models and from the important impact the states have in nuclear astrophysics, especially to determine the rate of the triple alpha process responsible for helium burning in stars [2].

We report here combined results from a set of measurements where ^{12}C* is being studied using three different and complementary experimental procedures. In the first case; the β-delayed triple-α particle decay of ^{12}B and ^{12}N is studied in a highly segmented coincidence set-up, secondly; the same β-delayed reaction is being studied using the implantation technique [3]. Thirdly; the pααα coincidences from the low energy reaction ^{10}B(^{3}He, pααα) are being studied using the highly segmented coincidence set-up by letting ^{3}He of 2.45 MeV interact in a thin ^{10}B target.

The *β*-decay approach is exploited in a series of experiment carried out at the ISOL-facilities ISOLDE at CERN and IGISOL at Jyväskylä, Finland. There, the isotopes ^{12}N and ^{12}B are stopped in thin stopper foils in the centre of very efficient charged-particle detection setups (Double Sided Si strip detectors) which detect all three *α*-particles emitted from unbound states populated in these decays with high efficiency.

If instead the ^{12}N or ^{12}B nuclei are being implanted in the active area of a Si micro strip detector [4], the summed energy of the three *α*-particles will be measured. The advantage of this approach is that it is free from any energy-loss before the active area of the detector. Another advantage is that the implantation method holds the possibility of extracting absolute branching ratios in the decays since the number of implanted ions can be directly compared with the number of subsequent decays. The identity of the implanted ion is given by the implantation energy in the absence of isobaric contaminants in the beam.

The ^{3}He + ^{10}B reaction allows us to gain complementary information on both the ^{9}B and ^{12}C resonances compared to what is known from beta decay as we can populate states non accessible to the β-decay due to energy limitations and selection rules e.g. resonances with negative parity in ^{12}C or positive parity in the case of ^{9}B, as well as gain information on energy levels situated above the Q-beta values. The ^{9}B* + α channel gives us information on the states in ^{9}Be* [5], its mirror nucleus, which influences the ααn reaction and therefore also contributes to the helium burning. This reaction was studied before [6] in the 60's, but with very limited technology. With the development of segmented detectors [7] and fast electronics, detection of 4-particle coincidences with a much improved resolution is demonstrated.

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This work was supported through EURONS (European Commission contract no. 506065), and by the Spanish CICYT through project number FPA2005-02379.

Neutron Excess Nuclei of Hydrogen and Helium Studied at ACCULINNA

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Recent results on resonance states in ^{5}H and ^{9}He nuclei and on the search for a resonance state in ^{7}H, are presented. The reactions ^{3}H(t,p)^{5}H, ^{2}H(^{8}He,p)^{9}He, and ^{2}H(^{8}He,^{3}He)^{7}H were employed in these experiments made at beam energies of 58 MeV, in the case of triton projectile, and 180 MeV, in the case of ^{8}He.

In the context of clustering structures revealed in ^{6}He and ^{8}He by means of direct reactions new results are presented. These are data on the elastic and inelastic scattering and on the 1n and 2n transfer reactions occurring in the ^{8}He+p system at ^{8}He beam energy of 200 MeV. In an experiment, where 150 MeV ^{6}He projectile nuclei bombarded a helium gas target, the four-body ^{4}He(^{6}He,2α)nn breakup reaction was investigated in a geometry suitable for revealing quasi-free α,2α scattering events. The data are discussed in terms of correspondence between the observed $k_{n\text{-}n}$ *vs.* $Q_{nn\text{-}\alpha}$ momentum correlations and the ground state of ^{6}He.

Probing Single-Particle Structure near the Island of Inversion by Neutron Knockout from ^{26,28}Ne and ^{30,32}Mg *

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Nuclear shell structure is observed to evolve with increasing proton-neutron asymmetry, leading to the weakening of magic numbers well-established for stable nuclei and the appearance of new shell gaps [1]. A typical example is given by the neutron-rich region between the oxygen and magnesium isotopes where the $N = 20$ magic number is broken at ^{32}Mg and a new shell gap arises at $N = 16$. Modern large-scale shell model calculations employing the new SDPF-M effective interaction, which is valid for a broad range of nuclei in this region, propose a mechanism in which a number of nuclear structure phenomena are well reproduced [2]. A transitional region of nuclei in which the $N = 20$ magic number weakens is suggested to exist between the $N = 16$ and $N = 20$ isotones.

Nucleon knockout reactions from intermediate-energy ion beams are well suited for probing the single-particle structure of exotic nuclei [3]. Results are presented from the single-neutron knockout measurement from ^{26,28}Ne and ^{30,32}Mg. These nuclei lie in the proposed transitional region between the neutron-rich $N = 16$ and $N = 20$ isotones. For the ^{27}Ne knockout fragment, a near degeneracy of normal and intruder states is observed in agreement with SDPF-M predictions. While no evidence of a broken $N = 20$ magic number is found for ^{26}Ne, negative parity states in the ^{27}Ne and ^{29,31}Mg knockout residues are populated, yielding direct evidence of intruder configurations in the ground states of ^{28}Ne and ^{30,32}Mg. Spectroscopic strengths to these negative parity states are deduced and found to compare well with single-particle occupancies predicted in SDPF-M calculations, confirming the predictive power of the SDPF-M effective interaction in this region.

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*Supported by the United States National Science Foundation under contracts PHY-0110253 and PHY-0244453, by the UK Engineering and Physical Sciences Research Council (EPSRC) under Grant No. EP/D003628, by a Grant-in-Aid for Specially Promoted Research (13002001) and a Grant-in-Aid for Young Scientists (14740176) from the MEXT and by the RIKEN-CNS collaboration project on large-scale nuclear structure calculations.

Coupled SU(3) models of rotational states in nuclei and quasi-dynamical symmetry

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We will report a first step towards the development of a model of low lying nuclear collective states based on the progression from weak to strong coupling of a combinations of systems in multiple SU(3) irreps. The motivation for such a model comes partly from the remarkable persistence of rotational structure observed experimentally and in many model calculations. We consider the spectra obtainable by coupling just two SU(3) irreps by means of a quadrupole-quadrupole interaction. For a particular large value of this interaction, the two irreps combine to form a single (strongly-coupled) irrep while for zero interaction the weakly-coupled results are mixtures of many irreps. A notable result is the persistence of the rotor character of the low-energy states for a wide range of the interaction strength. Also notable is the fact that, for very weak interaction strengths, the rotational states of the yrast band approach those of a vibrational sequence while the B(E2)transition strengths remain close to those of an axially symmetric rotor.

Search for Chirality in Real Nuclei

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Chirality in nuclear rotation is a novel collective feature predicted for odd-odd nuclei from angular momentum coupling considerations [1]. In the work [1], it is pointed out that the rotation of triaxial nuclei may lead to the appearance of chiral doublet bands. The Interacting boson fermion-fermion model (IBFFM) [2] also well reproduce the level schemes of the chiral candidates, as for instance these in ^{134}Pr. In addition, crucial experimental observables for the understanding of nuclear structure and for checking the reliability of the theoretical models are the electromagnetic transition probabilities.

As it is pointed out in our recently published work [3], for the first time the lifetimes of the levels of the doublet bands in ^{134}Pr were measured by means of the recoil-distance Doppler-shift (RDDS) and Doppler-shift attenuation (DSAM) methods using the Euroball spectrometer and Cologne plunger device. Exited states in ^{134}Pr were populated in the fusion evaporation reaction ^{119}Sn(^{19}F,4n) ^{134}Pr. Reduced transition probabilities in ^{134}Pr are compared to the predictions of the two quasiparticle+triaxial rotor (TQPTR) and IBFF models. Our lifetime measurements and the theoretical analysis do not support static chirality in ^{134}Pr, as suggested on the basis of the similar energies of the two positive parity bands [1]. The experimental B(E2) values are larger in Band 1 than in Band 2 whereas the B(M1) values are slightly larger in Band 2 than in Band 1. The experimental difference between the B(E2) values cannot be reproduced assuming a rigid triaxial shape (TQPTR) which would also result in a pronounced staggering of the B(M1) values not found in the experimental data. The experimentally observed transition matrix elements can be reproduced by taking into account the fluctuations of the nuclear shape (IBFFM). This means that the chirality in ^{134}Pr if existing has mainly a dynamical character, the nuclear system fluctuating between chiral and achiral configurations, which couples the two sectors and generates the differences in the transition rates. Thereby the coupling due to shape fluctuations seems to play a central role. However, it may also indicate that the coupling of the two quasiparticles to the shape degrees of freedom is the prominent mechanism.

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3-D Unrestricted TDHF Calculations of Heavy-Ion Collisions

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We utilize the Time-Dependent Hartree-Fock (TDHF) method to calculate heavy-ion fusion cross sections for stable and neutron-rich nuclei. The calculations involve modern Skyrme forces and are carried out on a large 3-D Cartesian lattice using the Basis-Spline collocation method. We present TDHF studies without any spatial symmetry restrictions or time-reversal invariance assumptions. This introduces many additional terms into the Skyrme energy functional, including spin-currents and tensors [1]. The importance of these new terms will be discussed. One of the appealing features of TDHF is that one can follow the time-evolution of the nuclear density distributions during fusion, involving neck formation, surface vibrations and rotations of the system, which provides further insight in to the collision process. An example is shown in Fig.1.

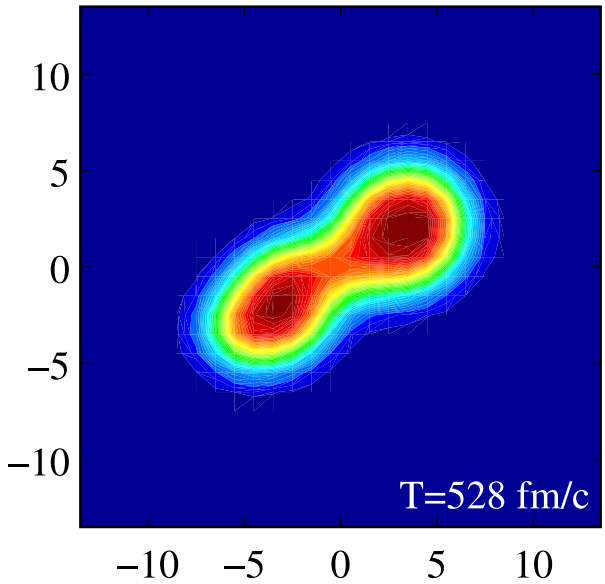

Figure 1: TDHF time-evolution for the $^{22}Ne+^{16}O$ collision at an impact parameter of $b = 6.35$ fm and initial Neon orientation angle $\beta = 60°$ using the SLy4 interaction. The initial energy is $E_{cm} = 95$ MeV. During the evolution the combined system makes four revolutions.

In the second part of the talk, we study fusion reactions of systems involving a spherical projectile and a deformed target nucleus. The computations involve two separate steps: first, a TDHF calculation for a given initial orientation of the deformed nucleus, and secondly a semiclassical time-dependent Coulomb excitation calculation to determine the relative orientation probability of the deformed nucleus near the distance of closest approach [2].

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Supported by U.S. Department of Energy grant DE-FG02-96ER40963 and by National Energy Research Scientific Computing Center.

Recent Progress in the Development of a Polarized Target for Reactions with Radioactive Ion Beams

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Polarization observables in nuclear reactions with stable beams have provided important information concerning not only structural properties of nuclei but also reaction mechanisms. Traditionally, polarized probes have been important in areas as diverse as resonant scattering, nuclear matter distributions, one and two nucleon transfer reactions, giant resonances and nuclear astrophysics. The exciting results obtained in the past combined with the need for new and efficient experimental tools in the field of radioactive ion beams (RIBs) have motivated an effort to explore polarization phenomena in the context of exotic nuclei.

We are currently developing a cryogenic target of polarized protons to be initially used in resonant scattering studies with RIBs [1]. Protons in plastic foils with thicknesses between 20 and 200μm are dynamically polarized via microwave irradiation in a magnetic field of 2.5T and at temperatures of ~0.1K. Once maximum polarization is achieved, the magnetic field is decreased to a value such that the beam and the recoils are able to reach the target and the detectors respectively while maintaining the target polarization at a reasonable value in the so-called frozen spin mode. The operation of such target system requires a cooling scheme where the target is situated in the isolation vacuum of a cryostat in open connection to the vacuum of the beamline. Two directions are being followed: the first one uses two parallel polarized foils mounted on a copper tube to form together a closed volume. Cooling of the foils is then achieved first by thermal contact with the copper tube and subsequently via a superfluid ^{4}He film that can be added through capillaries in between the foils. A second approach consists in placing a single plastic foil inside a small refrigeration chamber equipped with thin (~300nm), uniform silicon nitride windows. In both cases the polarization is monitored with a NMR coil attached to the target.

Recently we have performed several tests aimed to characterize the target system and to measure excitation functions of cross sections and analyzing powers using the thick target technique. An ideal reaction for a proof of principle is the scattering of ^{12}C by polarized protons in inverse kinematics, as the resonant nucleus exhibits levels well separated in energy, with well established values of angular momentum and the analyzing powers are well known from experiments with polarized beams of protons. Initial tests have been performed at the Injector 1 Cyclotron at PSI at energies of 38 and 80MeV. Beam intensities between 10^4 and 10^7pps have been obtained, which are in the range of currently available RIBs. We report on the results of these first measurements and the technical details of the experimental setup.

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*This work was supported by the U.S. Department of Energy under contract DE-AC05-00OR22725

Exploring the changing of shell structure of nuclei at N=50

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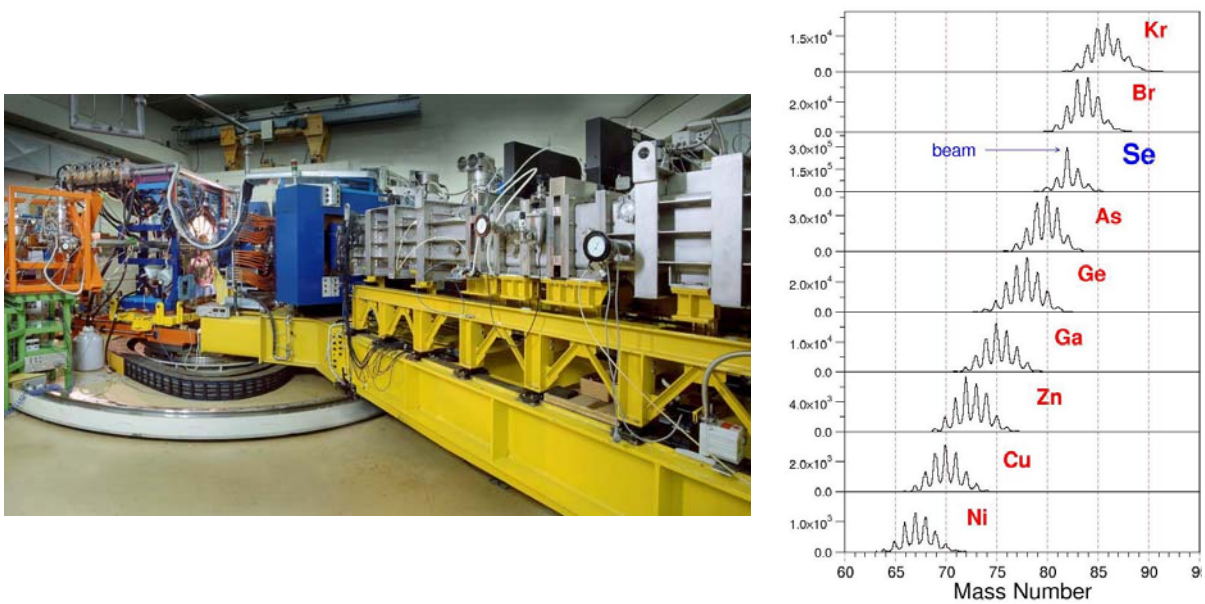
Future perspectives in nuclear structure both for proton and neutron rich nuclei rely on radioactive nuclear beams as well as on high intensity beams of stable ions. Especially for neutron rich nuclei, deep-inelastic and multi-nucleon transfer reactions can be used to populate yrast and non-yrast states. Particularly powerful is here the combination of large acceptance spectrometers with highly segmented γ-detector arrays. Such devices, eventually complemented by large coverage particle detectors, can provide the necessary channel selectivity to identify very rare signals. An example is the CLARA γ-ray detector array coupled with the PRISMA spectrometer at the Legnaro National Laboratories (LNL). The physics aims achievable with this setup complement studies performed with current radioactive beam (RIB) facilities.



Mass distributions(left) obtained with the PRISMA spectrometer (right) for the different elements populated in the $^{82}Se + ^{238}U$ reaction at 505 MeV of beam energy.

The study of nuclei with large proton/neutron ratios allow to probe the density dependence of the effective interaction. Changes of the nuclear density and size in nuclei with increasing N/Z ratios are expected to lead to different nuclear symmetries and excitations. Recent results obtained for the N= 50 shell closure will be presented.

Level density of ^{60}Ni from neutron evaporation spectra

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The level density of ^{60}Ni in the region below the particle separation energy has been obtained from neutron evaporation spectra measured in the ^{59}Co(d,n) and ^{58}Fe(^{3}He,n) reactions at the Edwards Accelerator Laboratory at Ohio University. The main limitation of such a technique is an unknown distortion of the neutron spectra due to direct and pre-equilibrium reaction mechanisms. The purpose of this experiment was to measure the level density of ^{60}Ni and estimate the contribution of the direct reaction mechanism, which is expected to be different for different incoming particles. The energy spectra and angular distribution of neutrons have been measured from both reactions. Both angular distributions exhibit a forward peaking shape due to the contribution from direct reaction mechanism The level density function has been extracted from neutron spectra taken from backward angles. The good statistics in the region of known discrete levels of residual ^{60}Ni allowed one the absolute normalization of the obtained level density function. The level densities of ^{60}Ni obtained from both reactions agree well, which indicates that the compound reaction is the major contribution to the differential reaction cross sections taken from backward angles. The Fermi-gas level density parameters have been obtained and compared to systematics.

Magnetic Rotation in Nuclei: A Brief Review and open Questions

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In the early 1990's very regular "rotational-like" sequencies of strongly enhanced magnetic dipole (M1) transitions were observed for the first time in near-spherical nuclei in the lead region [1,2]. These observations were subsequently explained using the tilted axis cranking model [3]. In contrast to normal rotational bands in deformed nuclei, this type of structure was interpreted as arising from a spontaneous symmetry breaking by anisotropic currents resulting from the occupation of a few nucleon orbits with large angular momenta. Whilst the first observation of these regular M1 bands was made with the TESSA 3 and OSIRIS generations of gamma ray detector arrays it was the use of much more powerful gamma spectrometers, such as Gammasphere, Eurogam and subsequently Euroball, that provided an opportunity to study the detailed properties of these structures in the lead and other mass regions. In recent years evidence for related structures, but this time composed of electric quadrupole transitions, has also been found in the light cadmium nuclei [4]. Many detailed review articles have been produced over the last few years covering both the experimental and theoretical aspects of these structures, see for example [5-7].

Some of the key experimental results will be reviewed along with their interpretation. This will primarily focus on the achievements of Gammasphere in helping to unravel the story behind a new mode of spin generation in nuclei. The talk will also attempt to highlight some of the outstanding issues which could potentially be explored in future using Gammasphere.

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New Spectroscopic Studies of the N=Z Nuclei ^{74}Rb, ^{76}Sr and ^{78}Y

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In recent years, Recoil decay tagging has been at the forefront of the study of excited states of heavy nuclei at the limits of stability [1]. In particular, Recoil-alpha tagging has been used for the study of nuclei with cross sections as low as 25 nb extracted from total production cross sections of 1 b [2]. Other tagging methods such as tagging with electron cascades, isomeric states, and protons have allowed state of the art research to be performed with very low fusion cross sections. However, tagging with electrons (positrons) from the β-decay, Recoil-beta tagging (RBT), at the focal plane of a recoil separator has not been successfully pursued. The difficulty can be attributed to the fact that the β-decay is a three body process, which means that there is no characteristic β-particle energy to tag on. Furthermore, beta decays usually involve much longer lifetimes compared to those of alpha and proton decays from nuclei near the proton drip line, thus making it difficult to observe correlations. There is however a distinct subset of nuclei, namely those odd-odd N = Z nuclei with $J^{\pi} = 0^{+}$ ground states, which decay almost entirely by the process of Fermi super-allowed beta decay. Such nuclei (particularly, in the mass 70 - 80 region) are suitable for study via the RBT technique due to their very short β-decay lifetimes and high end point energies.

A proof of technique experiment has been performed to study ^{74}Rb, where some γ-rays are already known to exist [3]. This was done at the University of Jyvaskyla using the GREAT spectrometer located at the focal plane of the RITU separator [4,5] and the JUROGAM γ-detector array at the target position was used to detect the prompt γ-rays. Results from this experiment will be discussed to demonstrate that clean identification of a reaction channel produced with a cross section much smaller than the total fusion cross-section can be achieved. The talk will also focus on a discussion of new results that have been obtained for T=0, 1 states in ^{74}Rb from the test experiment. In addition, the method has been used to perform the first identification of gamma transitions from excited states in the odd-odd N =Z nucleus ^{78}Y. These results will be presented. The talk will also reveal new high-spin results in the even-even N = Z nucleus ^{76}Sr which were obtained from a Gammasphere experiment. The latter data allow the yrast band in this nucleus to be observed beyond the $g_{9/2}$ proton and neutron band crossing for the first time and will be compared with recent cranked relativistic Hartree-Bogoliubov (CRHB) calculations [6].

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Strength of octupole correlations in the actinides *

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Octupole correlations have attracted much attention over the years, and the actinide nuclei remain an interesting source of information because they offer the possibility to investigate the interplay between collective rotation and octupole degrees of freedom. In previous work by I. Wiedenhöever *et al.* [1], it was suggested that, in the lightest Pu isotopes, strong octupole correlations lead to the absence (239, 240) or delay in frequency (238) of the strong proton alignment observed in the heavier (241, 242, 243, 244) Pu isotopes. More evidence supporting this suggestion has emerged from recent detailed studies in U and Pu nuclei with Gammasphere.

A series of so-called "unsafe" Coulomb excitation experiments has been carried out with Gammasphere at ATLAS. Ground state bands and octupole band structures have been identified in $^{237-239}$U and $^{236-244}$Pu. In contrast to its isotone ^{237}U, the energy differences in ^{239}Pu between states of same spin and opposite parity are getting smaller at high spin, and become almost degenerate at spin 53/2 [2]. In addition, in $^{238-240}$Pu the staggering factor, which is proportional to the energy difference between states of positive and negative parity (and, hence, measures the extent to which the two bands can be viewed as one), are getting smaller and comparable to those seen in nuclei with octupole deformation at high spin, while in their U isotones the staggering factors stay constant (above 200 keV). Furthermore, the $(I+1)^+ \rightarrow I^-$ E1 linking transitions were observed at high spin in ^{240}Pu, in addition to the $I^- \rightarrow (I-1)^+$ linking γ rays. This can be viewed as further evidence for an octupole rotor. Moreover, the estimation of the D_0 moments from the branching ratios between the inter- and in-band transitions, also supports the conclusion of stable octupole deformation present at high spins in the three lightest Pu isotopes. Additional indication of stronger octupole correlations in ^{239}Pu comes from the small difference between the decoupling parameters extracted for the $K = 1/2^+$ and $K = 1/2^-$ sequences. This is in contrast with the situation in ^{237}U, where the differences are much larger.

It has been shown that strong octupole correlations or stable octupole deformation impact the magnitude of the alignment gain i_x and its evolution with rotational frequency [3]. The $^{238-240}$Pu isotopes are strikingly different from the other nuclei in the neighboring region. At $\hbar\omega \sim 0.25$ MeV, the noticeable rise of alignment in other nuclei is absent in these three isotopes. All the data available today indicate that strong octupole correlations in these three Pu isotopes have a considerable impact on their structure and that a transition from an octupole vibration to stable octupole deformation occurs at high spin.

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*This work was supported by the U. S. Department of Energy, Office of Nuclear Physics, under contract NO. W31-109-ENG-38, and the National Science Foundation.

A global optical nuclear potential for nucleon-nucleus scattering

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A new global optical potential for elastic nucleon-nucleus scattering will be presented. This work was motivated by the advent of the recent generation of exotic nuclei accelerators. It has been fit to over 200 data sets within the nucleon projectile energy range of 40-160 MeV and a target size of $11<A<60$ where one potential in a Woods-Saxon basis describes both neutron and proton projectiles. The fits produced to stable and non-stable nuclei rival those of previous attempts by other authors; comparisons will be made. It is the hope that this potential will be a useful tool for experimental researchers who are working in this dynamic region of interest.

First measurement of the g factor of a mixed-symmetry state

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The first excited 2^+ state in collective even-even nuclei is a proton-neutron (pn) symmetric quadrupole excitation. An analog of this state is a so called mixed-symmetry state [1] with pn anti-symmetric parts in its wave function. In near-spherical nuclei, this state is also a one-phonon quadrupole excitation from the ground state, like its symmetric counterpart. It was identified in a number of nuclei close to magic shells, such as in the N=52 isotones [2.3.4], as well as in the vicinities of other shell closures.

Simplified, the symmetric and mixed-symmetry 2^+ states can be written as a superpositions of proton and neutron contributions, $|2^+_{\rm s}\rangle = |2^+_\nu\rangle + |2^+_\pi\rangle$, and $|2^+_{\rm ms}\rangle = |2^+_\nu\rangle - |2^+_\pi\rangle$, respectively [5]. While the pn content of the wave function of the $2^+_{\rm s}$ state has been determined in many cases from measurements of its g factor, such information is still missing for the $2^+_{\rm ms}$ state.

^{92}Zr and ^{94}Zr exhibit two states that have been identified as the symmetric and the mixed-symmetry one-phonon excitations. The first excited symmetric 2^+ states in both nuclei have a negative g factor [6] and therefore dominant neutron character.Thus the stable Zr isotopes present an ideal case for testing the two-configuration mixing assumption, as the mixed-symmetry 2^+ state should have a dominant proton character and a large positive g factor, as predicted by the shell model [4].

The lifetime of the mixed-symmetry state is 138(14) fs in ^{92}Zr [7] and almost twice as large in ^{94}Zr [8]. Hence ^{94}Zr was chosen as the best candidate for a g factor measurement. The experiment was carried out at the ESTU tandem accelerator at the Wright Nuclear Structure Laboratory at Yale University. A preliminary result of $g(2^+_{\rm ms}) = 0.6(3)$ confirms the assumption of a dominant proton configuration for the mixed-symmetry state.

This work was supported by the U. S. Department of Energy under contracts DE-FG02-91ER-40609, DE-FG52-05NA25929, and DE-FG02-88ER40417, and the U. S. National Science Foundation.

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Study of neutron-rich sd-pf shell nuclei using multi-nucleon transfer reactions*

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Nuclei in the sd-pf shell exhibit a rich variety of phenomena and physics. In nuclei far away from β-stability the neutron-proton interaction $V_{\sigma\tau}$ can become a driving force in determining the nuclear structure. Examples of this effect can be found in neutron-rich oxygen and fluorine isotopes. The latter can bind many more neutrons (up to ^{31}F) compared to oxygen (up to ^{24}O). The so-called "island of inversion" is another manifestation of the increased importance of the strong $V_{\sigma\tau}$ interaction. In this case the interaction between valence $f_{7/2}$ neutrons and $d_{5/2}$ protons favors the "intruder configuration" (corresponding to the promotion of a pair of neutrons across the N=20 shell to the $f_{7/2}$ orbital) and causes several N~20 nuclei (e.g. ^{30}Ne, ^{31}Na, ^{32}Mg) to have deformed ground-states despite having a "magic" number of neutrons. The understanding of the evolution of intruder configurations as protons are added along N~20 towards ^{40}Ca will provide important information on the underlying structure. Nuclei in this region have been mainly studied using reactions that are very selective. A more complete understanding of the nucleonic interplay and the underlying nuclear structure in the mass A~35 region can be obtained by applying less selective reaction mechanisms.

Two experiments were performed at the ATLAS facility of the Argonne National Laboratory to populate neutron-rich A~35 nuclei utilizing the reaction ^{208}Pb (^{36}S,X) at 230 MeV. In the first experiment a thin target of 0.5 mg/cm^2 was used to allow the reaction products to reach the particle detector. Identification of the target-like and projectile-like nature of the products as well as an event-by-event Doppler-shift correction was possible by utilizing the excellent spatial and timing resolution of the heavy-ion counter CHICO [1]. Gamma-radiation from the reactions was detected using GAMMASPHERE [2]. The second experiment utilized a 44 mg/cm^2 thick ^{208}Pb target providing high resolution GAMMASPHERE data. In addition to prompt gamma radiation both experiment were also sensitive to isomeric decay in the range of 10 ns to a few hundred ns. This allows for the search of new isomers in this mass region.

The analysis of the data sets reveals a wealth of information on neutron-rich Cl, S, P, Si, and Al isotopes. A detailed study of the intruder contributions and their effect in these nuclei is currently under way.
The observed level structures and transitions are compared to shell model calculations such as the Monte Carlo Shell Model using the SDPF interaction [3] and the Unified Shell Model Approach [4]. This comparison will test the models and help identify the underlying nuclear structure of the newly observed states.

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*This work was supported by the U.S. Department of Energy.

Production of light neutron-rich nuclei in fusion-evaporation reactions*

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Light neutron-rich nuclei provide an excellent opportunity to study the changes in nuclear shell structure that occur with increasing neutron number and are an important testing ground for shell model theories. Probably one of the most striking examples of shell modification is the occurrence of intruder ground states, which signal an inversion of the normal shell ordering. Intruder ground states are observed around ^{32}Mg (Z=10-12), "the island of inversion", and in ^{11}Be. An analogous situation appears in the Z=2 He isotopes, where the intrusion of sd excitations in p-shell configurations becomes important in the heavy helium isotopes. Finally, for Z=8, recent data on ^{20}O [1] show a reduction in the p-sd shell gap with increasing neutron number. It remains an open question whether the observed diminishing of the p-sd shell gap is restricted to O and F isotopes or extends also to neighboring nuclei.

In this talk I will discuss our work to extend the experimental data on light neutron-rich nuclei and to map the changes in shell structure. I will focus on new results on ^{18}N (Z=7), which is sufficiently far from stability to exhibit modified shell structure and yet still within the reach of stable beam facilities. ^{18}N was produced in the ^{9}Be(^{11}B,2p)^{18}N reaction at the 88" Cyclotron at LBNL and studied using the LIBERACE-STARS detector array – an array of large area segmented silicon detectors (E-ΔE) and six HPGe Clover detectors. A key aspect of this experiment was the use of a fusion-evaporation reaction to populate ^{18}N. So far, information on the excited states of ^{18}N has been obtained from ^{18}C beta-decay [2] and charge-exchange reactions [3]. These are highly selective reactions, while the fusion-evaporation reaction used here can provide a more comprehensive picture of the excitation spectrum. A second key aspect of the experiment was to use the 2 proton reaction channel. The large q-value for protons suppressed the evaporation of neutrons in conjunction with the 2p channel at the chosen beam energy. In this experiment the 2p tag uniquely identified the weak (sub milli-barn) ^{18}N products.

The ^{18}N γ-ray spectrum is shown in Fig 1. New transitions were observed at 629 and 301 keV. We estimate a limit of <20 ns for the lifetime of the state decaying by the 116 keV γ-ray. This is far shorter than the value of >600ns given in ref [2], from beta decay. The latest experimental observations will be compared to shell model calculations, and cross section for ^{18}N will be compared to various evaporation codes to test their predictive power in light neutron-rich systems.

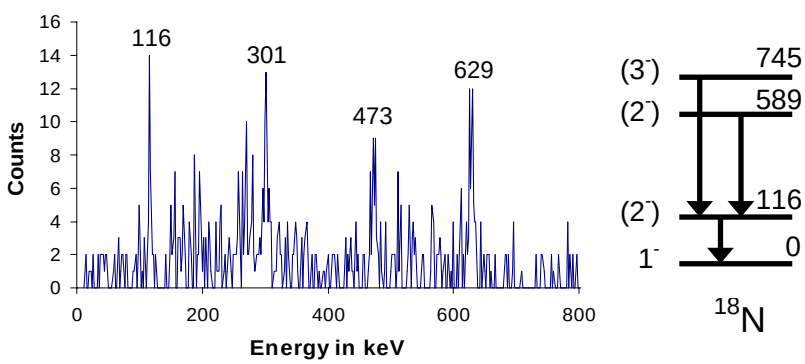

FIG. 1. 2p gated gamma-ray spectra obtained from the reaction ^{9}Be(^{11}B,2p)^{18}N and part of the ^{18}N level scheme.

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*This work was supported by the U.S. Department of Energy, Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 and Livermore National Laboratory under Contract No. W-7405-Eng-48.

Excitation Energies and Decay of Superdeformed States

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During the 1990s, many experiments were carried out aimed at studying superdeformation in nuclei with A≈190 using the Gammasphere, Eurogam II and Euroball III/IV arrays. Among the reasons for this focus were theoretical predictions that the superdeformed (SD) minimum in this mass region occurs at relatively low excitation energy and persists to spin I=0, allowing the description of the yrast SD bandhead as a quasi-vacuum configuration or "SD ground state". Through these experiments, great progress was made in mapping this island of superdeformation. Unfortunately, the fundamental properties of the SD states - that is, their excitation energy, spin and parity - were only successfully measured in a very small number of cases [1,2,3,4]. Since one of the primary motivations for studies of SD nuclei is the opportunity they offer to test nuclear models under extreme conditions, this represented a real problem; without the excitation energies and quantum numbers, no such tests can be made.

The process by which the decay from the second minimum occurs became another focus of theoretical attention. The interest arose in part because of the surprising rapidity with which the decay occurs - in every known case, the bands lose all of their intensity from just two or three consecutive levels. A variety of models of the decay have been put forward [5], but as yet neither the cause of the abrupt decay and nor the reason for the remarkable similarity of the decay profile over a wide range of isotopes has been established.

More recently, new results have been obtained both through work on discrete decays [6,7] and the application of quasi-continuum analysis techniques [8,9]. These results open up the opportunity for systematic studies of properties such as binding energies and two-particle separation energies in the SD well. They are the first steps in the process that will allow the accurate characterization of the SD shell gaps, and provide an important benchmark for meanfield models. They also provide excellent opportunities to compare the decay processes from bands at well-established but markedly different excitation energies along a single isotope chain.

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Fusion reaction of halo nuclei: A real-time wave-packet method for three-body tunneling dynamics

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There has been a long standing controversy on the role of halo nucleon in the fusion process. To obtain deep and reliable understanding on the reaction mechanism, we have been developing a time-dependent wave-packet approach [3]. We describe the reaction as a three-body problem, and the three-body Schrödinger equation is solved accurately with the time-dependent method. The wave-packet approach has several favorable aspects. First we can obtain intuitive picture for the reaction dynamics by visualizing the wave-packet dynamics. Indeed the significance of the Coulomb breakup effect is clearly seen in the wave-packet animation which we show in Fig.1. Second, it is not necessary to consider the complicated boundary condition for the three-body breakup channels. Third, very high partial waves in the projectile can be incorporated which we found are important to obtain convergent fusion probability.
We previously reported fusion probabilities of halo nuclei mostly for the case of the head-on collision [3]. We now include a full range of impact parameter, for $0 \leq J \leq 30$, then, for the first time, present results of fusion cross sections calculated with the time-dependent wave-packet method. Calculations are performed for fusion cross sections of ^{11}Be - ^{209}Bi and ^{6}He - ^{238}U for which recent measurements are available [1, 2]. We show results for ^{11}Be reaction in Fig.2. Recent experiments suggest that the halo neutron does not enhance fusion cross section [1, 2]. Our calculation suggests even slight suppresion of the fusion cross section by adding a halo neutron.

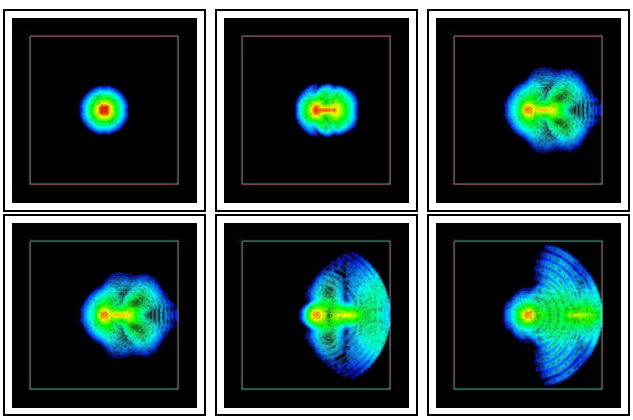

Figure 1: Time evolution of the density distribution of the halo neutron in the rest frame of the projectile. From top-left to bottom-right. A significant breakup and transfer components are seen toward the target (right direction).

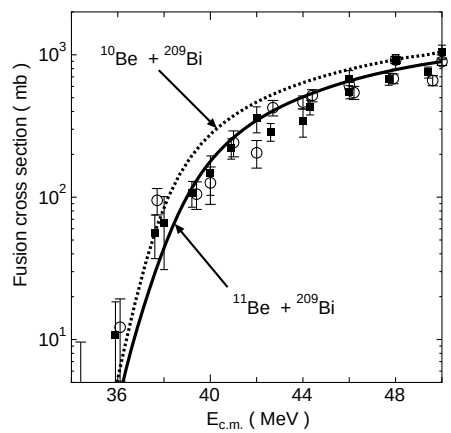

Figure 2: Calculated fusion cross section of ^{11}Be and ^{10}Be on ^{209}Bi, in comparison with measurement [1, 2].

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Pairing and continuum effects for low-frequency vibrational excitations

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Independent particle motion is a key concept to understand microscopic mechanisms of various deformations and collective excitations in atomic nuclei. Stable nuclei are spatially well localized system in which only tightly-bound orbits are involved in the low-energy properties, on the other hand, weakly-bound nuclei are unique systems in which many-body correlations between weakly-bound orbits and continuum states play essential roles.

In the present study, I point out that the novel spatial structure of quasiparticle wave functions caused by pairing correlations and coupling to continuum states [1,2] plays crucial role to produce coherency among two-quasiparticle states in weakly-bound nuclei; namely the microscopic mechanisms for emergence of collective motions in unstable nuclei are essentially different from those in stable nuclei. The distinctive effects on low-frequency vibrational excitations are emphasized by performing the Hartree-Fock-Bogoliubov (HFB) plus quasiparticle random phase approximation (QRPA) calculation for the first 2^+ states in neutron-rich Ni isotopes. In Fig.1, the $B(E2)$ values obtained by the HFB plus QRPA calculation with Skyrme SLy4 force are shown. For comparison, the results obtained by the resonant BCS plus QRPA and RPA calculations are also plotted. While approaching the neutron drip line, the $B(E2)$ values in the HFB plus QRPA increase, but decrease in the resonant BCS plus QRPA, and much smaller in the RPA calculation. The crucial role of qualitative change of the spatial structure of quasiparticle wave functions by pairing and continuum effects, that is taken into account in the HFB plus QRPA calculation, is obviously shown [2].

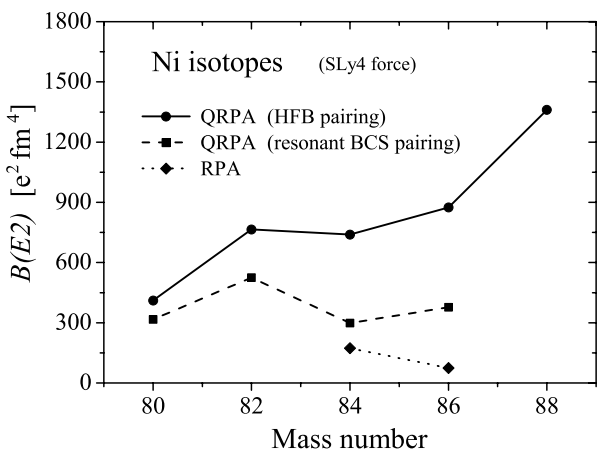

Figure 1: The $B(E2)$ values of the first 2^+ states in neutron rich Ni isotopes obtained by the HFB plus QRPA, resonant BCS plus QRPA, and RPA calculations with Skyrme SLy4 force.

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Di-neutron correlation in deformed neutron-rich Mg isotopes

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Di-neutron correlation in nuclei close to the neutron drip line is one of the current issues being investigated extensively. In light two neutron halo nuclei ^{6}He and ^{11}Li, the pairing correlation between the valence neutrons plays a decisive role for the binding, and it is suggested that the two halo neutrons display an attractive correlation in such a way that they are spatially localized with respect to their relative distance, in a range smaller than the size of the nuclear matter radius. Recently, Matsuo *et al.* pointed out the presence of di-neutron correlation in medium mass nuclei based on the Hartree-Fock-Bogoliubov (HFB) calculation [1]. However their analysis was limited to spherical nuclei which are far outside experimentally reachable regions.

In the present study, I explore the possibility of di-neutron correlation in neutron rich Mg isotopes, $^{36-40}$Mg, which are expected to be reachable in the next generation radioactive beam facilities. Because their ground states have prolate deformation [2], I perform the HFB calculation allowing axially symmetric deformation by developing a new computer code based on the 2D polar coordinate representation. An indication of di-neutron correlation is the coupling to continuum states with unlikely high Ω, z-component of single-particle angular momentum. This new grid representation is suitable to take into account the coupling accurately. The analysis using the two-body correlation density concludes the presence of the di-neutron correlation in $^{36-40}$Mg (see Fig.1), and the influence on the soft $K^{\pi} = 0^{+}$ vibrational modes is studied.

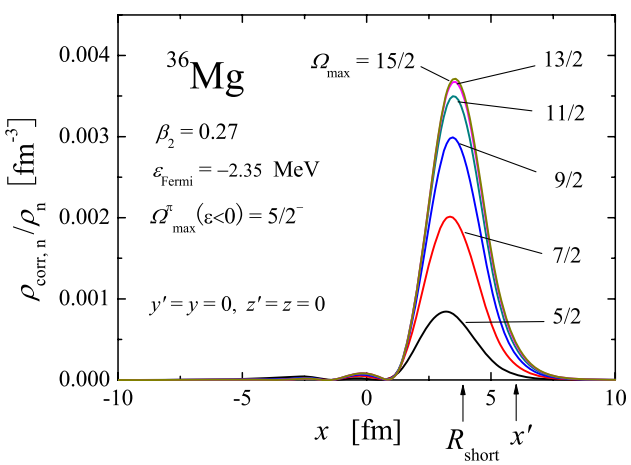

Figure 1: Dependence of the neutron two-body correlation density, $\rho_{corr,n}(\vec{r}\uparrow, \vec{r}'\downarrow)/\rho_n(\vec{r}'\downarrow)$, on Ω_{max} in prolately deformed ^{36}Mg. Here Ω_{max} is the maximum value of Ω in our HFB calculation. The symmetry axis is chosen to be the z axis. The two-body correlation density is plotted as a function of $\vec{r} = (x, 0, 0)$. The reference neutron position $\vec{r}' = (x', 0, 0)$ is fixed at the external position $x' = R_{short} + 2$ fm, where R_{short} is the half density radius on the x axis.

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Sensitivity of soft vibrational modes on quadrupole deformations in ^{32}Mg and ^{34}Mg

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Presently, the breaking of N=20 spherical magic number and striking enhancements of $B(E2; 0_1^+ \to 2_1^+)$ in ^{32}Mg and ^{34}Mg are under lively discussions in connection with onset of quadrupole deformation, pairing correlation and the continuum coupling effects. In order to get clear understanding of the nature of quadrupole deformation and pairing correlations in these nuclei, it is strongly desired to explore, both experimentally and theoretically, excitation spectra of these nuclei. For this aim, we have recently constructed a new computer code which carries out deformed Quasiparticle-RPA calculations based on the coordinate-space Hartree-Fock-Bogoliubov formalism. Using this code, we made a detailed analyses of the interplay among the quadrupole particle-hole, the monopole-pairing and the quadrupole-pairing correlations in building up low-frequency vibrational excitations in neutron-rich Mg isotopes. In these systematic calculations, the deformed Woods-Saxon potential, the Skyrme-type interaction without the momentum dependent terms and the density dependent contact pairing interaction were used. The HFB equations were solved on the two-dimensional lattice consisting of the cylindrical coordinates. We are particularly interested in the question how the properties of low-frequency collective modes depend on the magnitude of static quadrupole deformation β_2 of the mean field. Thus, we carried out a systematic Quasiparticle-RPA calculation treating β_2 as a parameter and investigated how the properties of these modes change as function of β_2. Figure 1 shows the calculated excitation energies and isoscalar quadrupole (octupole) strengths for the lowest $K^\pi = 0^+$ and 2^+ (0^- and 1^-) excitation modes in ^{32}Mg and ^{34}Mg. We obtained strongly collective $K^\pi = 0^+$ modes (carrying $50 \sim 80$ W.u. in intrinsic strengths) at about 2 MeV in the $\beta_2 = 0.3 \sim 0.5$ region; they are mainly generated by neutron pair fluctuation associated with the monopole and the quadrupole pairing correlations. It was found that the quadrupole pairing significantly enhances the pair transfer strengths to these $K^\pi = 0^+$ excited states. The γ-vibrational-type collective $K^\pi = 2^+$ modes were obtained at about 3 MeV in the deformed region with $\beta_2 \geq 0.3$; they are generated by coherent two-quasiparticle excitations of neutrons and protons. It is clearly seen in Fig. 1 that the transition strengths for octupole vibrational excitations greatly increase as the quadrupole deformation grows. In the superdeformed region ($\beta_2 \sim 0.6$), the intrinsic transition strength becomes about 100 W.u. for the $K^\pi = 0^-$ mode. On the basis of these theoretical calculations, we suggest that the octupole strengths will be greatly enhanced if the ground states of ^{32}Mg and ^{34}Mg are strongly deformed.

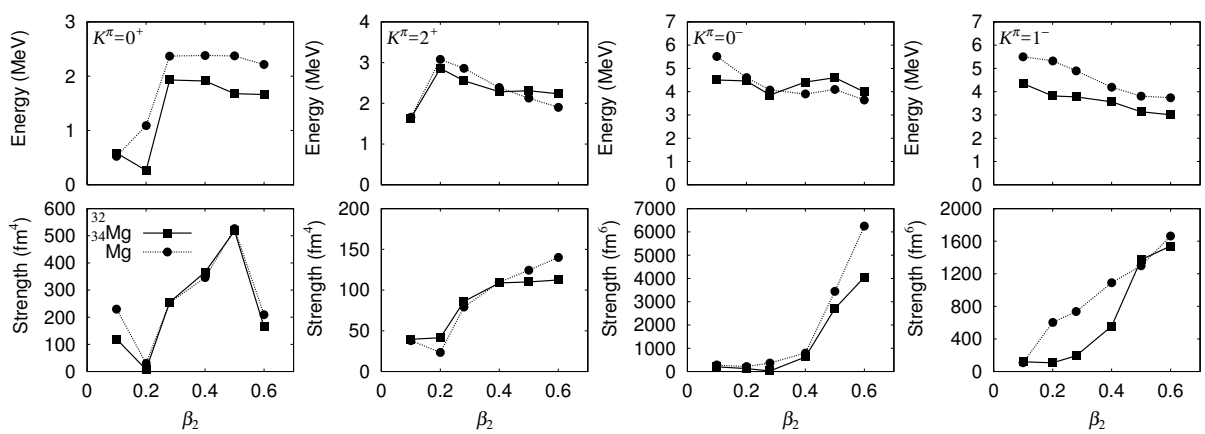

Figure 1: Excitation energies [*upper panel*] and isoscalar quadrupole (octupole) strengths [*lower panel*] for the lowest $K^\pi = 0^+$, 2^+, 0^- and 1^- excitation modes in ^{32,34}Mg, plotted as functions of the static quadrupole deformation parameter β_2 of the mean field. The filled squares and the filled circles indicate the calculated values for ^{32}Mg and ^{34}Mg, respectively.

A quadrupole-coupling model for doublet bands in doubly odd-nuclei

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One of the most intriguing phenomena discussed in medium and heavy nuclei is the appearance of the nearly degenerate doublet bands in doubly odd nuclei. Previously these bands were interpreted as a manifestation of the chiral doublet bands. However, most of recent experiments and analyses do not support this interpretation. Recently we proposed a pair truncated shell model (PTSM) where the even-even core made by the collective pairs couples with a neutron and a proton in high-j orbitals [1]. The PTSM successfully describes the properties of doubly odd nuclei, both energy spectra and features of electromagnetic transitions [2-3]. However it is not easy to extend its applicability to nuclei far from the magic numbers and moreover the structure of the wave-functions is rather complicated to analyze.

In this talk we propose a quadrupole coupling model (QCM) in which the even-even core couples with a neutron and a proton in the $h_{11/2}$ intruder orbitals through a quadrupole-quadrupole interaction. In the QCM we assume that the doubly-odd nucleus with the neutron number N and the proton number Z consists of the even-even core made by the N-1 neutrons and Z-1 protons, a neutron and a proton in $h_{11/2}$ orbitals. In the usually particle-rotor approach it is assumed that the core is a rigid rotor, but in this model we do not have such an assumption. The information of the core is experimentally provided by the excitation energies of the corresponding even-even nucleus.

It is well known that the staggering of B(M1)/B(E2) ratios for the yrast bands is observed for certain nuclei, such as in ^{130}Cs and ^{134}La, but not observed in ^{134}Pr, which was believed to be a good candidate for chiral doublet bands. Figure 1 shows the comparison of B(M1)/B(E2) ratios in ^{134}Pr. It is seen from the figure that the present theoretical approach well describes the behavior of the B(M1)/B(E2) ratios.

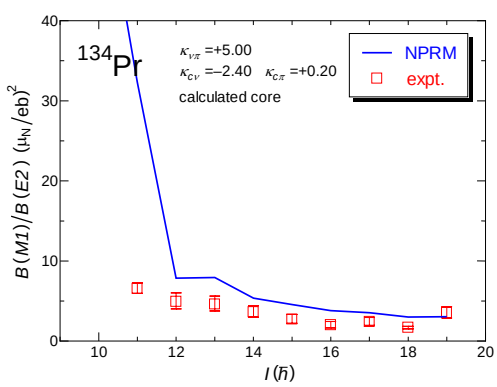

FIG. 1. Comparison of B(M1)/B(E2) ratios for the yrast bands between theory (NPRM) and experiment (expt.)

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Coulomb Excitation of Odd-A Neutron-Rich Radioactive Beams Near ^{132}Sn *

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Coulomb excitation of even-even neutron-rich nuclei near ^{132}Sn has been a tremendous success [1] at the Holifield Radioactive Ion Beam Facility (HRIBF). Because of the more complicated level structures in an odd-A or odd-odd nucleus, extending such studies to odd-mass nuclei is in general difficult. However, studies of odd-A and odd-odd nuclei are important, since they often provide additional information on nuclear structure that cannot be obtained from even-even nuclei. This paper reports results from the first experiment at the HRIBF aimed at studying heavy odd-A neutron-rich nuclei via Coulomb excitation.

By using a 400-MeV A=129 radioactive beam and ^{50}Ti targets, excited states in ^{129}Sb and ^{129}Te were populated by Coulomb excitations. The CLARION, Hyball, and a Bragg detector were used to detect gamma rays, charged particles, and to monitor the beam composition, respectfully. Doppler corrected (event-by-event) gamma rays that are correlated with the ^{50}Ti ions were obtained and peaks in the resulting spectrum were identified as in ^{129}Sb or ^{129}Te, which were the main components of the mixed beam. Data analysis resulted in B(E2) values for four transitions in ^{129}Sb. These values are compared to B(E2)'s measured [2] in ^{123}Sb, the heaviest odd-A Sb isotope for which B(E2) measurements exist prior to our study, see Fig. 1(a). The B(E2) values shown in Fig. 1(a) indicate similar trends between ^{123}Sb and ^{129}Sb. However, the newly measured B(E2, $7/2^+ \rightarrow 3/2^+$) in ^{129}Sb is substantially smaller than that in ^{123}Sb. The excitation from the $7/2^+$-ground state to the $11/2^+$-excited state in ^{129}Sb is considered to be a single $g_{7/2}$ proton coupled to the $0^+ \rightarrow 2^+$ excitation of its even-even core. Therefore, normalized B(E2, $7/2^+ \rightarrow 11/2^+$)'s in ^{129}Sb and ^{123}Sb are compared to B(E2, $0^+ \rightarrow 2^+$)'s in their even-even neighbors in Fig. 1(b). This comparison shows that the coupling of the $g_{7/2}$ proton seems to have the effect of reducing the B(E2) values. Both this and the phenomenon shown in Fig. 1(a) call for further theoretical investigations, which may provide valuable information on single proton levels in this region.

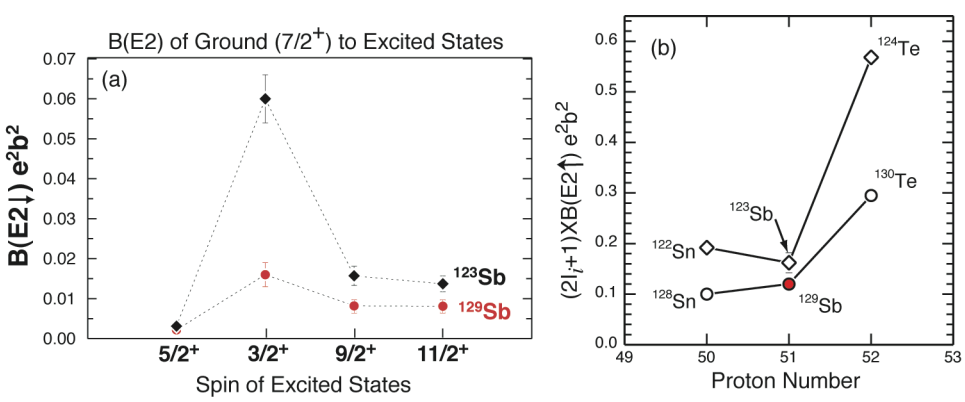

FIGURE 1: (a) B(E2) values corresponding to excitations from the ground state ($7/2^+$) to four excited states measured in ^{129}Sb from this work (circles) compared to those measured [2] previously in ^{123}Sb (diamonds). (b) B(E2, $7/2^+ \rightarrow 11/2^+$)'s deduced for ^{129}Sb (this work) and ^{123}Sb [2] compared to B(E2, $0^+ \rightarrow 2^+$)'s [3] in their even-even neighbors.

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*This work was supported by the U.S. DOE under contract # DE-AC05-00OR22725

Triaxial Strongly Deformed Bands in ^{171,172}Hf? *

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Wobbling, a unique excitation mode of nuclei with triaxial deformation, has been established in ^{163,165,167}Lu and, possibly, ^{161}Lu [1]. A number of strongly deformed (SD) bands were also identified in neighboring $^{168,170,173-175}$Hf [2], but the predicted wobbling mode was not observed. Whether these Hf bands are triaxial (TSD) or not remains an open question. In our Gammasphere experiment at ANL using the ^{48}Ca(^{128}Te, xn) reaction, three proposed SD bands in ^{172}Hf and one in ^{171}Hf, extending up to $111/2^+$, were identified with intensities 0.9% - 3.7%, respectively. The three bands in ^{172}Hf have very similar dynamical moments of inertia ($J^{(2)}$), but the linking transitions between them, the characteristic of wobbling sequences, could not be found. The $J^{(2)}$ values of the SD bands in Hf fall into two groups, one increasing and the other decreasing (see figure). All three bands in group-A (with increasing $J^{(2)}$ values) are linked to known structures with definitive spin/parity assignments. Quasiparticle configurations involving $(\pi i_{13/2})^2 \otimes (\nu i_{13/2})^2$ or $\pi(i_{13/2} i_{11/2}) \otimes (\nu i_{13/2})^2$ were proposed for these bands. The bands in group-B seem to have higher spins and excitation energies, with deformations significantly larger than that of bands in group-A and Lu, most likely resulting from additional quasi-neutrons occupying $(\nu j_{15/2})^2$ orbitals. The Hf bands have very different intrinsic structures than the Lu bands. Theoretical calculations (cranking, particle-rotor, and RPA) agree fairly well with observations in Lu nuclei. It is also possible that Hf bands in group-A are associated with the predicted TSD minima. However, serious disagreement between calculated and measured properties of bands in group-B, majority of SD bands in Hf, constitutes a challenge for further investigations of triaxiality for nuclei in this region.

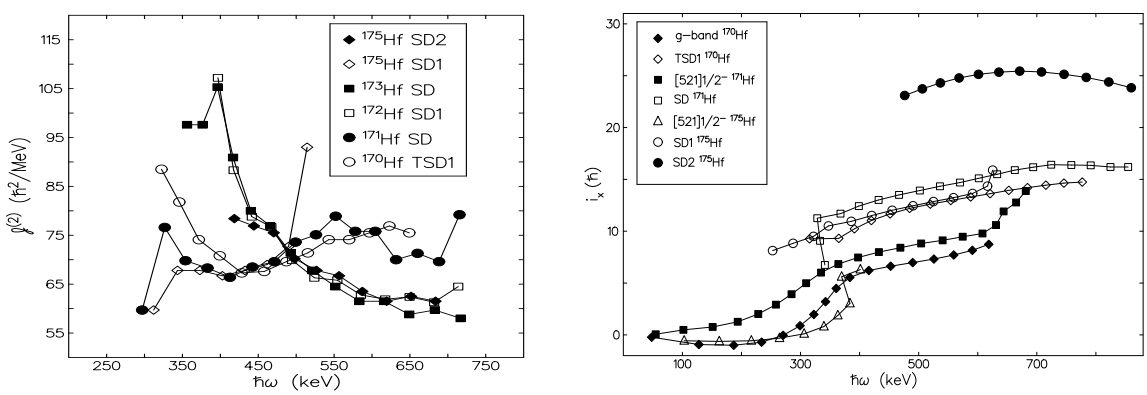

FIG. 1. Dynamical moments of inertia and alignments of SD bands in Hf isotopes.

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[2] D. J. Hartley *et al.*, Phys. Lett. **B** 608, 31 (2005), and references therein.

*This work was supported by the DOE (MSU, ANL, UML, UT) and the NSF (USNA).

Even-parity Bands in ^{108,110,112}Ru

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Earlier theoretical calculations[1] of Hartree-Fock energy surfaces suggested a shape transition from near prolate spheroidal to triaxial in going from 108 to 110 and 112 in Ru. Triaxial deformation also was proposed in level structure studies[2].

By accumulating 5.7×10^{11} triple or higher fold events with Gammasphere following the spontaneous fission of ^{252}Cf we have considerably extended and expanded the level schemes of ^{108,110,112}Ru. The even-parity ground band and γ-vibrational bands in these neutron-rich nuclei now reach ~ 20^+ and ~17^+, respectively. Two-phonon quasi-γ-vibrational bands are identified in ^{110,112}Ru. Total Routhian Surface (TRS) calculations suggest triaxial shapes with γ–values of -22°, -25° and -29° at $\hbar\omega$ = 0 MeV, and -27°, -32° -59° at $\hbar\omega$ = 0.4 MeV in ^{108}Ru, ^{110}Ru and ^{112}Ru, respectively. The soft and sharp band crossings in their ground bands are interpreted by CSM calculations as alignment of an $h_{11/2}$ neutron pair. The signature-splitting in the γ bands is quite unusual with ^{110}Ru having the smallest splitting among the three but surprisingly the signature splitting of ^{108}Ru is reversed in comparison to those of $^{110,\ 112}$Ru (see Fig. 1). These data could be interpreted in terms of a γ-soft ^{108}Ru and more rigid triaxial ^{112}Ru, but the suddenness of the shift is unexpected and not consistent with the γ values from TRS calculations. Moreover, a curious bifurcation of the ground-state band in ^{110}Ru is observed above the sharp band crossing at 12^+ with levels of same spin and parity very close-lying.

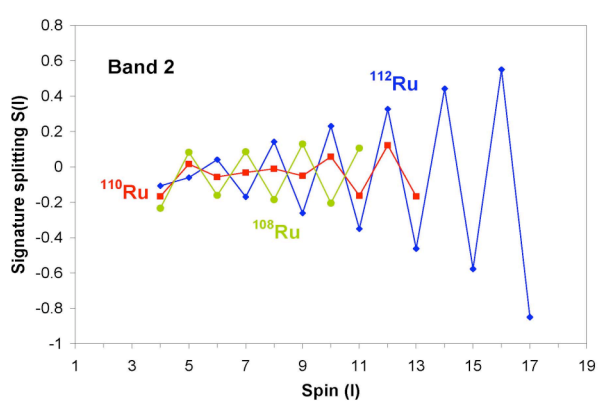

Fig. 1 Signature splitting of the γ-vibrational band.

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Deep Inelastic Reactions with CHICO: The Case of ^{48}Ca + ^{208}Pb *

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Over the last few years, our collaboration has initiated a program to investigate the properties of neutron-rich nuclei above doubly-magic ^{48}Ca. At the onset, the primary motivation for these studies was the expectation that substantial modifications can occur to the intrinsic shell structure of nuclei with a sizable neutron excess [1,2]. Deep inelastic reactions on thick targets with ^{48}Ca beams are one of the experimental approaches we have utilized. In the experiments, the γ rays were detected by Gammasphere [3]. The success of this approach has been demonstrated in a number of publications on the onset of a new shell gap at $N = 32$ in the neutron-rich Ti and Cr isotopes [2,4]. Our experimental results have also led to a number of shell-model calculations with the most modern interactions.

However, due to Doppler broadening effects, the method used thus far was not sensitive to fast transitions emitted before the nuclei are fully stopped. The transitions from higher spins, or from collective states, which are lost in thick target data, can be detected with proper Doppler correction if a thin target is used and the direction of the emitting nucleus is determined. These transitions are important for testing further theoretical calculations, and search for signatures of collectivity.

The experiment was performed with a 285 MeV ^{48}Ca beam bombarding on a 1 mg/cm^2 ^{208}Pb target at ATLAS. The heavy-ion counter CHICO [5] was used to detect the target-like and projectile-like products at the same time. The γ rays, emitted in flight by both reaction products, were detected by Gammasphere. Event-by-event Doppler correction was applied based on the velocity vectors of the reaction partners determined from the intrinsic position and time information of CHICO, and the direction of the emitted γ rays given by the position of the Ge detectors in Gammasphere. CHICO was calibrated with events corresponding to Rutherford scattering. The energy losses of the reaction products in the target vary with scattering angle for the target-like and projectile-like products. Therefore, an iterative method was applied to determine the masses of the binary products. Energy losses were also subtracted for the determination of their velocities. With an average velocity of about 10% of the speed of light, the FWHM of γ rays from projectile-like fragments was about 1.5% after Doppler correction. New transitions, which were totally absent in the thick target experiment, have been observed. The level scheme of ^{49}Sc, for example, was extended to higher energy. ^{50}Ca and ^{50}Ti are among the other nuclei where fast transitions were observed for the first time. A detailed account of the technique and the results will be presented.

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*This work was supported by the U. S. Department of Energy, Office of Nuclear Physics, under contract NO. W31-109-ENG-38, and the National Science Foundation.

Structure of the Even-Even Neutron-Rich ^{56,58,60}Cr Isotopes *

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The existence of the $N = 32$ sub-shell above doubly-magic ^{48}Ca has been firmly established in a series of recent experiments [1,2]. Shell model calculations with the GXPF1A effective interaction are able to account for this gap as resulting from a weakening of the $\pi 1f_{7/2} - \nu 1f_{5/2}$ proton-neutron monopole interaction as protons are removed from the $1f_{7/2}$ orbital, combined with a significant $\nu 2p_{1/2}$-$\nu 2p_{3/2}$ spin-orbit splitting [3]. With the $\pi f_{7/2}$ shell half-filled, Cr isotopes are among the nuclei best suited for studying the possible role of collectivity in the region. Recent studies of odd, neutron-rich Cr isotopes above $N = 32$ indicate an increasing involvement of the shape-driving $g_{9/2}$ orbital in the low-lying structure of neutron-rich Cr isotopes [4]. Experimental information on the excited states in the even-even, neutron-rich Cr nuclei provides further tests of the suitability of the *fp* shell-model space for the description of their level structure and of the possible shape-driving influence of the $\nu g_{9/2}$ orbital.

The yrast states of the neutron-rich Cr isotopes were populated via two deep inelastic reactions of ^{48}Ca on 50 mg/cm^2 ^{208}Pb and ^{238}U targets at beam energies ~20% above the Coulomb barrier. Another approach used here for producing neutron-rich Cr isotopes involved fusion of ^{48}Ca projectiles with ^{14}C radioactive targets (thickness $100\mu g/cm^2$, ~ 90% enrichment). The beam energy was selected as 130 MeV to optimize two-proton evaporation producing ^{60}Cr. Reaction products were dispersed according to their charge-to-mass (A/q) ratio with the Fragment Mass Analyzer (FMA). An ion chamber behind the focal plane was used to provide Z resolution and separate ^{60}Cr residues from other isotopes with stronger yields.

The deduced level schemes of ^{56,58,60}Cr represent significant extensions over previous knowledge. Specifically, despite a low-spin structure reflecting the $N = 32$ sub-shell closure in ^{56}Cr, evidence was found at higher energy for a negative-parity sequence associated with prolate, collective rotation. This band exhibits striking similarities with those seen in the odd neighbors ^{55,57}Cr. The data collected for ^{58}Cr demonstrate unambiguously that the level scheme proposed recently by Marginean *et al.* [5] from a PRISMA + CLARA experiment is in error, raising considerable doubt about an interpretation in terms of a $E(5)$ dynamical symmetry proposed in the latter work. In addition, the lowest observed negative-parity state in ^{58}Cr is ~1.1 MeV lower than that in ^{56}Cr, a trend similar to that exhibited by the $9/2^+$ ($\nu g_{9/2}$) bandheads in the odd Cr neighbors. Furthermore, the properties of the sequence built on this negative-parity state differ significantly from those seen in ^{56}Cr, consistent with the spherical or slightly oblate shape proposed for ^{59}Cr by Freeman *et al.* [6]. The yrast sequence observed for the first time in ^{60}Cr is also consistent with an interpretation in terms of an oblate deformation.

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*This work was supported by the U. S. Department of Energy, Office of Nuclear Physics, under contract NO. W31-109-ENG-38, and the National Science Foundation.

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