The structure of isobaric excitations in N=Z nuclei *

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The isobaric excitations provide invaluable information on the pairing component of effective nuclear forces in $N \sim Z$ nuclei. The aim of this paper (see Ref. [1] for details) is to discuss the necessary extensions to the mean-field approximation in order to account in a consistent manner for (**i**) the Wigner energy, (**ii**) the T=1 and T=2 states in even-even (e-e) N=Z nuclei as well as (**iii**) T=0 and T=1 states in odd-odd (o-o) N=Z nuclei. We argue that this goal can be achieved when the model includes simultanously isoscalar and isovector pairing correlations and takes into account [at least approximately] number- and isospin projection. The latter is realized within the simple cranking approximation which provides a deeper understanding of the underlying physics through a number of analogies to well known high-spin phenomena. Furthermore, we show that within such a framework also the standard BCS treatment of nuclear pairing does not longer apply. The necessary modifications are schematically drawn in Fig. 1 [left part] and can be summarized as follows: (**i**) The T=2 states in e-e nuclei and T=1 in o-o nuclei are obtained by iso-cranking the vacuum state [false vacuum for the case of o-o nucleus] so that $T_x = \sqrt{T(T+1)}$; (**ii**) The T=1 states in e-e nuclei require two-quasiparticle (2qp) excitations and subsequent iso-cranking; (**iii**) The T=0 states in o-o nuclei [or more generally the minimal isospin states T=$|N-Z|/2$ in o-o nuclei] are 2qp states. The numerical estimates of the excitation energies of T=2 and T=1 states in e-e N=Z nuclei and the difference between excitation energies of T=1 and T=0 states in o-o N=Z nuclei are shown in Fig. 1 [right panel]. The agreement between theory and experiment is indeed excellent. For further details concerning these calculations we refere reader to Ref. [1].

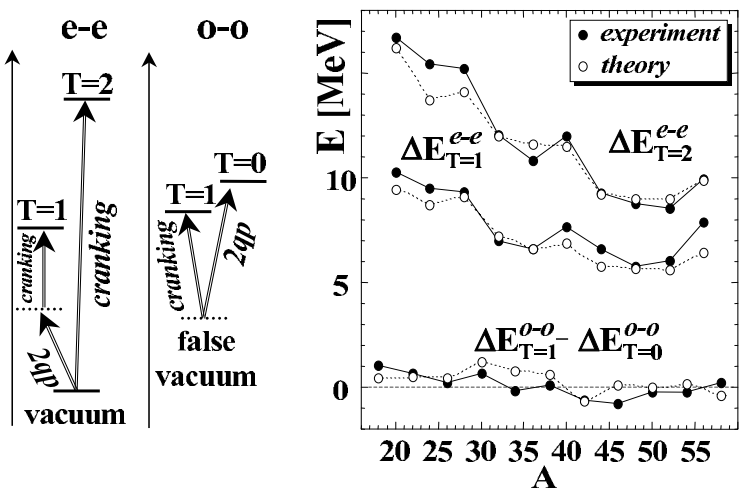

FIG. 1. Schematic illustration of the calculation scheme [left] applied to compute excitation energies of T=0,1, and 2 isobaric excitations in N=Z nuclei [right].

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Three-body observables for the low energy breakup of dripline nuclei

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Breakup reactions are frequently used to probe properties of nuclei at the edge of stability, considering their propensity for falling apart, arising from very low binding energies. From a theoretical point of view, these reactions become particularly challenging at low energies. Then, most approximations are not suitable, and a rich interplay of multistep processes, multipolarity mixing and nuclear-Coulomb interference, are present. The new generation ISOL facilities reflect the need for a solid theoretical description of low energy breakup reactions.

The great technological improvements on radioactive beams and detection systems, offering much better statistics, allow for detailed exclusive/coincidence measurements where before only integrated observables were possible to obtain. Theoretically, it is essential that the full kinematics is incorporated in the calculation and that observables for each specific experimental setup can be constructed.

In this talk, we review the Continuum Discretised Coupled Channels (CDCC) method for calculating the breakup of loosely bound projectiles $a = b + x$, where the $b + x$ continuum is explicitly included [1]. As an application, we discuss in detail the results for the breakup of ^{8}B on ^{58}Ni at 26 MeV, measured at the Notre Dame Laboratory [2-3].

The Coulomb Dissociation process has been suggested as providing an indirect measurement of low energy direct capture reactions with astrophysical interest. The Notre Dame ^{8}B breakup experiment was initially designed to determine the relative strength of the E2 component in the Coulomb Dissociation process, an important ingredient that has generated some controversy in the community [4]. The DWBA calculations for this reaction [5] predicted a very large nuclear contribution for the ^{8}B* centre of mass (c.o.m.) cross section, an effect that was already present for impact parameters as large as 20 fm. The first CDCC results for this reaction [6] found that the ^{8}B angular distribution was extremely sensitive in particular to the continuum-continuum couplings. A strong multipole nuclear-Coulomb interference was evident in those results.

From the CDCC two-body scattering amplitude it is possible to construct the triple differential cross sections (such as $d^3\sigma/d\Omega_b d\Omega_x dE_b$) with full three-body kinematics, necessary to describe the inclusive measurements in [2-3]. These observables contain more information of the physical process than the integrated c.o.m. angular cross sections reported in [6]. Also, the CDCC model space has to be larger in order to obtain stable results. We show that the three-body observables display even more clearly the importance of higher order effects present in the low energy breakup of loosely bound projectiles.

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Formation of superheavy elements in heavy-ions collisions

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The process of the synthesis of *superheavy elements* (SHEs) is not yet understood completely. In the presented work [1,2] we make an attempt to describe the cold fusion reactions of the type X + (Pb,Bi) → SHE + 1n at subbarrier and near barrier energies. The process of the formation of SHEs is subdivided into three steps. 1. The capture of two spherical nuclei and the formation of a common shape of the two touching nuclei. Low-energy surface vibrations and transfer of few nucleons are taken into account in the first step of the reaction. 2. The formation of a spherical or near spherical compound nucleus. 3. The surviving of the excited compound nucleus due to evaporation of neutrons and γ-ray emission in competition with fission. The following reactions were analyzed in detail: (^{58}Fe, ^{64}Ni, ^{70}Zn, ^{78}Ge) + ^{207}Pb, (^{50}Ti, ^{54}Cr, ^{58}Fe, ^{59}Co, ^{62,64}Ni, ^{65}Cu, ^{66,68,70}Zn, ^{71}Ga, ^{74,76,78}Ge, ^{75}As, ^{80,82}Se, ^{86}Kr, ^{87}Rb, ^{88}Sr) + ^{208}Pb, (^{58}Fe, ^{64}Ni, ^{70}Zn, ^{78}Ge) + ^{210}Pb and (^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni, ^{70}Zn, ^{78}Ge, ^{86}Kr) + ^{209}Bi. The presented model describes well the available experimental cross-section data for elements with Z=104-112,118 (see fig also) and allows for predicting cross-section values for the synthesis of so far unknown heavier elements.
The SHE production in reactions with similar target and projectile [(^{124}Sn, ^{130,136}Xe) + ^{136}Xe] is considered. Reactions with similar target and projectile may be very important for determination of chemical properties of SHEs due to high reaction cross sections, see fig. The calculations are made for two different values of inner barrier, which taken place at the shape evolution stage.

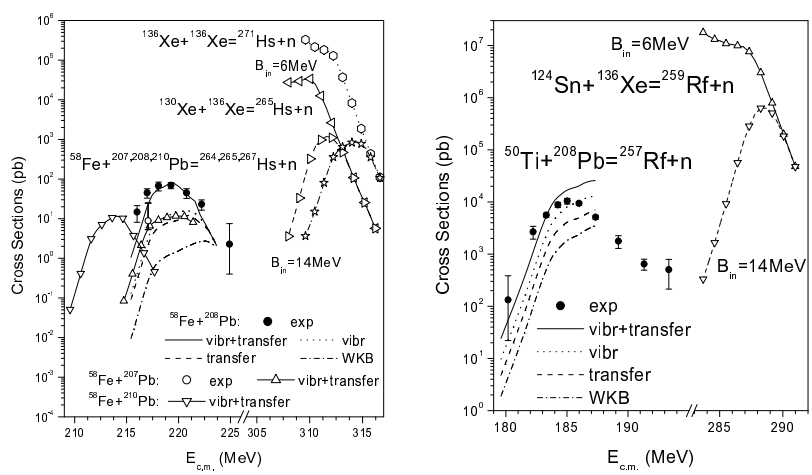

FIG. 1. Calculated excitation functions for the reactions ^{58}Fe+^{207,208,210}Pb →^{264,265,267}Hs+n and ^{130,136}Xe+^{136}Xe →^{265,271}Hs+n (left) and ^{50}Ti+^{208}Pb →^{257}Rf+n and ^{124}Sn+^{136}Xe →^{259}Hs+n (right). The continuous curve shows the results which take into account for both the low-energy 2^+ and 3^- vibrations and the neutrons transfer channels. For reactions ^{58}Fe+^{208}Pb →^{265}Hs+n and ^{50}Ti+^{208}Pb →^{257}Rf+n the dotted and the dashed curves show the results based on solely the 2^+ and 3^- vibrations and the neutron transfer channels, respectively. The results of the one-dimensional WKB approach last two reactions are shown by the dash-dotted curves. The results of calculations including both vibrations and transfer enhancements obtained for other reactions are additionally marked by symbols, see assignments in figs. The experimental data are taken from [3,4].

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Subbarrier heavy ions fusion enhanced by subbarrier nucleons transfer and subbarrier fusion of nuclei far from the β-stability line

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We discuss a semiclassical model for the description of subbarrier fusion of heavy ions which takes into account the coupling to the low-energy surface vibrational states and to the few-nucleon transfer with arbitrary reaction Q-value. The subbarrier transfer of nucleons during barrier penetration is described by using the WKB approach and does not use special proposal on the low-energy behavior of the transfer coupling. The coupling with the low-energy surface vibrations in the model is considered by using traditional simplified coupled channels approach [2,3]. This model is correct in the case of nucleons transfer with the large positive Q-value. The fusion reactions ^{32}S + ^{100}Mo, ^{36}S + ^{96}Mo, ^{28,30}Si + ^{58,62,64}Ni, ^{28}Si + ^{94,100}Mo, ^{40}Ca+^{90,96}Zr, ^{16,18,20,22,24}O + ^{58}Ni and ^{28}Si + ^{124,126,128,130,132}Sn are analyzed in the framework of this model. The calculated fusion cross section, mean angular momentum and its dispersion for these reactions are good agreed with available experimental data. It is shown that the fusion cross sections and mean angular momentum quantities are significantly enhanced by few-nucleon transfer with large positive Q-value, see fig for example.

This model is applied for the fusion reactions between nuclei near to the neutron drip line and nuclei close to the β-stability line. The neutrons transfer has extremely large positive Q-value and small values of neutrons separation energy for such collision systems. The fusion reactions ^{18,20,22,24}O + ^{58}Ni and ^{28}Si + ^{124,126,128,130,132}Sn are discussed in detail, see fig. It is shown that the subbarrier fusion cross sections and the mean angular momenta are strongly enhanced by neutrons transfer for these reactions. It is found, that the slope of energy dependence of subbarrier fusion cross section is changed due to neutron transfer. The maximums are appeared in the energy dependencies of the both mean angular momentum and its dispersion in the case of neutron transfer with positive Q-value.

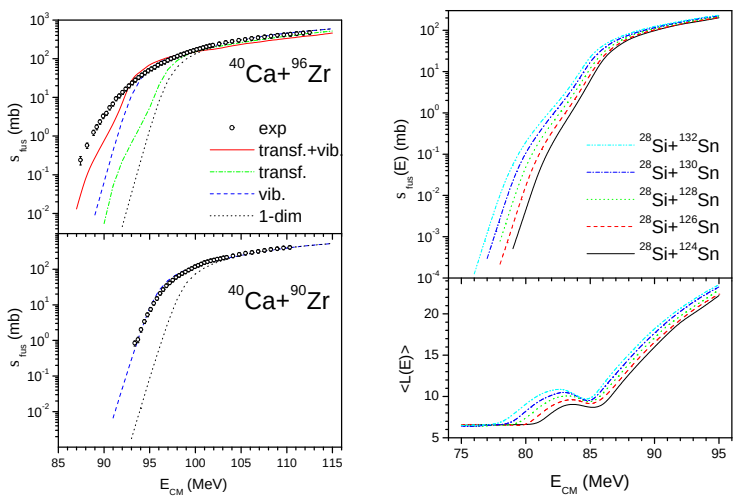

FIG. 1. Left: Fusion cross sections for the reactions ^{40}Ca+^{96}Zr (top) and ^{40}Ca+^{90}Zr (bottom). Experimental data (dots) are taken from [4]. Right: Fusion cross section (top) and mean angular momentum (bottom) for the reactions ^{28}Si+^{124,126,128,130,132}Sn.

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Recent Applications of the Shell Model Embedded in the Continuum

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Astrophysical models of stars rely strongly on certain characteristics (e.g. astrophysical factors) of nuclei involved in the chains and cycles of thermonuclear reactions [1]. Many of these reactions involve weakly stable or unstable nuclei. The influence of scattering continuum on the structure of bound and quasi-bound states in these nuclei becomes very important, making standard nuclear structure theories hard to justify. On the other hand, these nuclei are good candidates to be described as open quantum systems, where all the couplings between (quasi-)bound and scattering states are accurately taken into account.

Our aim is to apply the quantum open system formalism to describe phenomena in nuclei close to the drip lines using the Shell Model Embedded in the Continuum (SMEC). This formalism relies on the explicit division of the Hilbert space of the Schrödinger equation into two disjointed subspaces, namely the subspace of (quasi-)bound states and the subspace of scattering states [2]. At the initial stage, the first one is described by means of the usual nuclear shell model and the other one in terms of coupled channels equations. Then all the couplings between these subspaces are taken into account in terms of the residual nucleon-nucleon interaction. This modifies the scattering solutions as well as the spectroscopic quantities on the structure side. The crucial modification is that the effective Hamiltonian is no longer hermitian and resonance states acquire a width which is directly related to the imaginary parts of these Hamiltonian eigenvalues. As a result, both the structure of nuclei and cross sections are modified [3].

I report on our recent results concerning the astrophysical factor for the reaction ^{7}Be$(p,\gamma)^8$B and the elastic cross section for ^{16}O$(p,p)^{16}$O. I present also the extension of this model for the description of emission of one or two protons from a dicrete state with the example of the second 1^- state of ^{18}Ne [4].

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THE THEORY OF CONTROLLING THE SPONTANEOUS GAMMA-DECAY OF EXCITED AND RADIOACTIVE NUCLEI

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The paper discusses the theory of controlling gamma-radioactivity of nuclear sources and targets. For the first time we have created the theory of influence on the probability of spontaneous radiation and life-time of gamma-radioactive nuclei [1]. We have considered the general system which included the excited nucleus, the system of this nucleus electrons, the system of zero-energy (in vacuum state) electromagnetic modes and the system of N resonant or non-resonant atoms (screen) situated at the distance $L \gg \lambda_{eg}$ from the excited nucleus. The phenomenon of spontaneous nucleus decay controlling is a result of interaction of the excited nucleus with zero-energy electromagnetic modes, interaction of these modes with the atoms of screen, interaction of the excited nucleus with electrons system.

It is shown for the first time that the decay parameters greatly depend on the sign and magnitude of the radiation shift (radiation correction) of the resonance level position (nuclear analog of the Lamb shift for atom electrons.) This shift is determined by processes of nucleus interaction with all zero-energy electromagnetic field modes (the lowest by energy or ground). It was shown that the resonant screen effect in all cases appears to be more significant than for the nonresonant one. It is shown for the first time that the most influence on the nucleus spontaneous decay process will be realized in the case when the modes of the electromagnetic field in the zero-energy state, which interact with the nucleus, occur to be mutually synchronized. For this case the radiative life-time may be increased by many orders of magnitude.

The methods of the gamma-decay optimization (e.g. change by several orders of spontaneous radiative life-time) is also discussed

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Relativistic Mean-Field Description of Exotic Nuclear Structure

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Models based on the relativistic mean-field approximation provide a microscopically consistent, and yet simple and economical description of the nuclear many-body problem. By adjusting just a few model parameters: coupling constants and effective masses to global properties of simple spherical nuclei, it has been possible to describe many nuclear structure phenomena, not only in nuclei along the valley of β-stability, but also in exotic nuclei with extreme isospin values and close to the particle drip lines.

The relativistic Hartree-Bogoliubov model has been applied in studies of structure phenomena that include: the strong isospin dependence of the effective spin-orbit interaction and the resulting modification of surface properties, the suppression of the spherical $N = 28$ shell gap for neutron-rich nuclei and the related phenomenon of deformation and shape coexistence, the structure of the proton drip line nuclei in the region $31 \leq Z \leq 73$, and ground-state proton radioactivity in nuclei $53 \leq Z \leq 73$. The model has also been used to calculate parity violating elastic electron scattering on neutron-rich nuclei, and neutron density distributions for atomic parity nonconservation experiments. The relativistic random phase approximation, based on effective mean-field Lagrangians with nonlinear meson self-interaction terms, has been used in the analysis of the dynamics of isoscalar dipole modes and of the structure of pygmy resonances.

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THE METHOD OF SPATIAL 3-D DETECTING OF REMOTE OR SOLITARY RADIOACTIVE SOURCES BY CORRELATION OF INTENSITY OF RADIATION

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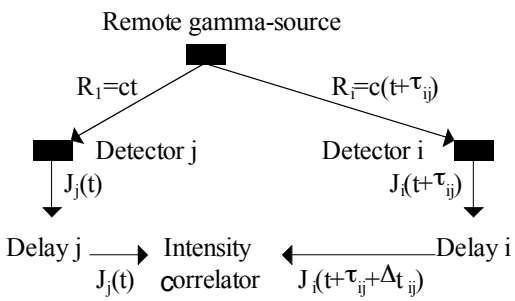
The intensity correlation method of spatial and angular (three-dimensional) location of solitary or remote sources of gamma-radiation or neutrons is suggested and studied. The main idea of the method is based on the phenomenon of pair correlation of intensities $J_j(t) = \varepsilon_j |\xi_j(t)|^2$ and $J_i(t+\tau_{ij}) = \varepsilon_i |\xi_i(t+\tau_{ij})|^2$ of gamma-radiation measured by two separated detectors i and j [1]. Here $\xi_k(t) = \Sigma_n \Psi_k(\mathbf{R}_k, t-t_{kn})$ are sums of pulse spherical waves $\Psi_k(\mathbf{R}_k, t-t_{kn}) \equiv F(t-t_{kn})\exp(i\mathbf{k}\mathbf{R}_k)/R_k$ of gamma-radiation coming from a remote gamma-source, location $\mathbf{r}_o$ of which is to be found. The pair correlation function $K_{ij}(\tau_{ij})$ of intensities $J_j(t)$ and $J_i(t+\tau_{ij})$ for two spatially separated independent detectors, situated at $\mathbf{r}_i = \mathbf{R}_i+\mathbf{r}_o$, $\mathbf{r}_j = \mathbf{R}_j+\mathbf{r}_o$ and having the effectiveness ε_i and ε_j of the quantum detecting, equals



$$K_{ij}(\tau_{ij}) = \langle J_i(t)\, J_j(t+\tau_{ij})\rangle - \langle J_i(t)\rangle \langle J_j(t+\tau_{ij})\rangle.$$

Here $\tau_{ij} = (R_i-R_j)/c$ is the time-delay of measured intensities $J_j(t)$ and $J_i(t+\tau_{ij})$ in different detectors i and j from the same remote detected gamma-source.

For the studied case of quasi-stationary source of gamma-radiation and for the usual case of the random Gaussian process of quanta detecting $\xi_k(t)$ the correlation function of intensity has the form

$$K_{ij}(\tau_{ij}) = \varepsilon_i\varepsilon_j \{\langle\xi_i(t)\, \xi_i^*(t)\rangle \langle\xi_j(t+\tau_{ij})\, \xi_j^*(t+\tau_{ij})\rangle + \langle\xi_i(t)\, \xi_j(t+\tau_{ij})\rangle \langle\xi_i^*(t)\, \xi_j^*(t+\tau_{ij})\rangle + \langle\xi_i(t)\, \xi_j^*(t+\tau_{ij})\rangle \langle\xi_i^*(t)\, \xi_j(t+\tau_{ij})\rangle\} - \langle J_i(t)\rangle \langle J_j(t+\tau_{ij})\rangle = \varepsilon_i\varepsilon_j |\langle\xi_i(t)\, \xi_j^*(t+\tau_{ij})\rangle|^2 = \langle n_i\rangle \langle n_j\rangle \left|\int_{-\Delta\omega/2}^{\Delta\omega/2} |F(\omega)|^2 \exp(-i\omega\tau_{ij})\, d\omega\right|^2.$$

Here $F(\omega) = \int_{-\infty}^{\infty} F(t)\exp(-i\omega t)\, dt$; $|F(\omega)|^2$ - the spectral intensity (having the spectral half-width $\delta\omega$) of the single detected gamma-quantum after detector (on the exit of detector); $\Delta\omega$ - the spectral band of the intensity correlator (signal acquisition and processing system); $\langle n_i\rangle$ and $\langle n_j\rangle$ are the averaged quantity of detected gamma-quanta in the detectors i and j.

For the usual case $\Delta\omega<\delta\omega$ we have the correlation function

$$K_{ij}(\tau_{ij}) \approx 4\langle n_i\rangle \langle n_j\rangle |F(0)|^4 |\sin(\Delta\omega\tau_{ij})/\tau_{ij}|^2.$$

The maximum value of this correlation function is equal $K_{ij}(0)= 4\langle n_i\rangle \langle n_j\rangle |F(0)|^4 |\Delta\omega|^2$ and corresponds to the additional delay $\Delta t_{ij} = -\tau_{ij}$ of the registered intensity signal $J_i(t+\tau_{ij})$ from one of the detectors (i) or both detectors (i and j) introduced in the correlator.

For three-dimensional location of the remote source of gamma-radiation it is necessary to use three or more spatially separated independent detectors, situated at $\mathbf{r}_1$, $\mathbf{r}_2$, $\mathbf{r}_3$,..., and three or more independent intensity correlators. For this case the position of the detected remote source $\mathbf{r_0}=\{x_0, y_0, z_0\}$ of gamma-radiation may be calculated using the system of equations

$$[(x_i- x_0)^2+(y_i- y_0)^2+(z_i-z_0)^2]^{1/2} + c\Delta t_{ij} = [(x_j- x_0)^2+(y_j - y_0)^2+(z_j-z_0)^2]^{1/2};$$

for maximum values of correlation functions $K_{ij}(0)$ for different pairs ij ($i\neq j$=1,2,3...) of gamma-detectors.

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HFB theory for nuclei near the drip-lines: continuum coupling *

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Near the neutron or proton drip lines, large pairing correlations are expected which can no longer be described by a small residual interaction. Furthermore, the outermost nucleons are weakly bound (which implies a large spatial extent), and they are strongly coupled to the particle continuum. These features represent major challenges for the mean field theories.

We solve the Hartree-Fock-Bogoliubov equations for deformed, axially symmetric even-even nuclei on a two-dimensional lattice. High accuracy is achieved by representing the operators and wavefunctions in terms of Basis-Splines; a combination of the Galerkin and collocation method is utilized [1]. This work represents a natural extension of the 1-D calculations for spherical nuclei by Dobaczewski et al. [2]. Test results for ^{22}Ne using a Skyrme mean field and a constant pairing Hamiltonian are shown in Fig. 1. The HFB lattice Hamiltonian has been directly diagonalized using LAPACK yielding a quasiparticle energy spectrum up to $E_n = 2000$ MeV. In calculating observables, we cut off this spectrum at an equivalent s.p. energy of about 60 MeV. These first results are a successful test of our numerical algorithm to perform pairing calculations in two dimensions for nuclei near the drip lines. Calculations with realistic pairing interactions (density-dependent delta-forces) are now underway.

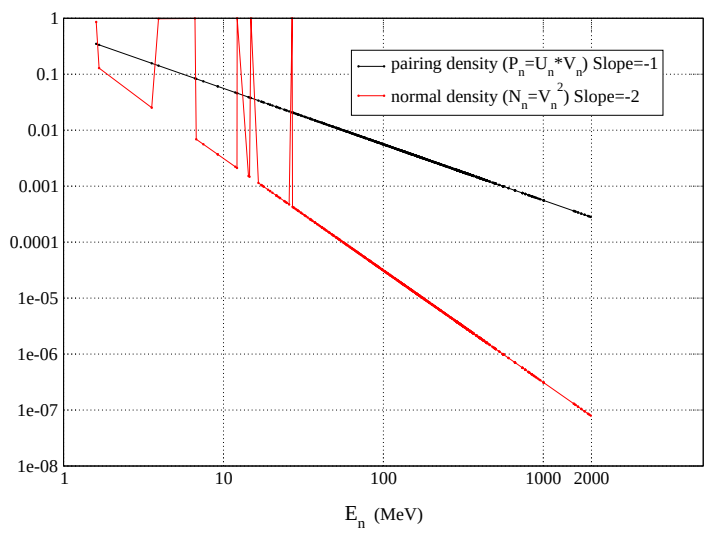

FIG. 1. Quasiparticle energy spectrum of normal and paring densities.

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Possibilities to describe the production of rare isotopes close to drip-line in the Fermi energy domain *

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In the Fermi energy domain, the production of rare isotopes with large neutron/proton excess has to be considered as a two step process including the production of excited nucleus in the first stage and its de-excitation in the latter stage. The deep inelastic transfer and the incomplete fusion determined by a geometric overlap of nuclei are assumed as a production mechanisms of excited nuclei. A cooling via emission of fast pre-equilibrium particles is introduced in an approximate way using simple phenomenological assumptions. Various modes of de-excitation ranging from particle evaporation to statistical multifragmentation are examined. A possibility to describe a broad range of data in both symmetric and asymmetric systems and in normal and inverse kinematics will be discussed (see also [1]).

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Isospin Dynamics in Fusion Processes: Collective Dipole Bremsstrahlung

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We evaluate the pre-equilibrium Dipole photon radiation accompanying the fusion of charge asymmetric ions. Following a semiclassical approach we estimate the collective bremsstrahlung emission in a fusion dynamics described via a microscopic quantum transport model.

We study energy, charge and mass dependence of this contribution to the Giant Dipole Resonance (GDR) photon emission in hot nuclei.

The dynamical origin of the extra GDR strength will show up in a characteristic anisotropy of the dipole γ-emission, being this dipole oscillation constrained on the reaction plane.

We stress the interest in experiments with the new available radioactive beams. Apart the importance of a better analysis of this new pre-equilibrium phenomenon, we suggest the possibility of using such characteristic signal to select fusion paths in dissipative collisions with exotic nuclei.

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Damping of giant resonances in non-Markovian approach *

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The relaxation mechanisms of collective motion and temperature dependence of the damping widths in many-body systems have been much investigated during recent years. In this contribution the damping widths of the giant dipole resonances in heated nuclei are calculated and discussed on the base of the semiclassical second RPA[1] as well as within the nuclear fluid-dynamics method[2,3].

The expression for collisional relaxation time, τ_c, is taken within framework of two approaches: ***i***) it is calculated using the non- Markovian collision integral of the Landau-Vlasov transport equation[4]; ***ii)*** the time τ_c is obtained on the base of decay rates of the interparticle interactions within framework of the exciton model[5]. The collision integral in approach ***i)*** is taken in a modified form with allowance for reaching the local equilibrium in system. In particular, in the approach ***ii)*** a dependence of the $\tau_c(\omega, T)$ on collective vibration frequency and the temperature agrees with that one from[6], when the mean square matrix element of interparticle collision from[7] is used.

The width of the giant dipole resonance is calculated as a function of excitation energy for the Sn and Pb nuclei region. The widths calculated within nuclear fluid-dynamics method[2,3] show much weaker variation with temperature in comparison with those ones according to the semiclassical $SRPA$.

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ANISOTROPIC ALPHA DECAY AND NUCLEAR DEFORMATIONS

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A renewed interest has been raised by recent experimental results on *alpha* anisotropy on Fr and Pa isotopes [1]. A miscroscopic description of the alpha decay of the odd mass nuclei for axially deformed nuclei was proposed few years ago [2]. Realistic mean field + pairing residual interaction within BCS approximation in a very large single particle basis was used. Systematic calculations for At and Rn isotopes, as well as for ^{221}Fr, were performed. The barrier penetration process is treated within the WKB approximation. In the Table the calculated widths and predicted values of the function $W(\vartheta) = 1 + \sum_{L=2,4} Q_L B_L U_L A_L P_L(cos\vartheta)$ are reported for a few selected cases. Here A_L are the theoretical A-coefficients, Q_L are coefficients that take into account the dimensions of the sourse and detectors, B_L describes the orientation of the nuclei and U_L corrects B_L for unobserved intermediate transitions. A pronounced anisotropic emission of the alpha particles is predicted, as a function of the deformation for deformed nuclei. Calculations were initially performed for At and Rn isotopes. We found that alpha decay is an excellent tool to probe intrinsic deformations in nuclei.

New calculations on Pa - isotopes, making use of a improved single particle basis [3] were performed. They show a very nice agreement with the new data [1]. The new approach uses a single particle basis consisting of two different harmonic oscillator potentials and allows to reproduce, in even-even nuclei, the experimental total widths for α decay within 20%. Comparison with other microscopic approaches will be presented.

	β_2	Γ_{exp}	Γ_{th}	A_2	A_4	$W(0^o)$	$W(90^o)$	$\frac{W(0^o)}{W(90^o)}$
$^{205}_{86}Rn$	0.005	2.68(-24)	6.76(-25)	0.022	0.000	1.022	0.989	1.034
$^{207}_{86}Rn$	0.016	8.17(-25)	8.50(-26)	0.076	0.000	1.076	0.962	1.118
$^{209}_{86}Rn$	0.023	2.62(-25)	4.27(-26)	0.111	0.001	1.112	0.944	1.177
$^{219}_{86}Rn$	0.081	1.15(-22)	2.05(-22)	0.398	0.008	1.406	0.804	1.749
$^{221}_{87}Fr$	0.069	1.55(-24)	1.08(-24)	-0.288	0.005	0.717	1.146	0.626
$^{241}_{95}Am$	$^{0.220}_{0.08}$	3.34(-34)	2.09(-34)	1.158	0.070	1.500	0.736	2.038
$^{243}_{95}Am$	$^{0.220}_{0.08}$	1.96(-33)	1.17(-33)	-	-	-	-	-

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WEAK PAIRING CORRELATIONS WITHIN A SELF-CONSISTENT APPROACH CONSERVING EXPLICITELY THE PARTICLE NUMBER

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The description of the structure and elementary excitations of atomic nuclei within the HFB or its BCS approximation, suffers from well-known deficiencies in weak pairing regimes. Such situations are encountered for instance at or near (sub-)shell closures, at high enough angular velocities and for quasi-particle states such as high-K isomers. These defects have been attributed to the particle number particle breaking inherent to the HFB approximation. In this contribution we would like to propose and illustrate a tractable method which is free from these difficulties in that it conserves explicitly the particle number yet preserves the computational environment of state of the art HFB or HF plus BCS calculations, using e.g. Skyrme or Gogny current parametrisations of the effective force. Its purpose may be summarized by qualifying it of highly truncated self-consistent deformed shell model calculations. It starts from the hamiltonian H = K + v, where K is the kinetic energy and v the 2-body effective force. Introducing a mean field *V* one may trivially rewrite H as H = K + *V* + w, where w = v – V is the residual interaction. The latter is diagonalized in a n-particle/n'-hole basis built on the sp eigenstates associated with the 1-body Hamiltonian *H* = K + *V*. The rate of convergence of the solution in terms of the complexity factors of the considered basis states (n or n') is of course contingent upon a judicious choice of *V*. This potential is defined as the convolution of the 1-body reduced density matrix ρ associated with the correlated wavefunction Ψ in a HF fashion, i.e. *V* = tr ρ v', where v' stands for the antisymetrized interaction v. The problem has thus to be solved self-consistently so as to incorporate in *V* all the 1-body properties associated with Ψ. We have performed such calculations using the standard SIII Skyrme force [1] for the p-h channel and a delta force fitted for BCS calculations for the p-p channel [2]. The discussion of our results will include some general aspects of our method as the fast convergence of the calculations. Indeed, for 0^+ solutions, we have shown that 3p-3h configurations do not add any significant physical results while pair transfers, in accordance with the physical ideas supporting the BCS ansatz, are found to be the dominant correlation mechanism. We will also show that near some shell closures, the pairing correlations which are vanishing in a BCS approach, are quenched yet still present in our approach. Various isomeric state energies of the ^{178}Hf nucleus are reproduced within 100-200 keV, demonstrating thus the ability of our approach to deal, using the **same** Hamiltonian, with strong pairing solutions as well as with solutions where the pairing correlations are reduced due to the well-known blocking effect in qp isomers. To conclude, we stress that the method which is presented here, while respecting an important conservation rule, appears to be both tractable and physically successful.

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Molecular-like Structure in Light Neutron-rich Nuclei

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The survey of the molecule-like structure is one of the most challenging subjects in light neutron-rich nuclei. In Be isotopes, recently, decay into fragments of He isotopes (^{4}He, ^{6}He, ^{8}He) has been observed from the excited states of ^{10}Be and ^{12}Be, and the presence of two-center configuration is suggested.

As for the multi-cluster configurations in light α-nuclei beyond the two-center systems, the existence of $N\alpha$ states has been predicted around the threshold energy in the so-called Ikeda diagram. For example, it has been suggested that the second 0^+ state of ^{12}C has 3α-like molecular configuration. However, according to a lot of theoretical analyses the state is not necessary to have a linear-chain of 3α, but is described as a weak-coupling state with triangular shape or ^{8}Be+α configuration.

Recently, the discussions of the well-developed cluster structure are extended to the neutron-rich nuclei, and the role of valence neutrons which stabilize the linear-chain structure has been pointed out. For example, von Oertzen has extended his analyses for the molecular structure in Be isotopes [1] to C isotopes, and the linear-chain state consisting of 3α and valence neurons around it has been speculated. Even if the 3α-system without valence neutrons (^{12}C) does not have a linear-chain structure, the valence neutrons around it are expected to increase the binding energy and stabilize the linear-chain state.

Here, we perform a microscopic calculation for the Be isotopes and the C isotopes and study these well-developed molecular-like states. The appearance of prolonged structure with the α-α core in ^{10}Be [2] and ^{12}Be [3] is shown to be successfully described by the α+α+n+n+$\cdots$ model, where the orbits for the valence neutrons are classified based on the molecular-orbit (MO) model. In MO, the orbit of the valence neutron perpendicular to the α-α axis (z-axis) is called π-orbit, and one along the axis is called σ-orbit. The antisymmetrization imposes the forbidden space for the valence neutrons; the π-orbit must have at least one node perpendicular to the axis, and the σ-orbit must have at least two nodes since two α-clusters along the z-axis already occupy the orbitals with $n_z = 0, 1$.

In ^{10}Be, all of the observed positive-parity bands and the negative-parity bands are described within the model. The second 0^+ state of ^{10}Be has a large α-α structure with a $(1/2^+)^2$ configuration (the σ-orbit for the two valence neutrons). An enlargement of the α-α distance due to two-valence neutrons along the α-α axis makes their wave function smooth and reduces the kinetic energy drastically. A large E2 transition probability between states which belong to a rotational band (0_2^+, 2_3^+, 4_2^+) is a signature for the presence of such states. ^{12}Be is also investigated using α+α+$4n$ model, in which four valence neutrons are considered to occupy the $(3/2^-)^2(1/2^+)^2$ configuration. The energy surface of ^{12}Be is shown to exhibit similar characteristics, that the remarkable α clustering makes the binding of the state with $(3/2^-)^2(1/2^+)^2$ configuration properly stronger in comparison with the closed p-shell $(3/2^-)^2(1/2^-)^2$ configuration. This effect is suggested to play a crucial role in accounting for the dissipation of the $N = 8$ magic number in ^{12}Be.

The molecule-like structure of the C isotopes is investigated using a microscopic α+α+α+n+n+$\cdots$ model, where both π-orbit and σ-orbit are introduced around three α-clusters. The valence neutrons which occupy the π-orbit increase the binding energy and stabilize the linear-chain of 3α against the breathing-like break-up. However, ^{14}C with the π-orbit does not show clear minimal energy against the bending-like path. The combination of the valence neutrons in the π- and the σ-orbit is promising to stabilize the linear-chain state against the breathing- and bending- modes, and it is found that the excited states of ^{16}C is one of the most promising candidates for such structure.

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Proton Emission from Odd–Even and Odd–Odd Deformed Drip–Line Nuclei

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One of the most exciting subjects in contemporary nuclear physics is the search for the limits of stability of nuclei. Recent measurements on spherical [1] and deformed proton emitters, in the region of heavy nuclei with $50 < Z < 82$, make possible to define almost completely the borders of proton stability. Important aspects of nuclear structure can be learned from proton decay, since it is a probe for small components of the wave functions of the decaying states and helps to determine the deformation of nuclei and the angular momentum of the ground state [2]. The theoretical description of proton emission from spherical systems was studied by various authors [1,3], and the experimental results are well reproduced within these models. In the case of deformed nuclei, to study proton emission, one has to determine resonances in deformed system. The search of complex energy eigenvalues in a nonspherical system was solved only recently [4]. The Schrödinger equation was solved exactly [4] for a deformed Saxon–Woods potential with a deformed spin-orbit term, imposing outgoing wave boundary conditions. The states obtained with this procedure are the Nilsson bound states and resonances.
Assuming that the proton moves in a single particle Nilsson level, we have developed a model that leads to the exact evaluation of the half–life for the decay. The model was applied to all measured odd [2] and even [5] deformed decaying nuclei, considering deformed those systems where spherical calculations provide unreasonable spectroscopic factors.
The available data were accurately and consistently reproduced for all deformed proton emitters from the ground and isomeric states and the fine structure decay. The calculations provide information on the deformation and angular momentum J of the decaying nuclei, giving unambiguous assignments to the decaying states. This type of information might be difficult to extract using other probes in this unstable mass region. Our results support the nuclear structure predictions of ref. [6] for nuclei at the proton drip line.

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Microscopic coupled-channel study of molecular resonances in ^{12}Be

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Recently, the breakup experiment of ^{12}Be into ^{6}He+^{6}He has been performed using a 378 MeV ^{12}Be beam [1]. The results indicate the existence of the exotic ^{6}He+^{6}He molecular states in the 10 to 25 MeV excitation energy interval, with spins in the range of $4\hbar$ to $8\hbar$.

In order to investigate the nuclear structure of these exotic molecular states in ^{12}Be, we perform a microscopic coupled-channel (CC) calculation of ^{6}He+^{6}He elastic and inelastic scattering. We use the double-folding interactions based on the realistic nucleon-nucleon interaction, DDM3Y. In the present CC calculation, we take into account the excitation to the 2_1^+ state (E_x=1.8 MeV) and the 2_2^+ state (E_x ~5 MeV) of which existence is strongly suggested theoretically. The transition density to the 2_1^+ state is calculated by the microscopic ^{4}He+n+n cluster-model wave function [2], while that to the 2_2^+ one is done by the collective model assuming the quadrupole deformation [3]. The strength of the latter density is determined so as to reproduce the energy-non-weighted sum rule value of the soft-quadrupole mode from which the theoretical B(E2:$0^+ \rightarrow 2_1^+$) value is subtracted [4].

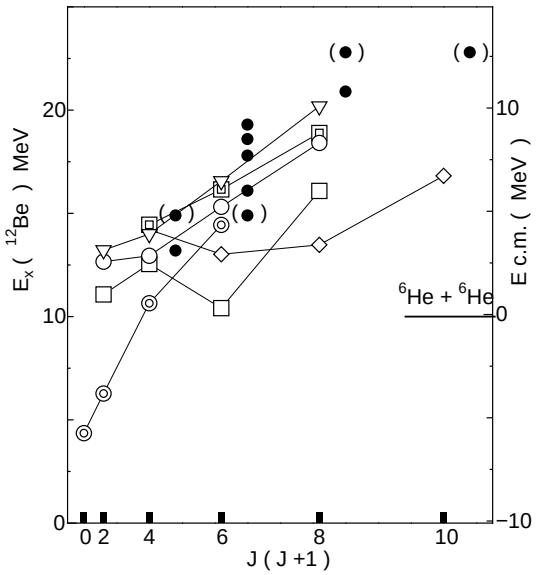

Fig. 1. Molecular bands of the ^{6}He+^{6}He system obtained by CC calculation. The solid squares in parentheses represent the spin unknown states observed in breakup experiment [1]. See text for details about each molecular band.

We include the elastic (0^++0^+) channel and the 0^++2_1^+, 2_1^++2_1^+, 0^++2_2^+ inelastic-channels in the CC calculation. In Fig.1, we show the ^{6}He+^{6}He molecular bands obtained by solving the CC equations. The double circles and squares show the bands in which the dominant component is the elastic and $[0^+ \otimes 2_1^+]_{I=2,L=J-2}$ channels, respectively, while the bands shown by the inverse triangles, circles, diamonds and double squares have the dominant component of the $[0^+ \otimes 2_2^+]_{I=2,L=J-2}$, $[2_1^+ \otimes 2_1^+]_{I=4,L=J-2}$, $[2_1^+ \otimes 2_1^+]_{I=4,L=J-4}$ and $[2_1^+ \otimes 2_1^+]_{I=2,L=J-2}$, channels, respectively. The resonances observed in the breakup-reaction experiment are also plotted in the figure by the solid squares. It is seen that the observed resonances coincide in energy and spin with the calculated resonances belonging to the molecular bands in which the inelastic-channel components are dominant. The channel coupling effects are not so strong for the inelastic channels and the populations of the dominant channel component are less than about 60~80 %. Therefore, the calculated molecular bands of the inelastic channels can be interpreted in terms of the so-called "weak coupling states" in which two interacting ^{6}He nuclei keep touching their surfaces and rotate to each other by almost keeping their identities.

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A MODEL STUDY OF T=0 AND T=1 PAIRING IN A SINGLE J-SHELL*

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Recent advances in experimental techniques and new possibilities that are becoming available with the use of radioactive beams, are driving a renaissance of nuclear structure studies along the N=Z line. A subject of particular interest in these nuclei is the study of isoscalar (T=0) and isovector (T=1) pairing correlations. For more than 40 years since the initial suggestion by Bohr, Mottelson and Pines [1] of a pairing mechanism in the nucleus, analogous to that observed in superconductors, a wealth of experimental data has been accumulated supporting the important role of *nn* and *pp* "Cooper pairs". In contrast to this well established phenomenon, we are still searching for a clear signature of the formation of correlated *np* pairs.

In this work we present a study of competing isovector and isocalar pairing correlations within the framework of a spherical single j-shell space. We used the code OXBASH [2] introducing an effective two-body force of the form $V = xV_{J=0}^{T=1} + (1-x)V_{J=1}^{T=0}$, to model the mixture of the two types of interactions by the value of x. We will compare our results with those of a single *l*-shell [3], stressing the most relevant differences between the two cases. In particular, we find that an appreciable component of isoscalar pairing (~50%) favors a ground state with aligned spin.

We will also discuss the behavior of binding energy differences and relative excitation energies of the lowest T=0 and T=1 states in odd-odd N=Z nuclei in the presence of a *deuteron-like* (*np*, T=0) pair condensate. A connection with experimental data will be made.

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The performance of self-consistent models in the realm of exotic nuclei

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Continously developing experimental facilities produced in the last two decades a world of new nuclei outside the valley of stability. The new data thus acquired constitute severe probes for existing nuclear structure models, the liquid-drop model plus shell corrections (macroscopic-microscopic method) and the various brands of self-consistent mean-field models. All these models employ a great deal of phenomenological adjustment. New nuclei help enormously to scrutinise the predictive power of these various models and to improve on hitherto vaguely fixed aspects. The poster will discuss several key data and their value to discriminate models, e.g. binding of super-heavy elements, two-nucleon separation energies, isotopic shifts, neutron radii, or odd-even staggering.

Probably the most popular from the self-consistent models are the Skyrme-Hartree-Fock method (SHF), the Gogny force, and the relativistic mean field model (RMF). We will discuss and compare SHF and RMF. In both cases, the actual model parameters are adjusted phenomenologically and thus there exists a great variety of different parametrisations within SHF as well as RMF. The presentation will cover several different parametrisations to exemplify the versatility of the models and to evaluate possible systematic differences between SHF and RMF. We will compare formal aspects as well as the descriptive power. For example: the RMF has proven to be superior what spin-orbit properties is concerned while the SHF is more versatile in iso-vector trends; both aspects play a role in extrapolations to exotic nuclei. This hints that both models still deserve improvements. Data from exotic nuclei are crucial for this further development.

Atomic Electric Dipole Moments and Time-Reversal Symmetry Violation: Role of Ocupole Collectivity *

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Time-reversal symmetry violation has so far been observed only in kaons [1], and its orgin is still unclear. The search for electric dipole moments (EDMs) of neutral atoms provides a complementary window onto the same phenomenon. Experiments that search for EDMs can benefit by using atoms in which the moments can be enhanced by structural effects in either the atom or the nucleus.

Here we discuss an enhancement of the EDM in atoms whose nuclei have strong octupole correlations in the ground state [2,3]. After giving a rough estimate of the size of the enhancement, which depends sensitively on the matrix element of the time-reversal-violating nucleon-nucleon interaction, we discuss self-consistent mean-field calculations designed to capture the enhancement more precisely. We conclude that a source of radioactive octupole-deformed nuclei such as ^{225}Ra and ^{223}Rn would be worthwhile.

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Rotational Properties of Neutron Drip-Line Ne and Mg Nuclei *

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Moving away from stable nuclei by adding either protons or neutrons, one finally reaches the particle drip lines. The neutron-rich, weakly-bound nuclei close to the neutron drip line have very unusual properties: they are large, diffused, and superfluid [1].

In this work, the systematic behavior of rotational bands in deformed neutron-rich nuclei has been investigated with the cranked Skyrme-Hartree-Fock approach [2]. The variation of shape with rotation has been studied for the $\nu(f_{7/2})^n$ configurations in the series of even-even isotopes $^{30-38}$Ne, $^{32-40}$Mg. The Skyrme interaction SLy4 [3] has been used.

The analysis was performed in the deformation region where previous studies [4] have indicated the existence of highly deformed configurations ($\beta_2 \approx 0.35$). In particular, we studied isovector deformation effects, i.e., differences between proton and neutron deformations. According to our calculations, the quadrupole isovector deformations in the neutron-rich Ne and Mg isotopes are usually small. The strongest effect is predicted for the $\nu 3^6$ bands in the N=26 isotones at low spins. However, the difference in β_2^π and β_2^π is fairly small, it does not exceed 0.04. In all cases, proton and neutron deformations are practically identical at high angular momentum. As far as proton and neutron radii are concerned, they show very weak variation with spin. The behavior of the moments of inertia is also discussed.

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Additivity in the Highly-Deformed Rotational Bands in the A $\sim$ 130 Mass Region *

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In the present work [1] we perform theoretical analysis of rotational bands in the A $\sim$ 130 light rare-earth region. We carried out two different sets of self-consistent calculations: the cranked Skyrme Hartree-Fock (CHF) and the relativistic mean field (RMF) approach.

The Hartree-Fock analysis of the SD bands in A $\sim$ 130 nuclei has been accomplished within the cranking approximation (without pairing) with the Skyrme SLy4 interaction [2] used in the p-h channel. The self-consistent equations have been solved using the code HFODD (v1.75) [3] which employs the three-dimensional Cartesian harmonic-oscillator basis.

In the relativistic mean field (RMF) theory [4,5] the nucleus is described as a system of point-like nucleons (Dirac spinors) which interact in a relativistic covariant manner through the exchange of virtual mesons: the isoscalar-scalar σ-meson, the isoscalar-vector ω-meson and the isovector-vector ρ-meson. It is based on the one-boson exchange description of the nucleon-nucleon interaction. The RMF calculations have been performed with the NL1 parametrization [5] of the Lagrangian and the RMF-equations are solved in the basis of an anisotropic three-dimensional harmonic oscillator in Cartesian coordinates.

Our work provides a consistent understanding of the highly deformed rotational structures in the A $\sim$ 130 mass region. From our self-consistent results, we deduce effective single-particle quadrupole moments and alignments, according to Ref. [6]. The calculated quadrupole moments are compared with the recent experimental data from global lifetime measurements at GAMMASPHERE [7].

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