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PROPOSAL

Topical Center for RIB Theory

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Proposal for a Topical Center for RIB Theory

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February 2004

Prepared for
U.S. Department of Energy
Office of Science

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P.O. Box 2008
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managed by
UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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Abbreviations

CCSD	coupled clusters with singles and doubles
ChPT	chiral perturbation theory
CR	completely renormalized
CSM	continuum shell model
DMRG	density matrix renormalization group
EFT	Effective Field Theory
EOM	Equation of Motion
FSU	Florida State University
GHF	Gamow Hartree-Fock
GSM	Gamow shell model
HF	Hartree-Fock
HFB	Hartree-Fock-Bogoliubov
HRIBF	Holifield Radioactive Ion Beam Facility (ORNL)
JFA	joint faculty appointment
JIHIR	Joint Institute for Heavy Ion Research (Vanderbilt/UT/ORNL)
LLNL	Lawrence Livermore National Laboratory
NCSM	no-core shell model
NLO	next-to-leading order
NN	nucleon-nucleon
NNLO	next-to-next-to-leading order
NNN	three-nucleon
NSAC	Nuclear Science Advisory Committee
NSF	National Science Foundation
ORNL	Oak Ridge National Laboratory
PI	principal investigator
QCD	quantum chromodynamics
QRPA	quasiparticle random-phase approximation
RIA	Rare Isotope Accelerator
RIB	radioactive ion beam
SMMC	shell model Monte Carlo
T	three-body clusters
TDHF	time dependent Hartree-Fock
UNC	University of North Carolina
UT	University of Tennessee

1. Introduction: Nuclear Structure Theory in the RIA Era

Nuclear structure theory strives to build a unified and comprehensive microscopic framework in which bulk nuclear properties, nuclear excitations, and nuclear reactions can all be described. A new and exciting focus in this endeavor lies in the description of exotic and short-lived nuclei. The extreme isospin of these nuclei and their weak binding bring new phenomena to the fore which isolates and amplifies important features of the nuclear many-body problem. The new arena of nuclei with large neutron excess is therefore key to building a unified theoretical foundation for understanding the nucleus in all its manifestations—from the stable nuclei that exist around us to the most exotic nuclei, and even to exotic forms of nucleonic matter which exist, e.g., in neutron stars.

Currently, a variety of nuclear structure research facilities within the United States, in Europe, and in Japan provide experimental data concerning the properties of both exotic and stable nuclei. In order to address astrophysical questions related to nuclear physics, the National Science Foundation (NSF) recently created the Joint Institute for Nuclear Astrophysics. In addition to the current U.S. facilities, efforts are ongoing to build the Rare Isotope Accelerator (RIA), the next-generation low-energy nuclear facility. RIA is a near-term number-three priority of the U.S. Department of Energy, Office of Science (and the top priority within the Division of Nuclear Physics).

RIA and other exotic beam facilities allow unique insights into the quantum many-body nature of nuclei by providing access to their most extreme manifestations and by providing precise control of the number of neutrons in these systems. Recent theoretical and experimental achievements, coupled with the experimental discoveries that RIA will provide, are focusing new attention on a number of unsolved issues in nuclear structure and offer excellent scientific opportunities for the next decade and beyond. Given the advent of research on radioactive nuclei, particularly with the coming of the RIA, it is extremely important to prepare nuclear theory for its realization. At the present time, low-energy nuclear theory in the United States requires vitality at all levels, from graduate students, to postdoctoral appointees, and new university faculty and laboratory staff positions. There is an obvious need to generate a broad system of support and synergistic activity in the area of low-energy nuclear theory.

We propose to form a Topical Center for Radioactive Ion Beam (RIB) Theory that by its very nature will provide several research opportunities relevant to the advancement of nuclear structure theory during the next decade. The Center will focus theoretical research on many-body problems pertaining to exotic nuclei. Through this Center, we will develop quantitative microscopic nuclear theory that will help us understand experimental findings, allow us to make genuine predictions, and also allow us to make reliable extrapolations to unknown nuclear systems where experiment cannot reach. The Topical Center will act as a hub for a wider group of scientists working in this area and provide a way to seed new faculty and staff positions in low-energy nuclear research. The Center will also serve to train postdoctoral appointees and educate students.

We will discuss various aspects of the Topical Center throughout this proposal, which is structured as follows. In Section 2 we discuss the scientific challenges and opportunities in nuclear structure theory, the current status, and our proposed research in relation to these opportunities.

We turn in Section 3 to a discussion of the Topical Center, its goals and our plans to meet them. We include a list of scientific deliverables for the Center in this section. In Section 4 we discuss benefits of the Center and the leveraging for the Center. We conclude with a detailed budget in Section 5.

2. Science: Proposed Research

The atomic nucleus is a complicated quantum many-body system. On the one hand, nuclear interactions responsible for nuclear binding and governing the structure of excited states generate a plethora of complex phenomena. On the other hand, atomic nuclei often exhibit amazing regularities of structure. Nuclear structure theorists endeavor to understand both of these underlying facets within a unified theoretical framework. Nuclei also play an important role in matter production in the universe and in stellar evolution. They are also splendid laboratories for fundamental interactions and the Standard Model. The Nuclear Science Advisory Committee (NSAC) Theory Report *A Vision for Nuclear Theory* identified several areas of opportunity in nuclear theory during the next ten years. The areas to which this proposal relates are shown in the box below.

Areas of opportunity covered in this proposal

- *Nuclear effective field theory:* Developments will place two- and three-nucleon interactions on a firm chiral footing. These interactions can then be used to predict many-body nuclear structure.
- *Ab initio nuclear structure theory:* Developments will allow studies of medium-mass nuclei. Progress in larger nuclei will be achieved by optimizing the enormous configuration spaces.
- *Toward the universal microscopic energy density functional:* This functional will describe properties of finite nuclei as well as extended asymmetric nucleonic matter.
- *Nuclear structure at the interface:* The application of nuclear structure to such problems as electron-capture in stellar environments, r-process nucleosynthesis, neutrino astrophysics, symmetry violations, beta-beta decay processes, and superconductivity. These areas represent exciting fields that require low-energy nuclear theory input and promise breakthroughs in the next 10 years.

The scientific opportunities listed above will also enable us to answer several long-standing questions in nuclear structure research. These include understanding the following issues.

- *Changes in the effective nuclear interaction and the nuclear matter equation of state as a function neutron excess:* What is the isospin dependence of the effective nuclear interaction? What is the density dependence of the effective interaction? How does one characterize the transition from finite nuclei to bulk nucleonic matter?
- *Foundations of independent particle motion:* How does shell structure change as a function of increasing neutron number? What is the role of the continuum in weakly bound nuclei?
- *Excitation and decay properties of weakly bound systems:* How does one quantify nucleon halos and skins in near-drip line-nuclei? What are the soft modes of excitation of these weakly bound systems?

- *Element production in the universe and the nucleonic structures in stars:* What nuclear physics is important for understanding the production of r-process nuclei? What role does nuclear structure play in supernovae explosion mechanisms? What are the properties of neutron stars?
- *Weak nuclear processes:* What are the nuclear uncertainties in fundamental symmetry measurements in atomic nuclei?

The research proposed below envelops these questions. By developing new ideas and existing tools and developing new, state-of-the-art many-body algorithms, the Topical Center will span various areas of research which all impact nuclear structure theory and will pave the way to the RIA era. Our aim is to provide a quantitative and predictive basis for nuclear structure theory.

Understanding nuclei and predicting their behavior requires one to solve the complicated many-body problem with de facto unknown effective interactions. While this statement is obvious, its implementation has been quite difficult due to the computational challenges involved. Various methods have been employed; these are broadly classified, along with the nuclear landscape in Fig. 1.[1] The research described in this Topical Center proposal also maps well onto this figure. For example, no-core shell-model (NCSM) calculations will be performed using Effective Field Theory (EFT)–inspired interactions. We will investigate and apply methods that will allow us to pursue ab initio calculations in medium mass nuclei. We will also pursue methods that will enable us to find optimal basis state expansions in which to perform shell-model calculations for heavier nuclei. Finally, self-consistent mean-field theories based on density-functional theory (inducing superconducting correlations) are invaluable tools for furthering our understanding of nuclear properties that are unreachable by other techniques. Our understanding of the energy-density functional will lead to a quantitative description of nuclear masses, radii, and other nuclear properties. The practical implementation these methods requires excellent computational capabilities and parallel computing resources. By utilizing and developing new theory and computational tools, we will provide the community with reliable, quantitative predictions for nuclear structure.

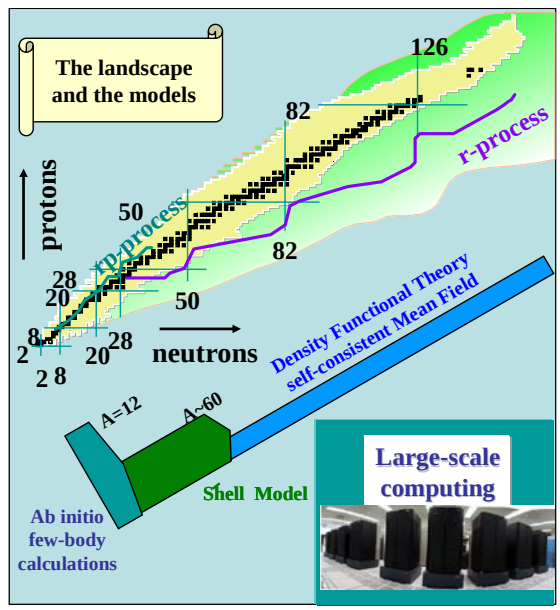

Fig. 1. The nuclear landscape and the theoretical models.[1]

We outline below our proposed research in relation to the major research opportunities and challenges as discussed in the NSAC Theory Report. Importantly, many of these activities require significant involvement of various researchers with diverse expertise. Bringing these people together in a cooperative environment that fosters research is a major objective of the Topical Center. *This also represents a different way of conducting business in nuclear physics, since we are advocating a focused research effort.* The Center will be necessarily broad in its suite of scientific applications. Its overarching focus will be on the scientific questions to be addressed by RIA, but the approaches to that science will be varied, enabling us by an integrated approach to have an enormous impact on nuclear physics and other areas of science, where the quantum many-body

problem plays an essential role, including, for example, atomic, molecular, and condensed matter physics and quantum chemistry. The following scientific sections briefly discuss the status of specific areas and our associated research goals for each of those areas.

2.1 Nuclear Effective Field Theory

Two of the major outstanding problems in theoretical nuclear physics are the nature of the interaction among nucleons and how this interaction gives rise to the myriad of properties of atomic nuclei. We will use the EFT approach to understanding the nature of nuclear forces starting from effective Lagrangians.[2]

Because it is now well-established that modern, high-quality nucleon-nucleon (NN) potentials do not correctly bind finite nuclei, the question is, what is missing in the nuclear-structure calculations? The current and best guess is three-nucleon (NNN) interactions. In that case, it is extremely important to have NNN interactions that are determined self-consistently with the NN interactions. In addition, one would like to develop nuclear interactions that are consistent with the chiral symmetry of quantum chromodynamics (QCD). The implications of the pattern of symmetry breaking should be preserved for the eventual derivation of nuclear forces from QCD.

EFT is the technique that allows for a model-independent formulation of the symmetry implications of low-energy QCD. There are three EFTs, each at a different level of resolution, that have possible applications to the research proposed for the Oak Ridge National Laboratory (ORNL) Topical Center: (1) EFT without explicit pions; (2) EFT with explicit pion fields, or chiral perturbation theory (ChPT); and (3) EFT for low-energy phenomena[3] and density functionals.[4]

In EFT without pions,[5] applicable for momenta below the pion mass, all interactions among nucleons are contact interactions. This simplicity allows for a full treatment of NN and NNN interactions in a self-consistent manner. The inclusion of the pion[6] increases the range of applicability of the theory and is currently the best approach for developing high-quality NN interactions with chiral symmetry.[7] The complications introduced by the singular nature and long range of pion exchange require further research regarding the role of NNN forces.[8]

The NCSM for light nuclei[9] has so far been applied to nuclei up to A = 16. In order to extend this approach to heavier nuclei, self-consistent high-quality NN and NNN interactions are required as input to the calculations. Hence, the importance of the EFT/ChPT research discussed above. These NN and NNN forces then need to be renormalized for the model space of interest. Barrett and his collaborators have developed techniques for carrying out exactly this model-space renormalization to effective interactions.[10] G-matrix calculations have already been performed for ^{6}Li with a ChPT potential at next-to-leading order (NLO) and at next-to-next-to-leading order including three-body forces (NNLO+3NF),[11] as shown in Fig. 2.

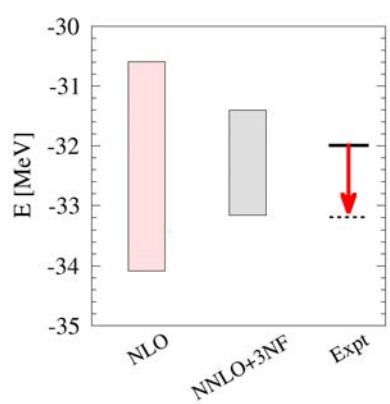

Fig. 2. Convergence of EFT for ^{6}Li. A three nucleon force is also included.

To extend the NCSM beyond A = 16, new theoretical techniques must be developed to determine effective interactions and effective operators appropriate for smaller model spaces—i.e., effective interactions that will yield convergent results for heavier nuclei but in smaller model spaces.

2.2 Microscopic Nuclear Structure Theory

The NCSM accurately describes the structure of light nuclei up to about mass 16. This work demonstrated that a local NN interaction is not adequate to describe the properties of nuclei, and that three-nucleon interactions play a very important role. The description of weakly bound systems and medium mass nuclei poses several challenges. For weakly bound nuclei, the inclusion of continuum states that possess the correct asymptotic behavior becomes necessary. Another problem concerns the increasingly large dimension of the model spaces. Clearly, improved effective interactions could yield converged results for heavier nuclei in smaller model spaces. However, it is also necessary to develop new methods that accurately solve the many-body problem in huge model spaces. Two promising candidates are the coupled cluster method and the density matrix renormalization group methods.

2.2.1 Development of nuclear coupled-cluster theory

The coupled cluster method originated in nuclear physics over 40 years ago when Coester[12] and Coester and Kummel[13] proposed an exponential wave function *ansatz* to describe correlations within a nucleus. The basic coupled cluster *ansatz*—in which the ground-state many-fermion wave function is obtained by applying the exponential wave operator, constructed using cluster operators, to the reference Slater determinant—is an immediate consequence of the linked and connected cluster theorems. Early applications of the coupled cluster method to finite nuclei were undertaken by the Bochum group in the 1970s.[14] The Manchester group has also pursued the coordinate-space formulations of coupled-cluster theory.[15] In spite of many advantages that the coupled cluster theory offers, a systematic development and implementation of this interesting and powerful many-body theory in nuclear physics applications has been only sporadic.[16] The view from computational quantum chemistry is entirely different: a large variety of coupled-cluster methods for ground, excited, closed-shell, open-shell, non-degenerate, and quasi-degenerate electronic states of atoms and molecules have been developed and efficiently coded, so that nowadays coupled cluster methods applied to computational chemistry enjoy tremendous success over a broad class of problems related to molecular structure, molecular properties, and chemical reactivity (see, e.g., Ref. 17).

Recent calculations in nuclei, namely for ^{4}He and ^{16}O, have obtained respectable results for both the ground state[18] and excited states.[19] These calculations proceed by first computing a G-matrix[20] for a given model-space and then computing the cluster amplitudes within that space. So far, this work has considered a few basic, quantum-chemistry-inspired approximations, in which one- and two-body clusters are solved for completely in an iterative fashion[21] (this implementation is called coupled clusters with singles and doubles, or CCSD) and higher-order effects due to three-body clusters are estimated by adding noniterative corrections to the energy.[22] For excited states, the quantum-chemistry-inspired equation of motion coupled cluster formalism[23] and its recent noniterative extensions[22] were employed with great success.[19] These and related methods will be developed further, so that accurate coupled-cluster calculations for small and medium-size nuclei become not only possible, but perhaps also routine.

In recent calculations, the reliability of various approximations was investigated by comparing the results obtained with a given method with the results of the exact diagonalization of the Hamiltonian in the same model space. Suitably defined variants of the completely renormalized (CR) approach that includes noniterative triples corrections[17,24,25] were also employed. With this method, one is able to correct the ground- and excited-state energies for the effects of three-body clusters by adding the a posteriori noniterative corrections to CCSD and excited state energies. The CR-CCSD(T) method ["T" stands for three-body clusters or, as chemists say, triples; "(T)"

indicates their noniterative treatment] is capable of providing the fully quantitative description of ground and excited nuclear states.[19]

Clearly, the preliminary findings need further study. For example, it is very important to compare the CCSD and CR-CCSD(T) results with the results of the full CCSDT[26,27] calculations, in which one solves for one-, two-, and three-body components of the cluster operator and for similar components of the corresponding excitation operator iteratively rather than by approximating three-body cluster and excitation components via noniterative energy corrections. It is also important to study the nature of higher-than-three-body clusters (e.g., quadruply excited clusters), which can be described in an iterative or noniterative fashion (see Ref. 17 and references therein). We will also consider the active-space coupled-cluster methods[27,28] in which we select the most important three- and four-body components of the cluster operators and excitation operators. The experience of quantum chemists is that methods of this type produce highly accurate results of CCSDT/EOMCCSDT quality at a small fraction of the effort related to the latter calculations. The preliminary calculations[18,19] briefly discussed above indicate that the coupled-cluster method will be quite successful in describing nuclear systems. Judging from the size of molecular and other many-electron problems that can nowadays be handled by coupled-cluster methods, it is conceivable that we will be able to apply these methods to nuclei in the mass 50–100 region. In addition to two-nucleon interactions which have thus far been considered, three-body forces will also be incorporated into the method. We will also implement techniques that allow us to calculate various nuclear properties such as radii, spectroscopic factors, and various transition matrix elements and compare our findings to experiment.

2.2.2 Shell-model basis optimization

Many shell-model applications require development of new methods that move beyond brute-force diagonalization of the nuclear Hamiltonian. In recent years several approximation methods have been developed that truncate the enormous shell-model Hilbert space to those states that accurately approximate the ground state. The density matrix renormalization group (DMRG) is such a truncation method.[29,30] Developed about a decade ago, DMRG has become unsurpassed for highly accurate computations of spin-chains and other one-dimensional lattice systems. Within DMRG, the lattice problem is divided into two sub-lattices. More and more lattice sites of each sub-lattice are included in the calculation of low-lying states, and after each step the problem is truncated to the most important states pertaining to each sub-lattice. This sophisticated growth and truncation scheme yielded accurate results for huge model spaces. Only recently have quantum chemists and nuclear physicists employed DMRG. In nuclear structure calculations the lattice sites become single-particle orbitals, and the sub-lattices consist of particle and hole orbitals, or proton and neutron orbitals, respectively. First applications to a pairing-plus-quadrupole Hamiltonian yielded excellent results, but more realistic shell model problems are more difficult to treat. Future investigations concern the optimal division of the problem into two sets of orbitals and the order in which the orbitals are included into the problem.

Within the related factorization method,[31] one approximates the low-lying shell-model states by products of suitable proton and neutron states. The optimal factors (i.e., the optimal proton states and neutron states) result from a variational principle and are the solutions of rather low-dimensional eigenvalue problems. The success of this method relies on the empirical finding that only a few of these product states have an appreciable norm, while most factors of such an expansion have exponentially small norms and can therefore be neglected. The factorization may reduce the dimensionality of the eigenvalue problem by three orders of magnitude for large pf-shell nuclei with realistic interactions while keeping an accuracy of about 0.1 MeV. Quantum numbers like spin and isospin are correctly reproduced even at severe truncations. Figure 3 shows the ex-

ponential convergence of the ground-state energies for ^{48}Cr and ^{56}Ni versus the relative dimension of the eigenvalue problem.

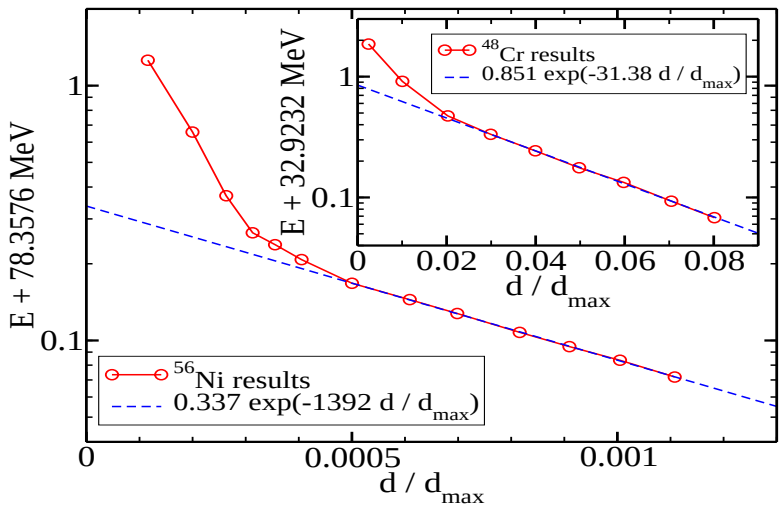

Fig. 3. Factorization method results for fp-shell nuclei.[31]

Future investigations will concern the treatment of nuclei with different active shells for protons and neutrons, and the treatment of very large problems by a factorization of the factors—i.e., for very large proton and/or neutron spaces it should be of advantage to treat these spaces as products of two smaller subspaces. The successful implementation of this research task will enable us to use the next generation of microscopic effective interactions and to give guidance in their development. For example, one immediate application of the factorization methods will be to develop a reliable effective shell-model interaction for the 0g-1d-2s shell-model space. Another important and interesting problem consists of computing double beta decay of the experimentally relevant isotope ^{76}Ge in a large model space.

2.2.3 Structure of weakly bound nuclei

Of significant current and future interest is the structure of exotic nuclei near the particle drip lines. Interest in these systems spans theoretical and experimental nuclear structure as well as nuclear astrophysics, especially in the context of stellar nucleosynthesis. This subject is particularly challenging due to the weak binding and the closeness of the open channels.[32] The main theoretical challenge is the correct treatment of the particle continuum. For weakly bound nuclei, the Fermi energy lies very close to zero, and the decay channels must be taken into account explicitly. As a result, many cherished approaches of nuclear theory, such as the conventional shell model and the pairing theory, must be modified. But there is also a splendid opportunity: the explicit coupling between bound states and the continuum, and the presence of low-lying scattering states invite strong interplay and cross-fertilization between nuclear structure and reaction theory. Many methods developed by reaction theory can now be applied to structure aspects of loosely bound systems. Here, the representative example is the recent continuum shell-model (CSM) description of the ^{16}O(p,γ)^{17}F capture reaction.[33] In CSM, continuum states (decay channels) and bound states are treated on equal footing. Consequently, correlations due to the coupling to resonances, the spatial extension effects in weakly bound states, the structure of resonances, and the structure of particle transfer form factors are properly described by CSM. So far, most applications of CSM have been concerned with the relatively simple situation where there is only one particle occupying the shell-model continuum. This happens since the continuum-continuum coupling is difficult to treat.[34]

A CSM treatment that includes two or more particles in the continuum was recently developed. A generalized completeness relation proposed by Berggren[35] paves the way for using Gamow states as shell-model basis states in a similar way as the ordinary bound states are used. Using the generalized completeness relation, one can treat a selected set of resonant states on the same footing

as bound states. The remaining part of the continuum is treated by means of the integral along a path in a complex momentum plane. This generalization offers a natural way for the separation of the resonant and the background part of the continuum, and at the same time, it opens possibilities for further simplifications.

Using Gamow states as a basis for shell-model diagonalization (called the Gamow shell model, or GSM) allowed consideration of more than one valence nucleon in the continuum for the first time.[36] In GSM, the effect of the continuum on the interaction matrix elements is automatically taken into account.[36] An example of GSM is represented in Fig. 4, which shows bound and resonant state calculations for helium isotopes as compared to experimental data.

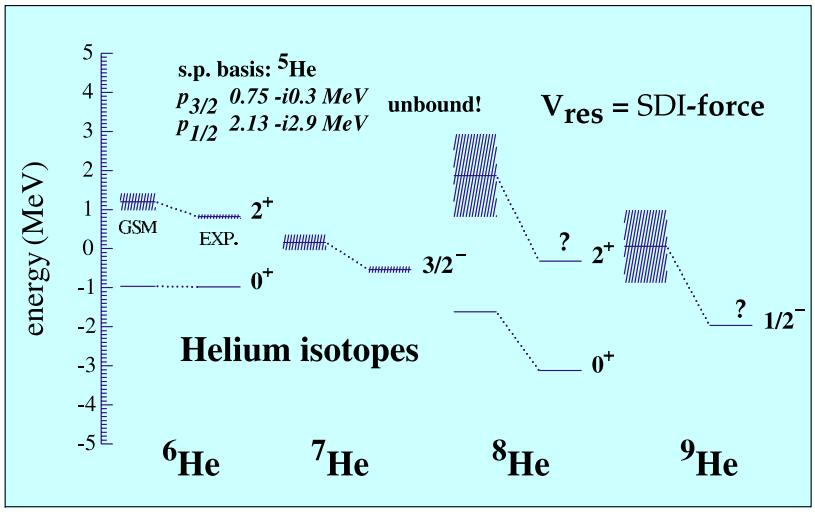

Fig. 4. GSM calculations of He isotopes.[36]

The initial stages of a broad research program recently begun involves applications of GSM to halo nuclei, particle-unstable nuclear states, reactions of astrophysical interest, and a variety of nuclear structure phenomena. The important step will be to develop effective finite-range interactions to be used in the GSM calculations. One would also like to optimize the path of integration representing the nonresonant continuum by means of the DMRG method. GSM calculations will be carried out in the Hartree-Fock (HF) basis; this helps optimize the GSM configuration space. To this end, a HF program in the Gamow basis (GHF) has been developed. The GHF method will also be used in the context of the density functional part of this proposal.

A recently proposed CSM treatment uses the projection formalism, in which the infinite continuum is effectively eliminated.[37] This procedure in turn leads to a new effective interaction between the nucleons. The main trade-off of such a projection is that the resulting effective interaction is no longer hermitian. Non-hermiticity in quantum mechanics indicates that the evolution of the system includes irreversible decay. The method is a direct extension of the traditional shell model which allows one to import many phenomenological parameters that took years to determine and that have been shown to work extremely well when applied to stable nuclei. The first exploratory study used interactions limited to pairing correlations, and the treatment of the reaction channels was conducted in a very limited manner. There are two main goals for the future work. The first is to determine the effective interaction between nucleons, and the second is to solve the related reaction problem.

The CSMs discussed thus far often contain an inert core and/or use an interaction that is fit to reproduce certain low-energy levels in nuclei of interest. An ab initio CSM approach would be based on an NCSM with effective realistic interactions. For light nuclei, the proper treatment of the continuum within the NCSM is important. Two major tasks toward this direction are the ex-

amination of the mean field used within the NCSM and the inclusion of continuum states in the NCSM basis.

A central feature of the NCSM is the inclusion of a harmonic-oscillator potential in the center-of-mass coordinate. This provides a convenient basis in which the intrinsic nuclear motion can be exactly separated from the center-of-mass if a truncation based on the total number of oscillator quanta is used. Although this choice of basis has great advantages, as the motion of the center-of-mass could be a serious contaminant in the calculated wave functions, it is also true that this basis has the wrong asymptotic radial behavior. Furthermore, experience has shown that one-particle, one-hole excitations, which are important for bulk radial properties and isospin mixing, tend to converge slowly with increasing model space. It is highly likely that the description of these states would be significantly improved with a better mean-field basis. Indeed, the HF mean field is explicitly intended to treat these excitations. A strategy would be to employ the standard NCSM effective interaction procedure in a large model space that is computationally intractable for the many-body calculation. In this larger model space, we solve for the HF mean field and perform a unitary transformation on the basis (a strategy already employed in the GHF calculations). With this new mean field, one can either perform a truncated many-body calculation or use the Lee-Suzuki procedure to derive a new effective interaction in a smaller space for the many-body calculation. In general, this is a straightforward procedure, and the primary problem to be addressed is the degree to which possible contamination by the center-of-mass will taint the results.

For the proper treatment of the continuum, we will investigate extensions of the NCSM to include unbound single-particle states. Several challenges abound, however—e.g., the nonorthogonality of these states with the oscillator basis; the separation between the included and excluded P and Q spaces, respectively, and the derivation of the effective interaction; and the separation between the intrinsic and center-of-mass states.

2.3 Toward the Universal Energy Density Functional

Self-consistent methods based on density-dependent effective interactions have achieved a level of sophistication and precision which allows analyses of experimental data for a wide range of properties and for arbitrarily heavy nuclei. For instance, a self-consistent *deformed* mass table has been recently developed[38] based on the Skyrme energy functional. The resulting rms error on binding energies of 1700 nuclei is around several hundred keV, which is comparable with the agreement obtained in the shell-correction approach.

Microscopic mass calculations require a simultaneous description of particle-hole, pairing, and continuum effects—the challenge that only very recently could be addressed by mean-field methods. Recently developed methods[39] allow one to approach the problem of large-scale deformed Skyrme Hartree-Fock-Bogoliubov (HFB) calculations by using the local scaling point transformation[40] that allows modifications of the asymptotic properties of the deformed harmonic oscillator wave functions. Deformed calculations were recently implemented using the parallel computational facilities at ORNL. These facilities allow for calculations in one day of a deformation table for 1,500 nuclei, as shown in Fig. 5. Future calculations, to be performed by researchers affiliated with the Topical Center, will take into account a number of improvements:

- Implementation of the exact particle number projection before variation[41]
- Improvement of the density dependence of the effective interaction, including (1) better treatment of the low-density dependence,[42] (2) corrections beyond the mean-field and three-body effects,[43] (3) the surface-peaked effective mass,[44] and (4) better treatment of pairing[45]

- Proper treatment of the time-odd fields[46]
- Inclusion of dynamical zero-point fluctuations associated with the nuclear collective motion[47,48,49]

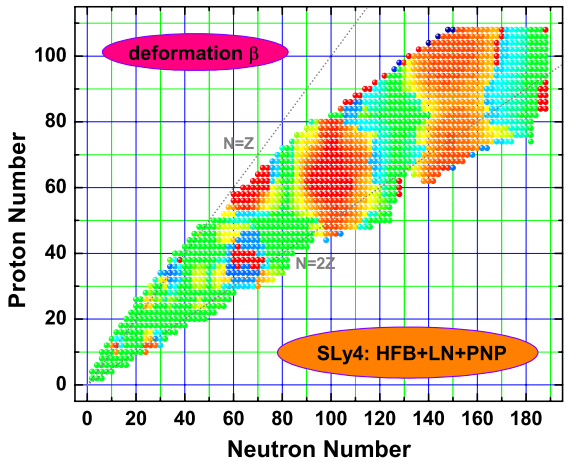

Fig. 5. Nuclear ground state deformations.[39]

The resulting extended functionals will be fitted to nuclear masses, radii, surface thickness, giant vibrations, and other nuclear characteristics.

An alternative to the basis expansion method is to solve the deformed HFB equations on a lattice. HFB calculations for spherical nuclei (1-D radial lattice) have shown that a proper description of dripline nuclei requires continuum states up to at least 60 MeV or higher. Currently available 3-D HFB lattice codes can only take into account continuum states up to about 10 MeV. The 2-D HFB continuum problem for dripline nuclei has also been solved on a 2-D grid in cylindrical coordinates using a Basis-Spline representation of wavefunctions and operators. B-Splines are a generalization of the well-known finite element technique.[50,51] While current 2-D lattices are linear, a major advantage of the B-Spline technique is that it can be extended to nonlinear lattices. Future directions will involve a 3-D HFB code.

These calculations are also important for providing the proper continuum bases for quasiparticle random phase approximation (QRPA) calculations. This is a joint U.S.-Japanese collaborative project supported by an NSF travel grant involving several members of this proposal. Dynamical nuclear properties may also be calculated using mean-field theory. Mean-field plus QRPA calculations of nuclear modes using state-of-the-art nonrelativistic and relativistic approaches are now routine.[52,53] Theoretical models now predict both properties of infinite nuclear matter and the distribution of collective strength in finite nuclei.

In this proposal we plan to study both *exotic modes of normal nuclei and normal modes of exotic nuclei.* Recently the University of Tennessee (UT)/ORNL/University of North Carolina (UNC) collaboration developed a fully self-consistent QRPA-HFB formalism to describe collective modes in neutron-rich nuclei,[52] including exotic isocalar dipole vibrations and pygmy modes. We intend to apply the QRPA formalism to calculate the radiative neutron capture cross sections for r-process nuclei.[54] Beta-decay and neutrino capture are also important astrophysically, and the same techniques may be applied to calculate them.

Another important question to be addressed concerns the sensitivity of the isoscalar giant-monopole resonance in ^{208}Pb to the density dependence of the symmetry energy.[55] Such sensitivity, if it exists, will have an impact on the extraction of the compression modulus of symmetric nuclear matter. These studies will also enable us to understand the relevance of the soft isovector-dipole resonance to supernova dynamics. That is, could the excitation of the Pygmy resonance by all neutrino flavors deposit sufficient energy behind the stalled supernovae shock to produce explosions?[56] We intend to develop a new-generation continuum QRPA code which will use the Berggren HFB basis of bound, decaying, and scattering states. Such a Gamow-QRPA approach will be superior to currently used methods based on matrix diagonalization.

2.4 Nuclear Structure at the Interface

A number of research areas require nuclear structure input to describe physical phenomena. For example, a microscopic theory of electron capture on nuclei and neutrino-nucleus scattering should be taken into account to properly model the supernova explosion mechanism.[57] Nuclear properties also have a significant influence on nucleosynthesis. Finally, nuclei are excellent laboratories for investigating physics beyond the standard model, and nuclear structure input is often essential to extract crucial information.

2.4.1 Nuclear structure, astrophysics, and weak nuclear processes

A model to calculate the stellar electron capture rates for neutron-rich nuclei was recently proposed.[58] These nuclei are encountered in the core collapse of a massive star. Using the Shell Model Monte Carlo (SMMC) approach and a pairing-plus-quadrupole Hamiltonian, one first calculates the finite temperature occupation numbers in the parent nucleus. One then uses these occupation numbers as a starting point for calculations using the random phase approximation. Using the RPA approach, one calculates electron capture rates, including both allowed and forbidden transitions. Such a hybrid model is particularly useful for nuclei with proton numbers $Z < 40$ and $N > 40$, where the allowed Gamow-Teller transitions are only possible due to configuration mixing by the residual interaction and by thermal unblocking of pf-shell single-particle states.

The SMMC method[59] has been used with great success to describe various nuclear properties and reaction rates. While pairing-plus-quadrupole interactions do not have a Monte Carlo sign problem, realistic effective nucleon-nucleon potentials do exhibit such a problem. The Monte Carlo sign problem comes from fluctuations in the sampling of the integrands that render the Metropolis algorithm unstable. In the past one overcame this problem through extrapolation techniques.[60] Extrapolation techniques work well for nuclei near stability, but pose some difficulty for neutron-rich nuclei. By completely restructuring the SMMC code, one is able to take advantage of the method from atomic physics that dramatically reduces the Monte Carlo sign problem described above. This method shifts the contour of integration to the HF minimum of a given Hamiltonian and eliminates fluctuations about that minimum.[61] We have tested this method in sd- and pf-shell nuclei with success for both thermal and ground-state properties of nuclei. Thus, one is in a position to study nuclear physics problems with realistic shell-model interactions and with rigor.[62] We will use the shifted contour technique to study a variety of neutron-rich nuclear phenomena, including electron capture $Z < 40$, $N > 40$ nuclei.

We propose to calculate neutrinoless double-beta decay, which is a complicated but essential task. It is complicated because the nuclear matrix element governing the decay is sensitive to all kinds of nuclear correlations, and there are no observed neutrinoless decays that one can try to reproduce. It is essential because experiments may soon be sensitive enough to see the decay, allowing us to determine the mass of the lightest neutrino and/or to understand the hierarchy in which the masses are arranged, provided the matrix element is known accurately enough. A method for incorporating high-lying excitations into an effective double-beta decay operator was recently developed. We plan to apply the method within the factorization method to improve calculations[63] in ^{76}Ge, one of the most important isotopes for experiment.

Another example of proposed research related to a test of the standard model involves parity and time-reversal symmetry, which can be violated through static moments (anapole moments for parity[64] and electric-dipole moments for time reversal[65]). Calculating them is important for understanding both the behavior of weak interactions in nuclei and physics beyond the standard model. They are usually evaluated in perturbation theory, which requires sums over intermediate states that can be handled by combining sophisticated Skyrme ean-field calculations with the QRPA.[66]

This project ties in with pursuing modern density-functional theory for nuclei and with the RIA program, which plans to produce some of the nuclei that will be used in dipole-moment experiments.

2.4.2 Nucleosynthesis in gamma-ray bursts

Gamma-ray bursts may originate from the deaths of very rapidly rotating high-mass stars.[67,68] The "collapsar" model[69] which describes such objects, produces an accretion disk surrounding a black hole and a jet which punches through the star that is eventually responsible for the gamma rays. There has been much work on the jet, but we instead focus on material that will be ejected from the accretion disk. This material may produce important nucleosynthesis products, and our goal is to understand this nucleosynthesis and the role of charge-changing weak interactions in determining element formation.

As free nucleons flow off the accretion disk, they combine to form nuclei. Elements produced in this way depend on the conditions in the outflow—i.e., the entropy, the timescale, and the electron fraction (which is the number of protons over the total number of nucleons). Complete calculations have not yet been done, but it has been suggested that if this outflow produces the requisite nickel to explain light curves, then other elements whose origin has been up to now a mystery may be produced here.[70] It was also pointed out[71,70] that a careful study of the charge-changing weak interactions is crucial to understanding the nucleosynthesis produced from the disk.

We will use existing calculations[72] of the neutrino and antineutrino fluxes coming from the disk for both optically thin and optically thick regions (the optically thick regions are not spherical but take on a doughnut shape). One can begin with simple models for wind trajectories such as those of Ref. [73], and use a nucleosynthesis reaction network. In the first stage we will calculate the effect of all the charge-changing reactions on free nucleons, and then move on to determine the effect of including such captures on nuclei. Key neutrino-nucleus reactions will be isolated. As input we will obtain estimates of these cross sections from microscopic nuclear theory calculations, thus improving the nucleosynthesis calculations.

3. Topical Center for RIB Theory

In the previous section, we discussed the science that would be performed by members of the Topical Center. In this section we outline various aspects of the Center as we currently envision it. We discuss our institutional readiness for hosting the Topical Center, our scientific expertise that enables us to host the Center, and our goals for the Topical Center.

3.1 Institutional Readiness to Host the Center at the JIHIR

We are institutionally prepared for a RIB Theory Center at ORNL/UT. Traditionally, the ORNL/UT theory group has been close to experimental efforts centered at ORNL's Holifield Radioactive Ion Beam Facility (HRIBF) and the low-energy experimental efforts worldwide. The Holifield facility has been producing exciting nuclear structure and nuclear astrophysics research for nearly 20 years. For the last seven years, it has been the leading U.S. effort in experimental ISOL techniques and rare isotope detection methods. Because HRIBF is being upgraded, ORNL will be the premier experimental RIB facility in the United States for 10+ years. It is thus natural for there to be a cogent nuclear theory effort in the same area at the Laboratory.

The Joint Institute for Heavy Ion Research (JIHIR, shown in Fig. 6) gives us a unique organization that will be useful for implementing several aspects of the Topical Center. The Joint Institute for Heavy Ion Research is a collaborative endeavor between the UT, Vanderbilt University, and ORNL. A large share of its funding comes from the state of Tennessee through the Science Alliance Center of Excellence at the UT. The remainder is provided by Vanderbilt University, the Department of Energy, and ORNL.

Fig. 6. Buildings of the Joint Institute for Heavy Ion Research (JIHIR).

The Joint Institute (1) supports guests, (2) supports workshops and meetings, and (3) operates a dormitory facility. It is housed in two buildings adjacent to HRIBF at ORNL. One of these is a dormitory/office building offering free lodging primarily to HRIBF users while running experiments and to other JIHIR short-term visitors. The other provides office space for visitors and employees of the JIHIR, and two conference rooms that can be used for specialized workshops and conferences. Full or partial support is provided to approximately 60 guests each year. Visits vary in length from a few days up to a full year.

During the last four years, the JIHIR has provided up to $65,000 per year to the UT/ORNL nuclear structure theory effort in support of 1.5 postdoctoral appointments and several visitors per year. Since its inception in 1984, the JIHIR has been one of the main centers of nuclear structure theory in the United States It was explicitly set up for this purpose and has been host for at least 55 long-term (with stays of two months or greater) theorists, including S. Aberg, R. Broglia, J. Dobaczewski, J. Dudek, W. Greiner, S. Gurvitz, A. Kruppa, G. Lalazissis, J. Maruhn, E. Ormand, W. Satula, Z. Szymanski, T. Vertse, and N. Zeldes. Additionally, the JIHIR hosts numerous short-term theory visitors each year.

The JIHIR is a unique institution for performing nuclear structure in the United States and provides a natural infrastructural starting point for the Center. The JIHIR directorate has been informed of our plans to create a Theory Center, and it is ready to help us in that effort.

We have been in discussions with Vanderbilt University and UT concerning future funding for additional office space to house members of the Center. At this time, Vanderbilt has committed $37,500 toward building additional office space at the JIHIR should this proposal become funded. We are also involved in discussions with ORNL, the state of Tennessee, and the Science Alliance at UT concerning matching funding of $425,000 from the state and $37,500 from the university for construction of new office space should this proposal become funded.

3.2 Scientific Expertise of Senior Personnel

The Topical Center for RIB Theory has been crafted as a single entity consisting of 13 investigators who have overlapping strengths and diverse expertise.

David Dean, Witek Nazarewicz, and Thomas Papenbrock of ORNL and UT have broad interests and expertise in low-energy nuclear structure physics and the quantum many-body problem. Dean is co-developer of the SMMC approach to microscopic nuclear structure calculations in medium- to heavy-mass nuclei. Nazarewicz is a co-developer of CSM and has experience and expertise in mean-field theory and its extensions and nuclear structure phenomenology. Papenbrock is a nuclear many-body theorist and works on several problems including the inclusion of relevant correlations via DMRG and wave function factorization.

Bruce Barrett and Bira van Kolck at the University of Arizona bring experience and expertise in both the many-body problem and EFT. Barrett is an expert on the nuclear many-body problem and effective interaction and operator theory, which is important for nuclear structure calculations. He is the co-developer of the ab initio NCSM for microscopically calculating the properties of light nuclei. Van Kolck is one of the co-developers of the EFT approach to understanding the nature of nuclear forces starting from effective Lagrangians.

Volker Oberacker and Sait Umar of Vanderbilt University's nuclear theory group have a long history of collaborative work with Physics Division staff at ORNL. Over the years, they have developed highly accurate HF and TDHF codes using modern numerical techniques and performed large-scale calculations for nuclear structure and heavy-ion reactions, and have investigated non-perturbative electromagnetic lepton-pair production in relativistic heavy-ion collisions. They are responsible for development of the Spline HFB approach.

Jonathan Engel at UNC is working on a number of projects in low-energy nuclear theory and at the interface of nuclear theory, astrophysics, and particle physics. Several of these fit in well with the goals of our proposed center. Engel is an expert in studies of nuclear dynamics and is responsible for development of QRPA algorithms.

Gail McLaughlin at North Carolina State University has expertise in neutrino and nuclear astrophysics and is working on several projects involving weak interactions and element synthesis that mesh well with the low-energy nuclear theory thrust of the RIB Center.

Erich Ormand at LLNL is an expert in low-energy nuclear structure calculations. He is a co-developer of NCSM for ab initio calculations in light nuclei and the SMMC approach to heavier nuclei.

Piotr Piecuch at Michigan State University is a world leader in the development, computer implementation, and applications of coupled-cluster theory for molecular electronic structure, excited electronic states, and molecular properties, including pioneering contributions in areas of multi-reference, renormalized, externally corrected, and high-order coupled-cluster methods, response and equation of motion coupled-cluster approaches, and spin-adapted coupled-cluster theory.

Jorge Piekarewicz and Alexander Volya from Florida State University (FSU) are experts in low-energy nuclear structure theory. Volya works on several problems, including CSM and pairing in nuclei. Piekarewicz has experience and expertise in relativistic mean-field studies of neutron-rich nuclei, low-energy effective operators in EFT, and the nuclear equation of state.

3.3 Roles of the Topical Center

In this section we discuss the various roles that the Topical Center will play in advancing nuclear structure theory. The Center's roles are associated to specific goals and activities.

3.3.1 Scientific role and deliverables

Goal: The Topical Center for RIB Theory will be science-driven.

As has been discussed in Section 2, the Topical Center will derive both excitement and success through its integrated approach to a theoretical description of RIA nuclei. In order to achieve the broad goal of revitalizing the nuclear theory field, the recent NSAC Theory Report "A Vision for Nuclear Theory" recommends that Topical Centers be formed.

The NSAC Theory Report states that proposals for a Topical Center "should be required to have a clear description of their relevance to the goals of the national nuclear science program, and they should contain a list of 'deliverable' results anticipated during the award period." Our scientific goals are taken from the research summaries detailed in Section 2.

Nuclear effective field theory

- We will develop the next generation of model-space effective interactions from NN and NNN interactions for investigating medium-to-heavy mass nuclei.
- We will investigate the description of weakly bound systems based on EFT-derived forces.
- We will use insights from EFT to develop nuclear energy density functionals that respect QCD chiral symmetry.

Microscopic nuclear structure theory

- We will develop CSM schemes for use in drip-line nuclei and for the description of excited nuclear states. The major task will be to develop effective interactions that will properly describe the coupling with the particle continuum.
- We will develop and apply DMRG and factorization methods for finite nuclei. In particular, we will perform structure calculations in the 1p-0f-0$g_{9/2}$ and 0g1d2s model spaces, and compute Gamow-Teller strengths for astrophysically relevant nuclei. We will also apply the DMRG and factorization method to nuclei which have different active model spaces for protons and neutrons.
- We will develop coupled-cluster theory for nuclei. We will incorporate three-body interactions and higher-order effects into the formalism and extend our coupled cluster approaches to excited state. We will develop efficient computer codes for a wide range of coupled cluster methods for the nuclear many-body problem. By the end of 5 years, we expect to approach neutron-rich nuclei in the mass 50–100 region.

Toward the universal energy density functional

- We will develop a reliable energy-density functional that will be used in HFB calculations and their extensions. This functional will include isospin-dependent terms relevant for very unstable nuclei, and will improve the density dependence of the effective interaction. We will implement symmetry projection (e.g., particle number, angular momentum) before variation and will include dynamical correlations due to quantum fluctuations. We will produce a more accurate global description of nuclei including binding energies, radii, and deformations.
- We will employ the functional to describe excited states of nuclei (e.g., within the QRPA approach). We will develop a continuum QRPA code based on the Berggren ensemble.

- We will provide microscopic nuclear physics input essential for astrophysical calculations.

Nuclear structure at the interface

- We will apply microscopic nuclear theory to problems of astrophysical interest such as electron capture on neutron-rich nuclei and neutrino interactions on nuclei. Our deliverable will be a description of these processes for relevant nuclei in the mass 60–120 region of the N-Z chart.
- We will improve calculations of double-beta decay so that crucial information about neutrino masses can be reliably extracted from the next generation of experiments. We will also improve calculations of atomic dipole moments to better constrain extra-standard models of particle physics.
- We will map out the role that neutrino interactions play in determining the nucleosynthesis that comes from the disk of a gamma-ray burst.

3.3.2 Focusing role

Goal: We will identify and solve problems specifically related to nuclei that will be investigated by RIA.

By focusing our research activities, this proposal represents a qualitatively different way of performing nuclear structure research. As has happened with other research communities, this will bring quite positive benefits to nuclear structure theory. As the research portfolio discussed in Section 2 indicates, our combined low-energy nuclear theory efforts cover many overlapping areas of research relevant to RIA theory.

David Dean will be the principal investigator (PI) of the Topical Center. His role will be to provide overall project integration for the Center. He will also be responsible for budget, reporting, and management aspects of the Center. The senior researchers will constitute the Scientific Board, which will be responsible for the scientific program of the Center.

The senior researchers also bring an international collaboration base, as indicated in Fig. 7. The group of senior researchers represents the starting point of the Topical Center. Each member brings complementary expertise to the quantum many-body problem and to nuclear astrophysics problems, and the effort includes world experts in computational many-body physics. The integrated effort will become clear as many researchers are involved in several projects together due to the many intellectual ties between the different research tasks. Table 1 broadly indicates the various research activities of the Center and the senior persons who will carry primary responsibility to deliver on the proposed science in these areas.

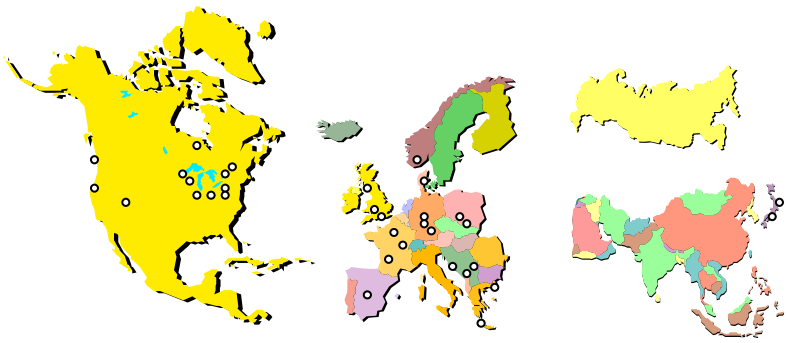

Figure 7: Our collaborations.

Table 1. Senior research roles in the Topical Center for RIB Theory

Area of research	Primary responsibility
Nucleon Effective Field Theory	van Kolck
Microscopic nuclear structure theory	Barrett, Dean, Nazarewicz, Ormand, Papenbrock, Piecuch, Volya
Energy density functionals	Engel, Nazarewicz, Oberacker, Piekarewicz, Umar, van Kolck
Nuclear structure at the interface	Dean, Engel, McLaughlin, Nazarewicz

3.3.3 Seeding role

Goal: The Topical Center will establish a six-person postdoctoral program. The postdoctoral program of the Center will involve shared postdoctoral appointments with our collaborating institutions.

The lack of a sufficient workforce in nuclear theory is a major concern. The need to train young people for future positions in low-energy nuclear theory is crucial to the success of the future RIA facility. The Center's goal for the seeding role addresses several of the issues that have been raised in the current Long-Range Plan and the NSAC Theory Report. While the Center will fund the postdoctoral appointments, each postdoctoral fellow will spend significant time at both the Center and at the collaborating institution. We think that this arrangement will enhance both the Center, through collaborations, and the various collaborating university programs.

The Center's six postdoctoral positions will be shared between the Topical Center at ORNL and the universities as outlined below and as schematized in Fig. 8.

- For the first half of the proposed lifetime of the Center there will be three postdoctoral positions at ORNL. These positions will then be associated with senior personnel at the University of Arizona, FSU, and UNC for the second half of the Center's proposed lifetime.
- Two postdoctoral positions will start out at Michigan State University and LLNL and then go to the Center at ORNL during the second half.
- The University of Tennessee will host one postdoctoral appointment though the lifetime of the Center.

Postdoctoral fellows at the universities will have frequent visits to the Center (up to 3 months per year each). The postdoctoral fellows will be guided by and work with the senior research personnel on tasks relevant to the Center and will be directed by senior personnel at the home institutions. Dean, Nazarewicz, and Papenbrock will be responsible for postdoctoral appointments when they are at the Center. During year four, we will host an Advanced Student Training program, discussed in Section 3.3.4, below.

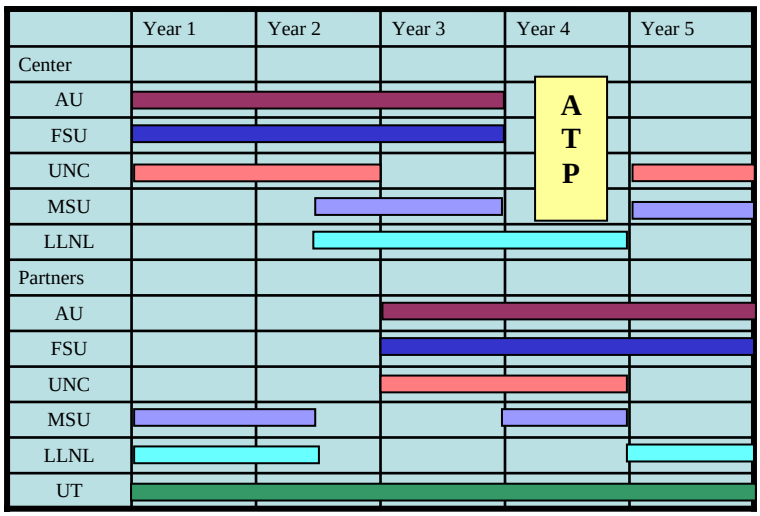

Fig. 8. Schedule for six postdoctoral positions during Topical Center's 5-year lifetime.
Key: AU = Univ. of Arizona, FSU = Florida State Univ., UNC = Univ. of North Carolina, MSU = Michigan State Univ., LLNL = Lawrence Livermore National Laboratory, UT = Univ. of Tennessee, ATP = Advanced Training Program

The Center will also act as a seeding institution for joint faculty positions with several universities, as discussed further in Section 4.

3.3.4 Training role

Goal: The Topical Center will host up to five graduate students who will perform research with members of the Center and will also host summer schools and an Advanced Student Training Program.

We think student training should be a very important part of any Center for RIB Theory. We have experience in this area already. JIHIR sponsored the 2002 RIA summer school, and Nazarewicz is a continuing co-organizer of the school. Dean co-organized the National Nuclear Physics Summer School in 2003, where Ormand and McLaughlin gave lectures. Ormand has also lectured at the RIA Summer School.

The Center will train graduate students in two ways. First, the Center will host up to five graduate students who will perform research with members of the Center. As with the postdoctoral program, mentoring of these students will be a shared responsibility between the Center staff and associated university faculty. The Center will provide a stipend and defray the educational cost of the students.

There will be one student position each at FSU, the University of Arizona, North Carolina State University, the University of Tennessee, and Vanderbilt University. While the Vanderbilt and UT students will spend most of their time at ORNL, the other four students will spend most of their time at their universities and will visit the Center often (up to 3 months a year per student).

The Center will also be involved in hosting summer schools and an Advanced Student Training Program. During year four of this proposal we will host a three-month program for nuclear structure theory students to learn about and apply various technologies that the Center will have developed in the first three years of the Center. Postdoctoral appointments and senior personnel will be involved in this training effort. The Topical Center will play a role in sponsoring the RIA Summer School each year.

3.3.5 Hosting and organizing role

Goals: The Topical Center will coordinate and sponsor workshops, conferences, and other collaborative efforts and host visitors.

Nuclear structure theory is an international endeavor. As we indicate above, our present effort involves numerous collaborators from many different institutions. We are involved in an NSF joint Japan/UT/NCU/Vanderbilt collaboration grant that is being used to foster communications among the United States and Japan theory communities interested in a microscopic description of medium-mass and heavy nuclei. *The Topical Center will work with other international organizations to coordinate both workshops and other collaborative efforts in low-energy nuclear theory.* This will include Joint INT/Center–sponsored workshops.

In addition to workshops, we will run a long-term visitor's program, hosting two to three 6-month visitors per year. We currently host short-term and occasional longer-term visitors through the JIHIR program. Typically, we host four to five visitors per year in this manner. We find this overlap with visitors extremely valuable. We will coordinate these visits for more fruitful discussions. Furthermore, our experimental colleagues at the HRIBF also benefit significantly from visits that we finance. Our present model, while useful, is limited to short-term visits.

Finally, we will organize workshops and conferences on various aspects of low-energy nuclear theory and RIB physics. *The Topical Center will be involved in holding one conference per year on low-energy nuclear theory.* Our activity in this area is already quite significant. For example, we have organized several workshops at the ECT* (Trento), most recently in 1999, 2001, and 2002. We have also organized workshops at the INT (Seattle), and various conferences, including major conferences such as ISOL'01, and ENAM'04, among others. We have also organized, or are in the process of organizing, three-month programs at the INT (Seattle).

4. Benefit Analysis for the Center

4.1 Current Status of the Field

In order to achieve the broad goal of revitalizing the nuclear theory field, the recent NSAC Theory Report *A Vision for Nuclear Theory* recommends that in addition to scientific deliverables, Topical Centers "would be expected to function as hubs of a wider network of scientists dispersed over various institutions (a focusing role), should have funds to support a sustained interaction and collaborations within this network, and should provide a vehicle to seed new faculty and staff."

Our goal with this proposal is to address the key issues laid out by the NSAC Theory Report. Low-energy nuclear theory faces several challenges in order to meet the needs of present facilities and the advent of RIA. We estimate that the number of active low-energy nuclear theorists who hold permanent positions at universities or national laboratories is on the order of 45 people, with

about two-thirds of these people being very active. This low number of people is not enough to attain the scientific goals of the community. We think a larger number of approximately 60 active theorists would be more appropriate. The researchers of this proposal represent an effort to focus research goals appropriately so that national nuclear needs related to the scope of the Center will be met in a timely fashion. Also, growth to meet the challenges of the next 20 years is very important. This has been recognized in numerous reports over the last few years, including the 2002 Long-Range Plan and the 2003 Vision for Nuclear Theory NSAC report.

4.2 Bridging and Seeding Positions

Since ORNL came under the management of UT-Battelle in 2000, the Laboratory has instituted Joint Faculty Appointments (JFAs) with its core universities, which are also involved in management and oversight of the Laboratory. The core universities are UT, Duke University, Georgia Tech, FSU, North Carolina State University, the University of Virginia, and Virginia Tech. At some point in the near future, Vanderbilt University may join this list. The deputy director of science and technology at the Laboratory, Lee Reidinger, has also indicated that joint faculty positions may also be extended to other institutions with a strong connection to the Laboratory. In the context of the Topical Center for RIB theory, we have discussed the potential of funding JFAs with Florida State (see the attached supporting letter from Florida State) and UT (new nuclear theory positions are contained in the Physics Department's long-range plan). Two institutions which are not a part of the core university system but which have interest in pursuing joint appointments are UNC and the University of Arizona. Should the Center become a reality, there would follow serious negotiations for these positions. It is clear from our discussions that JFAs are viable ways to provide scientific staffing for the Topical Center and also provide a vehicle to increase the number of faculty performing nuclear science research at the universities. We discuss four potential seeding opportunities in the following.

4.2.1 University of Arizona

The Department of Physics of the University of Arizona has for many decades supported a strong effort in nuclear physics. Currently, the nuclear theory group consists of four tenured professors, doing research in nuclear effective field theories, nuclear structure, and relativistic heavy-ion physics.

The department has also had a history of interest in bridge positions. The youngest professor in the group, Dr. Bira van Kolck, has been hired in a bridge position with the RIKEN BNL Research Center at Brookhaven. By the end of the 2003/2004 academic year, he will be full time at the University of Arizona.

The reputation of our nuclear effort has attracted to the group some of the top graduate students in the department. New faculty and further funds will allow for the continuation of this effort, and remedy the current situation in which we have had to turn away other good students.

A number of faculty working on various aspects of strong-interaction physics have retired or died in the recent years. A case has been made to the department that new hires are required for the healthy continuation of the prominent status of the University of Arizona in this field. The department head, Dr. Daniel Stein, has committed to the hiring of at least one new faculty working on modern nuclear theory within the next couple of years.

4.2.2 Florida State University

See the attached letter from the department chair at FSU.

4.2.3 University of Tennessee

In recent planning decisions by the UT Department of Physics and Astronomy, two faculty positions were promised to nuclear theory. One of these positions will be in many-body physics related to RIA, and another position will be related to fundamental symmetries. See the attached document concerning these plans.

4.2.4 University of North Carolina

The Department of Physics and Astronomy at UNC–Chapel Hill has developed a hiring plan to cover the next several open positions. Three of the first ten positions have been filled; among the remaining seven positions is one in theoretical nuclear astrophysics. This has been seen as including such fields as explosive nucleosynthesis, neutrino physics, or advanced stages of stellar evolution. A joint appointment between ORNL and this department has several advantages to both programs, and UNC would be very interested in further discussions. The timetable for filling such a position is not yet determined, but a joint appointment might accelerate the process.

4.3 Support to Experimental Activities

We often publish joint papers with experimental colleagues. We view interactions with our experimental colleagues as an invaluable part of our general scientific work. The Center will continue to provide support for the nuclear structure and nuclear astrophysics communities in this way.

In addition to our scientific discussions with experimentalists, and our theoretical developments and proposed research mentioned in the previous sections, members of the Center have been involved in making the scientific case for the Rare Isotope Accelerator (RIA) for many years. Currently, one of us is the chair of the RIA Steering Committee; three of us are members of the RIA Theory Steering Committee. We have contributed to numerous white papers and town meetings devoted to developing the scientific case for RIA (as indicated in Fig. 9). These meetings include the 1995 TUNL town meeting; the 1996 Long-Range Plan; the 1997 Columbus RIB physics report; the 2000 Durham RIA white paper; the 2001 Oakland town meeting; the 2001 NRC Report on Nuclear Science; the 2002 Long Range Plan; and the 2003 white paper on Interdisciplinary Aspects of RIA. We were also involved in Orbach's January 2003 strategic planning meeting for the Office of Science and have briefed the Office of Science, OSTP, and OMB on RIA. For over ten years we have been at the intellectual center of efforts to make RIA real.

Fig. 9. Making the case for RIA.

5. References

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