Prospects for New Science with EM Devices*

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Nuclear life in neutron-rich and proton-rich *Terra Incognita* is different from that around the stability line; the promised access to completely new combinations of proton and neutron numbers offers prospects for new structural phenomena. The main objective of this talk is to discuss some of the theoretical challenges and opportunities for nuclear structure research with new Electro-Magnetic Isotope Separators.

1. INTRODUCTION

Low-energy nuclear physics is undergoing a renaissance. Experimentally, there has been a technological revolution which made it possible to dramatically improve the "signal-to-noise" ratio. The next-generation experimental tools, to which this conference is devoted, invite us on the journey to the vast territory of nuclear existence which has never been explored by science. Hand in hand with experimental developments, a qualitative change in theoretical modeling is taking place. Due to the progress in computer technologies and numerical algorithms, it has became exceedingly clear that the unified microscopic understanding of the nuclear many-body system is no longer a dream. There has been real progress in many areas of theoretical nuclear structure. The effective field theory

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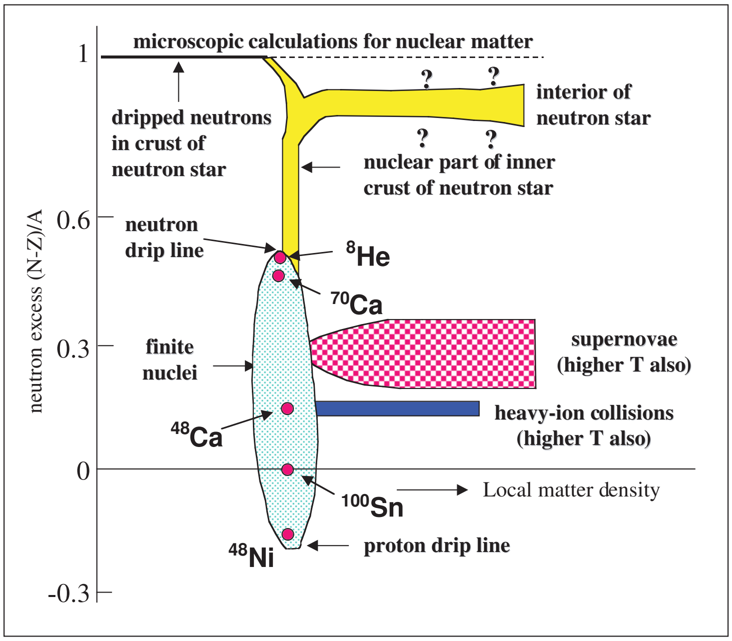

Figure 1. Diagram illustrating the range of nucleonic densities and neutron excess of importance in various contexts of the low- and intermediate-energy nuclear many-body problem. (Based on Ref. [1].)

offers hope for a link between QCD and nucleon-nucleon forces. New interactions have been developed which, together with a powerful suite of *ab-initio* approaches, provide a quantitative description of light nuclei. For heavy systems, *global* modern shell-model approaches and self-consistent mean-field methods offer the level of accuracy typical to phenomenological approaches based on parameters *locally* fitted to the data. By exploring connections between models in various regions of the chart of the nuclides, nuclear theory aims to develop a unified description of the nucleus.

From a theoretical point of view, short-lived exotic nuclei far from stability with "abnormal" neutron-to-proton ratios offer a unique test of those aspects of the many-body theory (e.g., effective interactions) that depend on the isospin degrees of freedom. Figure 1 shows the battlefield – the territory of various domains of nuclear matter characterized by the neutron excess, $(N-Z)/A$, and the isoscalar nucleonic density ($\rho = \rho_n + \rho_p$). In this diagram, the region of finite (i.e., particle-bound) nuclei extends from the neutron excess of about -0.2 (proton drip line) to 0.5 (neutron drip line). The next-generation radioactive nuclear beam (RNB) facilities will provide a unique capability for accessing the very asymmetric nuclear matter and for compressing neutron-rich matter approaching density regimes important for supernova and neutron star physics that are indicated in Fig. 1. The hope is that after probing the limits of extreme isospin, we can later go back to the valley of stability and improve the description of normal nuclei.

2. NUCLEAR STRUCTURE THEORY: QUESTIONS AND CHALLENGES

Theoretical nuclear structure deals with the nuclear many-body problem in the very finite limit of particle number. In the non-relativistic limit, the goal is to solve the many-body Schrödinger equation with the nuclear Hamiltonian $\hat{H}$:

$$\hat{H}\Psi = E\Psi. \tag{1}$$

Unlike other areas of the many-body problem (atomic physics, condensed matter physics), nuclear physics is still struggling to understand the origin of the force which produces nuclear binding. Although it is clear that the nucleon-nucleon (NN) interaction has its roots in quark-gluon dynamics, the microscopic derivation is not yet in place. To add insult to injury, due to strong in-medium effects, additional complications arise when one tries to derive the *effective* inter-nucleon interaction in the heavy nucleus. This brings us to the first major scientific question pertaining to Eq. (1): *What is the effective nuclear Hamiltonian?* In this context, some specific issues related to the RNB experimentation are: What is the $(N - Z)$ and mass dependence of the effective NN interaction? What is the interaction dependence on spin degrees of freedom? What is the interplay between strong, electromagnetic, and weak components of the NN force? What is the nuclear matter equation of state?

The second major challenge pertaining to Eq. (1) – *What is the nature of the nucleonic matter?* – concerns the properties of the many-body wave function Ψ. Here, the specific fundamental questions are: What is the microscopic mechanism of nuclear binding? Which combinations of protons and neutrons make up a nucleus? What is the single-nucleonic motion in a very neutron-rich envirovment? What are the collective phases of nucleonic matter? What is the nature of collective modes of the nucleus (a finite fermion system having a pronounced surface)? What are relevant collective degrees of freedom? How to understand microscopically the large-amplitude nuclear collective motion (fusion, fission, coexistence phenomena)?

Coming back to RNB physics, there are many theoretical challenges related to nuclei far from stability. Clearly, it is not "business as usual"! In many respects, weakly bound exotic nuclei are indeed much more difficult to treat theoretically than well-bound systems [2]. The major theoretical difficulty and challenge is the treatment of the particle continuum. The residual-interaction coupling to the continuum can influence nuclear binding, effective interaction, and core polarization. It can give rise to a new class of collective phenomena (soft modes). Continuum can also dramatically influence shell structure, many-body correlations (such as pairing) and can impact the appearance of cluster structures. Consequently, many cherished approaches of nuclear theory such as the conventional shell model and the pairing theory must be modified in order to properly take into account unbound states. But there is also a splendid opportunity: the presence of low-lying scattering states invites 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. And, of course, nuclear structure effects can clearly manifest themselves in reactions involving exotic nuclei. Some examples, nicely illuminating this point, are presented in the following sections.

3. PAIRING IN NEUTRON-RICH NUCLEI

A proper theoretical description of weakly bound heavy systems requires taking into account the particle-particle (p-p, pairing) correlations on the same footing as the particle-hole (p-h) correlations, which – on the mean-field level – is done in the framework of the theories based on the Hartree-Fock-Bogoliubov (HFB) method. In this method, it is essential to solve the equations for the self-consistent densities and mean fields in order to allow the pairing correlations to build up with a full coupling to particle continuum [3,4].

Since in finite nuclei no derivation of the pairing force from first principles is available yet, there are many variations in the choice of pairing forces used in calculations. Unfortunately, for drip-line nuclei, in which the pairing effects are crucially important due to the coupling to the continuum, the effective pairing interaction is not known. Recently, we discussed this problem in a series of papers [6–8] within the coordinate-space spherical HFB. In the actual HFB calculations based on the Skyrme forces in the p-h channel (as, e.g., the SLy4 parametrization [9] used in our work), contact pairing interaction is usually used. Two different forms have been used up to now – the volume type, $V^{\delta}_{\rm vol}(\mathbf{r},\mathbf{r}') = V_0\ \delta(\mathbf{r}-\mathbf{r}')$, or the surface type, $V^{\delta}_{\rm surf}(\mathbf{r},\mathbf{r}') = V_0\ [1-(\rho(\mathbf{r})/\rho_0)^{\alpha}]\ \delta(\mathbf{r}-\mathbf{r}')$, where ρ_0=0.16 fm^{-3} is the saturation density, V_0 defines the strength of the interaction, and α governs the intensity of interaction at low densities [6]. (The origin of the terms "volume" and "surface" has been discussed in Refs. [4,10].) In reality, however, the pairing interaction is most likely of an intermediate character between the volume and surface forms. In particular, the force which is a fifty-fifty mixture of both types,

$$V^{\delta}_{\rm mix}(\mathbf{r},\mathbf{r}') = \frac{1}{2}\left(V^{\delta}_{\rm vol} + V^{\delta}_{\rm surf}\right), \tag{2}$$

performs quite well [8,11] in reproducing the general mass-dependence of the odd-even mass staggering parameter $\Delta^{(3)}$ centered at odd particle numbers [12,13].

Figure 2 illustrates the impact of different pairing interactions on neutron pairing gaps in very neutron-rich isotones around N=82. The experimental data that exist for $Z{\geq}50$ do not indicate any definite change in neutron pairing with varying proton numbers. However, the surface pairing interactions (bottom panels) give a slow dependence for $Z{\geq}50$ that is dramatically accelerated after crossing the shell gap at Z=50. On the other hand, the volume and intermediate-type pairing forces predict a slow dependence all the way through to very near the neutron drip line. (It is worth noting that both experimentally and theoretically neutron pairing *decreases* in Sn and Te isotopes as one goes across the N=50 magic gap. We shall come back to this observation in Sec. 5.) It is clear that measurements of only several nuclear masses on neutron-rich nuclei with $Z{<}50$ will allow us to strongly discriminate between the pairing interactions that have different density dependencies.

4. SELF-CONSISTENT MASS TABLE

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 [14,15] based on the Skyrme energy

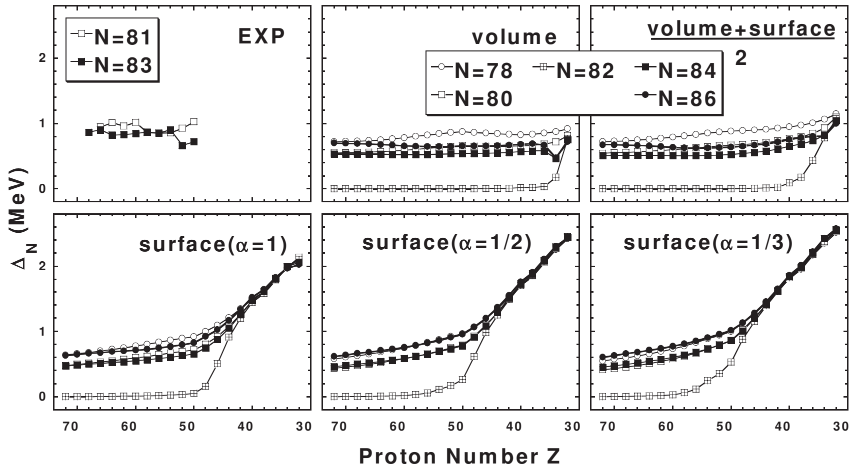

Figure 2. Comparison between the experimental neutron pairing gaps Δ_N (upper left panel) and the corresponding results of the spherical HFB method for the Skyrme SLy4 force [9] and five different versions of the zero-range pairing interaction (see text).

functional. The resulting rms error on binding energies of 1700 nuclei is around 700 keV, i.e., is comparable with the agreement obtained in the shell-correction approaches.

Such calculations require a simultaneous description of p-h, pairing, and continuum effects – the challenge that only very recently could be addressed by mean-field methods. Very recently we have developed methods [16–18] to approach the problem of large-scale deformed HFB calculations by using the local-scaling point transformation that allows us to modify asymptotic properties of the deformed harmonic oscillator wave functions. Such calculations can be optimized to take advantage of parallel computing. (For example, it takes only one day to calculate the full self-consistent even-even mass table considering prolate, oblate, and spherical shapes!) This enables theorists to optimize effective interactions by adjusting their parameters to experimental binding energies and other observables. While the results of calculations of a complete HFB mass table will be reported in separate publications [18], Fig. 3 shows the calculated deformations $|\beta|$ for 1553 particle-bound even-even nuclei with $Z\leq108$ and $N\leq188$ obtained with the SLy4 Skyrme interaction and the intermediate-type pairing force (2).

As one can see, there are several deformed regions around the neutron drip line where theory predicts significant deformations; hence the presence of rotational collectivity. The calculations also predict a very interesting effect of long sequences of semi-magic nuclei (e.g., Z=50 and N=82) intruding in the territory of unbound nuclei. This is the result of vanishing pairing correlations, for which the Fermi energy coincides with the last occupied level, while in the neighboring nuclei it is located higher.

5. COLLECTIVE MODES IN NEUTRON-RICH NUCLEI

Correlations due to pairing, core polarization, and clustering are crucial in exotic nuclei. In neutron drip-line systems, skin excitations (soft modes, pygmy resonances) represent new collective modes characteristic of weakly bound nuclei. Since the energy of the pigmy

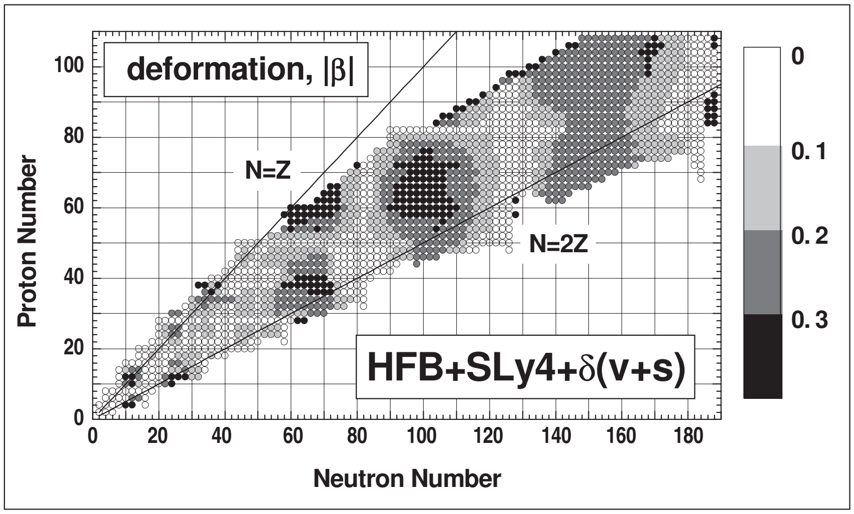

Figure 3. Ground-state quadrupole deformations $|\beta|$ obtained in large-scale deformed HFB calculations for particle-bound even-even nuclei with $Z{\leq}108$ and $N{\leq}188$. To produce such a mass/deformation table, it takes only one day on a modern parallel computer.

resonance in neutron-rich nuclei is close to the neutron separation energy, the presence of soft vibrational modes is also important in the context of the astrophysical r-process [19].

Figure 4 demonstrates, however, that one does not need to go all the way to the neutron drip line to see surprising deviations from well-established trends. The diagram shows the systematics of experimental data for 2^+_1 states around ^{132}Sn. Interestingly, both excitation energies and $B(E2)$ values exhibit an unusual pattern as one crosses N=82. Namely, there is a striking asymmetry in the position of 2^+_1 levels in N=80 and 82 isotopes of Sn and Te, and the $B(E2;0^+\rightarrow 2^+_1)$ rate in ^{136}Te stays unexpectedly low [20], defying common wisdom that the decrease in $E_{2^+_1}$ in open-shell nuclei must imply the increase in $B(E2;0^+\rightarrow 2^+_1)$.

In order to explain this unusual patter, we performed calculations using the Quasiparticle Random Phase Approximation (QRPA) with the separable quadrupole-plus-pairing Hamiltonian [21]. Whenever possible, s.p. energies were taken from experiment [22] (the remaining levels were calculated). For the two-body residual interaction used in QRPA, we took the quadrupole-quadrupole forces (with both isoscalar and isovector components) and the quadrupole pairing force [23]. The monopole pairing gaps were taken from experiment [12] except for magic nuclei (Z=50 and/or N=82) where we have used Δ=0.4 MeV. Since in QRPA we employed a large configuration space, the $B(E2)$ rates were calculated using bare charges.

Our calculations reproduce well the experimental pattern displayed in Fig. 4 [21]. The observed abnormal behavior in ^{136}Te and ^{134}Sn has been explained in terms of the reduction in the neutron pairing gap when going from N=80 to N=84 (resulting from the lowered density of the neutron s.p. states above N=82). As seen in Fig. 4, for larger values of $\Delta_n > 0.7$ MeV, one obtains the familiar pattern ($E_{2^+_1}$ increases while $B(E2)$ decreases), while at intermediate values of pairing both excitation energy and transition

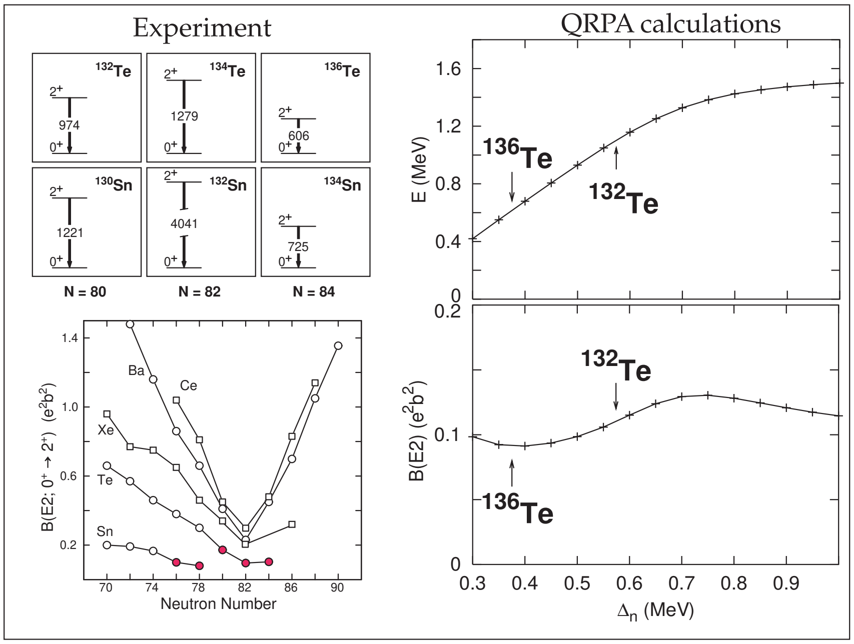

Figure 4. Left: experimental 2_1^+ levels in N=80,82,84 Sn and Te isotopes and measured values of $B(E2; 0^+ \rightarrow 2_1^+)$ for even-even Sn, Te, Xe, Ba, and Ce isotopes around neutron number N=82. Filled symbols indicate the recent RNB measurements at the HRIBF facility at ORNL (from Ref. [20]). Right: energy and $B(E2)$ of the 2_1^+ state in ^{136}Te as a function of the neutron pairing gap. The values of Δ_n in ^{132,136}Te are marked by arrows (from Ref. [21]).

rate *increase* with Δ_n. The idea of reduced neutron pairing in N=84 Sn and Te isotones is consistent with the experimental odd-even mass differences and results of mixed-pairing calculations shown in Fig. 2, and also explains the unusual lowering of the energies of 2_1^+ states in ^{136}Te and ^{134}Sn (which are primarily two-quasineutron in character).

6. CONTINUUM SHELL MODEL

The consistent treatment of continuum states, both in nuclear structure and reactions, is an old problem which has been a playground of the continuum shell model (CSM) [24,25]. In the CSM, including the recently developed Shell Model Embedded in the Continuum (SMEC) [26], the scattering states and bound states are treated on an equal footing. So far, most applications of the CSM, including SMEC, have been used to describe limiting situations in which there is coupling to *one-nucleon decay channels* only. There have been only a few attempts to treat the multi-particle case and, unfortunately, the proposed numerical schemes, due to their complexity, have never been adopted in shell-model calculations. Recently, we formulated and tested the multiconfigurational shell model in the complete Berggren basis [27], the so-called Gamow Shell Model (GSM). (For application to two-particle resonant states, see also Ref. [28].) By going into the complex momentum (or energy) plane, GSM overcomes a number of difficulties pertaining to the traditional CSM; in particular, it can easily be applied to systems containing several valence neutrons.

The main idea behind GSM is the use of Gamow (or resonant) states [29] – generalized eigenstates of the time-independent Schrödinger equation with complex energy eigenvalues. These states correspond to the poles of the S-matrix in the complex energy plane lying on or below the positive real axis; they are regular at the origin and satisfy purely outgoing asymptotics.

In GSM, the single-particle (s.p.) basis corresponds to eigenstates of a spherical single-particle finite potential (such as a Woods-Saxon potential). The generalized completeness relation involving Gamow states [30,31] can be written as:

$$\sum_n |\phi_{nj}\rangle\langle\tilde{\phi}_{nj}| + \frac{1}{\pi}\int_{L_+} |\phi_j(k)\rangle\langle\phi_j(k^*)|\, dk = 1, \tag{3}$$

where ϕ_{nj} are the Gamow states carrying the s.p. angular momentum, j, n stands for all the remaining quantum numbers, $\phi_j(k)$ are the scattering complex-momentum states, and the contour L_+ in the complex k-plane has to be chosen in such a way that all the poles in the discrete sum in Eq. (3) are contained in the domain between L_+ and the real energy axis. (In practical calculations, the integral in Eq. (3) is discretized.) If the contour L_+ is chosen reasonably close to the real energy axis, the first term in (3) represents the contribution from bound states and narrow resonances, while the integral part accounts for the non-resonant continuum. Gamow resonances and the Berggren basis (3) have been employed in a number of calculations involving one-body continuum [32]. Examples are s.p. level density calculations [33] and studies of deformed proton emitters [34,35].

The crucial problem pertaining to the interpretation of the CSM results is the selection of states associated with resonant excitations of the system. Bound states can be clearly identified, because the imaginary part of their energy must be zero. No equally simple criterion exists for resonance states. Fortunately, the coupling between scattering states and resonant states is usually weak; hence, one can determine the physical resonances by considering first the subspace of Gamow states (the so-called pole expansion) and then by adding the non-resonant continuum. In the following example of GSM calculations, we shall consider the case of $^{6-9}$He with the inert ^{4}He core and 2-5 active neutrons in the p shell. (For details and more examples, including the chain of neutron-rich oxygen isotopes, see Refs. [27,36].) Our aim is not to give the precise description of these light nuclei (for this, one would need a realistic Hamiltonian and a large configuration space), but rather to illustrate the method and underlying features.

A description of the neutron-rich helium isotopes, including Borromean nuclei ^{6,8}He, is a challenge for the GSM. ^{4}He is a well-bound system with the one-neutron emission threshold at 20.58 MeV. On the contrary, the nucleus ^{5}He, with one neutron in the p shell, is unstable with respect to the neutron emission. Indeed, the $J^\pi = 3/2^-_1$ ground state of ^{5}He lies 890 keV above the neutron emission threshold and its neutron width is large, Γ=600 keV. The first excited state, $1/2^-_1$, is a very broad resonance (Γ=4 MeV) that lies 4.89 MeV above the threshold. In our GSM calculations, the states in ^{5}He are viewed as one-neutron resonances outside of the ^{4}He core. For the s.p. field, we took a Woods-Saxon potential and for the residual interaction we assumed the surface-delta interaction. As seen in Fig. 5, GSM calculations reproduce the most important feature of ^{6}He and ^{8}He: *the ground state is particle-bound, despite the fact that all the basis states lie in the*

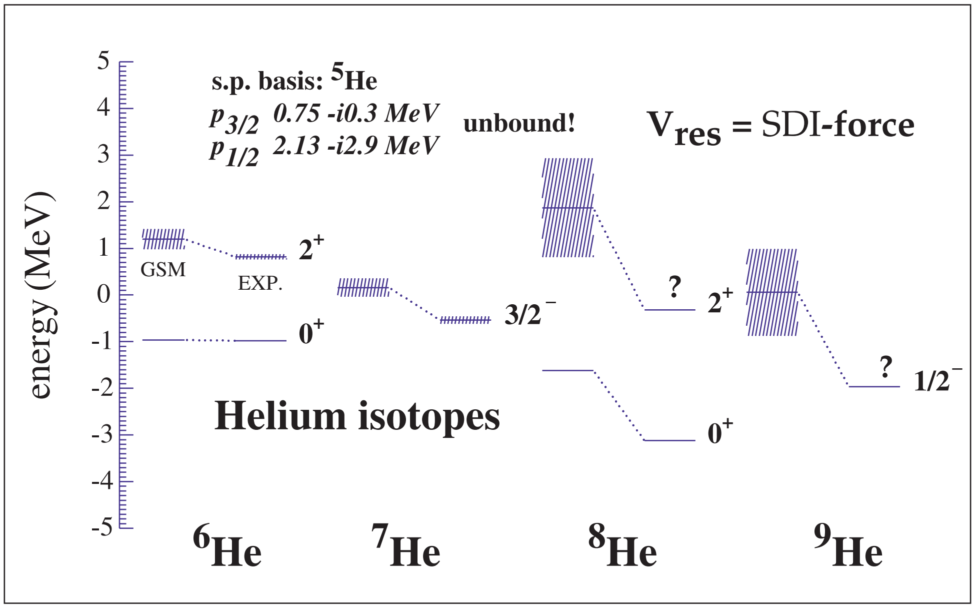

Figure 5. Experimental (EXP) and predicted(GSM) binding energies of $^{6-9}$He as well as energies of $J^{\pi}=2^+$ states in ^{6,8}He. The resonance widths are indicated by shading.

continuum. In spite of a very crude Hamiltonian, rather limited configuration space, etc., the calculated ground state energies reproduce surprisingly well the experimental data. The neutron separation energy anomaly (i.e., the *increase* of the neutron separation energy when going from ^{6}He to ^{8}He) is reproduced. Also, the energies of excited 2^+_1 states are in fair agreement with the data. As discussed in Refs. [27,36], the contribution from the non-resonant continuum to the ground state wave functions of Borromean systems ^{6}He and ^{8}He is very large.

7. Conclusions

The main objective of this brief review was to discuss various challenges in theoretical nuclear structure, especially in the context of RNB physics. There are many unique features of exotic nuclei that give prospects for entirely new phenomena likely to be different from anything we have observed to date. New-generation data will be crucial in pinning down a number of long-standing questions related to the effective Hamiltonian, nuclear collectivity, and properties of nuclear excitations.

This conference is about new experimental tools for research in low-energy nuclear physics. But also in nuclear theory we are witnessing dramatic progress both in technology and in methods. Microscopic nuclear physics calculations can be quantitative! As one experienced physicist remarked some time ago, nuclear theorists prefer to solve approximate (i.e., simple) models exactly or to solve exact (i.e., microscopic) models approximately rather than to do the real job. The time has come to start solving exact models exactly...

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