NUCLEAR STRUCTURE NEAR THE DRIP LINES*

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Nuclear Structure Near the Drip Lines

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Abstract. Experiments with beams of unstable nuclei will make it possible to look closely into many aspects of the nuclear many-body problem. Theoretically, exotic nuclei represent a formidable challenge for the nuclear many-body theories and their power to predict nuclear properties in nuclear terra incognita.

INTRODUCTION

One of the main frontiers of nuclear structure today is the physics of radioactive nuclear beams (RNB). One of the indications of the potential of this field is the large international interest in it [1-5]. At present there are only a few laboratories with radioactive ion beam capabilities. However, the prospects for new experiments and the success of the current programs have led to a number of RNB facilities under development and a number of further proposals worldwide, including the construction of the next-generation facilities in Europe, U.S., and Japan. There are several major key themes behind the RNB program [2]. They include: (i) nuclear structure (the nature of nucleonic matter), (ii) nuclear astrophysics (the origin of the Universe), and (iii) physics of fundamental symmetries (tests of the Standard Model).

The nuclear landscape, the territory of the RNB physics, is shown in Fig. 1. Black squares indicate stable nuclei; there are less than 300 stable nuclei, or those long-lived, with half-lives comparable to or longer than the age of Earth. Some of the unstable nuclei can be found on Earth, some are man-made, and several thousand nuclei are the yet-unexplored exotic species belonging to nuclear "terra incognita". Moving away from stable nuclei by adding either protons or neutrons, one finally reaches the particle drip lines where the nuclear binding ends. The nuclei beyond the drip lines are unbound to nucleon emission; that is, for those systems the strong interaction is unable to cluster A nucleons as one nucleus. (An exciting question is whether there can possibly exist *islands* of stability beyond the neutron drip line. One of such islands, indicated in Fig. 1, is a neutron star which exists thanks to gravitation. So far, calculations for light neutron drops have not produced permanent binding [6,7].)

The uncharted regions of the (N, Z) plane contain information that can answer many questions of fundamental importance for science: What are the limits of nuclear existence? What are the properties of nuclei with an extreme N/Z ratio? What is the effective nucleon-nucleon interaction in the nucleus having a very large neutron excess? There are also related questions in the field of nuclear astrophysics. Since radioactive nuclei are produced in many astrophysical sites, knowledge of their properties is crucial for our understanding of the underlying processes [8,9].

Nuclear life far from stability 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 challenges and opportunities of research with radioactive nuclear beams.

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FIGURE 1. The nuclear landscape: territory of radioactive nuclear beams. Some of the important physics themes are indicated schematically. They include: weakly bound nuclear halos, neutron skins and their excitation modes, modifications of shell structure at large N/Z ratios, proton emitters, proton-neutron superconductivity, nuclear tests of the Standard Model, and nucleosynthesis.

NUCLEAR MANY-BODY PROBLEM

The main goal of nuclear structure is to understand how does the nucleus, a fascinating many-body system bound by strong interaction, work. The answer to this question is of fundamental importance. After all, nucleonic matter makes up 99.9 percent of the Universe we live in.

The common theme for the field of nuclear structure is that of the nucleon-nucleon (NN) interaction which clusters nucleons together into one composite system. Figure 2 shows, schematically, our main strategy in our quest for understanding the nuclear force in the context of the hadronic and nucleonic many-body problem. The free NN force can be viewed as a residual interaction of the underlying quark-gluon dynamics of QCD, similar to the intermolecular forces that stem from QED. Some of the challenges related to the nature of the bare NN interaction and the structure of light nuclei have been addressed in the talk by Machleidt [11]; see also the review by Friar [12]. Due to in-medium effects, the NN force in heavy nuclei differs considerably from the free NN interaction. A challenging task is to relate this effective force to that between free nucleons (see Refs. [13–16] for recent developments). Figure 2 illustrates the intellectual connection between the hadronic many-body problem (quark-gluon description of a nucleon) and the nucleonic many-body problem (nucleus as a system of Z protons and N neutrons). It probably would be very naive to think of the behavior of a heavy nucleus directly in terms of the underlying quark-gluon dynamics, but undoubtedly the understanding of the bridges in Fig. 2 will make this goal qualitatively possible.

From a theoretical point of view, spectroscopy of exotic nuclei offers a unique test of those components of effective interactions that depend on the isospin degrees of freedom. Here, the important questions asked are [17]: What is the density dependence of the two-body force? What is the density and radial dependence of the one-body spin-orbit force? What is the form of the pairing interaction in weakly bound nuclei? What is the

Nuclear Forces and The Nuclear Many-Body Problem

FIGURE 2. From hadrons to heavy nuclei: main challenges in understanding the nuclear force. (From Ref. [10].)

role of the medium effects (renormalization) and of the core polarization in the nuclear exterior (halo or skin region) where the nucleonic density is small?

From the perspective of low-energy nuclear physics, the *effective* building blocks of a nucleus are protons and neutrons. In spite of this simplifying assumption, the dimension of the nuclear many-body problem is overwhelming. Nuclei are exceedingly difficult to describe; they contain too many nucleons to allow for an exact treatment and far too few to disregard finite-size effects. We have learned a great deal about nuclear modes using phenomenological models, often based on ingenious intuition and symmetry considerations. These models and approximations have been extremely successful in interpreting nuclear states and classifying nuclear excitations and decays. Based on this experience, and thanks to the developments in theoretical modeling and computer technology, we are now on the edge of the *microscopic description*. By taking advantage of modern many-body algorithms, one can shorten the cycle theory $\leftrightarrow$ experiment $\leftrightarrow$ theory.

While the very light nuclei can nowadays be described as A -body clusters bound by a free NN force, the conceptual framework of larger nuclei is still that of the nuclear shell model. There has been substantial progress in the area of the conventional shell model. The tractable configuration spaces are growing steadily, no-core calculations are coming, and microscopic effective interactions are being developed and employed. Traditional shell-model techniques make it possible to approach the collective nuclei from the pf shell; the calculations involve model spaces with dimensions of several millions. However, progress in this area is going to be very slow due to exploding dimensions when increasing the number of valence nucleons.

For nuclei close to the magic ones, the low-energy properties depend primarily on the behavior of a few valence nucleons. However, for nuclei with many valence particles, as well as for intruder configurations involving many particle-hole excitations, the concept of valence nucleons is less useful, and the valence and inner-shell nucleons have to be treated on an equal footing. Here, a useful starting point is the self-consistent mean-field theory with the density-dependent effective NN interaction. Thanks to developments in computational techniques, the Hartree-Fock-Bogolyubov (HFB) and relativistic mean-field (RMF) approaches employing microscopic effective interactions are now widely used and – in terms of their predictive power – favorably compare with results of more phenomenological macroscopic-microscopic models.

Figure 3 displays two-neutron separation energies for the Sn isotopes calculated in several state-of-the-art models based on the self-consistent mean-field theory: HFB-D1S (based on finite-range Gogny interaction D1S [18]), HFB-SkP and HFB-SLy4 (based on zero-range Skyrme parametrizations SkP [19] and SLy4 [20]), LEDF

FIGURE 3. Two-neutron separation energies, S_{2n} , for the Sn isotopes calculated in five microscopic models: HFB-D1 (courtesy of J. Dechargé), HFB-SkP and HFB-SLy4 (courtesy of J. Dobaczewski), LEDF (courtesy of S. Fayans), and RHB-NL3 (courtesy of G. Lalazissis). The experimental data are indicated by stars.

(local energy-density functional model with parametrization FaNDF⁰ [21]), and RHB-NL3 (relativistic Hartree-Bogolyubov model with NL3 parametrization [22]). All models nicely describe the existing experimental data; some interesting deviations are seen when approaching the proton drip line.

THEORETICAL CHALLENGES FAR FROM STABILITY

Nuclear life at extreme N/Z ratios is different from that around the stability line. The unique structural factor is the weak binding; hence the closeness to 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 must be modified. (For an extensive discussion of the theoretical perspectives far from stability, see the recent review [17].) But there is also a splendid opportunity: the explicit coupling between bound states and continuum, and the presence of low-lying scattering states invite strong interplay and cross-fertilization between nuclear structure and reaction theory.

How can one extend traditional tools of nuclear theory to account for the scattering of nucleons from bound single-particle orbitals to unbound states? The closeness of the particle continuum reverberates in two aspects of the theoretical description. Firstly, the particles forming a bound nuclear state can virtually scatter back and forth into the particle continuum phase space. This process must conserve the localization of the nuclear wave function which remains bound even with such a virtual scattering taken into account. A theoretical description of this kind of effect still remains virgin territory, although some progress has been made in the analysis of the virtual pair scattering [19,23]. Secondly, nucleons can very easily leave the nucleus altogether and enter the particle continuum through the real scattering. This is an old problem which, in the context of excited states near or above the particle threshold, has been addressed by the continuum shell model (CSM) [24–26]. In the CSM, the continuum states (decay channels) and bound states are treated on an 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 the CSM. Unfortunately, in many shell-model calculations for weakly bound nuclei (including those presented

at this meeting!) the continuum aspects are completely disregarded; hence their conclusions should be taken with a grain of salt (see, however, the recent study [27]).

Often, particle continuum is approximated by the quasibound states, i.e., the states resulting from the diagonalization of a finite potential in a large basis [28,29] or by enclosing the finite nuclear potential within an infinite well with walls positioned at a large distance from the nuclear surface [30,31]. More sophisticated methods of discretizing continuum include the Sturmian function expansions [32–35] and resonant (Gamow) state expansions.

How do well-established microscopic models of nuclear structure perform when extrapolated to exotic nuclei? Due to many uncertainties, we do not know a simple answer to this question. As an example, Fig. 4 shows

FIGURE 4. Similar to Fig. 3 except for very neutron-rich Sn isotopes.

the predicted two-neutron separation energies for the tin isotopes using the same models as in Fig. 3. Clearly, the differences between forces are greater in the region of “terra incognita” than in the region where masses are known. As seen in Fig. 4, the position of the neutron drip line for the Sn isotopes slightly depends on the effective interaction used; it varies between $N=120$ (HFB-D1S) and $N=126$ (RHB-NL3). Therefore, the uncertainty due to the largely unknown isospin dependence of the effective force gives an appreciable theoretical “error bar” for the position of the drip line. Unfortunately, the results presented in Fig. 4 do not tell us much about which of the forces discussed should be the preferred one since one is dealing with dramatic extrapolations far beyond the region known experimentally. However, a detailed analysis of the force dependence of results may give us valuable information on the relative importance of various force parameters.

CONTINUUM SHELL MODEL AND GAMOW STATES

The Gamow states are eigenstates of the time-independent Schrödinger equation with complex eigenvalues [36–38]. They are regular at $r=0$ and satisfy a purely outgoing wave type of asymptotics with the complex energy eigenvalue. The real part of the complex energy eigenvalue is the expectation value of the one-body Hamiltonian, while the imaginary part is related to the total decay width of the quasi-stationary state. The Gamow states are the poles of the S -matrix on the complex energy plane lying below the positive real axis. The closer they lie to the real axis, the more they resemble the bound states, and they can be associated with narrow resonances.

FIGURE 5. The distribution of Gamow energy eigenvalues w_i in the $(\text{Re}(w), \text{Im}(w))$ plane for (a) neutron drip-line nucleus ^{122}Zr (neutron eigenvalues), and (b) proton-rich nucleus ^{180}Pb (proton eigenvalues). (From Ref. [39].)

A generalized completeness relation proposed by Berggren [37] paved the way for using Gamow states as 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 energy plane.

Recently, the Gamow-state theory has been applied to calculate the single-particle level density and shell corrections for finite depth potentials [40,39]. Figure 5 illustrates the distribution of spherical Gamow eigenvalues for ^{122}Zr and ^{180}Pb (all partial waves are shown). For the neutrons in ^{122}Zr , the large-width Gamow states appear just above the $\text{Re}(w)=0$ threshold. However, for the protons in ^{180}Pb , the particle continuum is shifted effectively by ~ 8 MeV due to the presence of the Coulomb barrier. The proton Gamow states that appear at low energies are extremely narrow resonances, usually discussed in the context of proton emitters. Other applications of Gamow states to the description of resonances and drip-line nuclei can be found in Refs. [38,41,42].

SHELL STRUCTURE OF DRIP-LINE NUCLEI

A significant new theme concerns shell structure near the particle drip lines. Since the isospin dependence of the effective nucleon-nucleon interaction is largely unknown, the structure of single-particle states, collective modes, and the behavior of global nuclear properties is very uncertain in nuclei with extreme N/Z ratios. For instance, some calculations predict [17,43,44] that the shell structure of neutron drip-line nuclei is different from what is known around the beta-stability valley. According to other calculations [45], a reduction of the spin-orbit splitting in neutron-rich nuclei is expected. The gradual change of shell structure with neutron number is believed to give rise to new sorts of collective phenomena [29,46]. It is to be noted that the experimentally observed collapse of magic gaps seen in some neutron-rich light nuclei (the so-called islands of inversion [47–50]) might also be related to the predicted quenching of magic gaps [51].

The effect of the weakening of known shell effects in drip-line nuclei has significant consequences for the description of the astrophysical r -process. Although many of the astrophysically important neutron-rich nuclei, belonging to the terra incognita of Fig. 1 will not be experimentally accessible in the foreseeable future, their part of the (Z, N) chart has been already visited by Mother Nature in cataclysmic events such as supernovae. Consequently, valuable information on nuclear structure in terra incognita can be offered by astrophysical data. In particular, the analysis of the r -process abundances can provide an indirect experimental confirmation of the shell-quenching effect [52,53].

Nuclear Halos

Halo nuclei are symbols of RNB physics. The very weak binding of the outermost neutrons leading to a rather good decoupling of halo from the core simplifies many aspects of unrelaying nuclear structure and reaction mechanism. Much has been learned about halo nuclei. Few-body calculations, especially those based on the method of hyperspherical harmonics and the adiabatic hyperspherical method, have reached a high level of sophistication [54,55]. They give the basic understanding of many observed phenomena (momentum distributions, electromagnetic strength distributions) but often neglect the important structure aspects. Some of the questions asked in the context of halo nuclei are: What are the main dynamical degrees of freedom which affect the core-halo coupling? What is the degree of clusterization of the cores? Is the clusterization mechanism enhanced close to the neutron drip line? If so, what are its manifestations in heavier systems? What are modifications of the effective interaction in the halo region? Through halos, one hopes to learn more about the microscopic mechanism of clusterization found in "normal" nuclei (see the Ikeda diagram shown in Fig. 6), such as in the hypothetical three-alpha state of ^{12}C .

FIGURE 6. Ikeda diagram for light nuclei [56]. The threshold energy for each decay mode (in MeV) is indicated. The halo nucleus ^{11}Li , viewed as a three-body borromean system, is also shown.

SPECTROSCOPY OF PROTON EMITTERS

Proton radioactivity is an excellent example of the elementary three-dimensional quantum-mechanical tunneling. Lifetimes of proton emitters directly provide an indication of the angular momentum content of the

narrow proton resonance [57,58]. Experimental and theoretical investigations of proton emitters (or theoretically predicted ground-state di-proton emitters) are just opening up a wealth of exciting physics associated with the residual interaction coupling between bound states and extremely narrow resonances in the region of very low density of single-particle levels.

In general, proton emission half-lives depend mainly on the proton separation energy and orbital angular momentum, but depend rather weakly on the details of the intrinsic structure of proton emitters, e.g., on the parameters of the proton-core potential. This suggests that the lifetimes of deformed proton emitters will

FIGURE 7. Competition between gamma and proton decays in a deformed proton emitter.

provide direct information on the angular momentum content of the associated Nilsson state, and hence on the nuclear shape. Figure 7 shows, schematically, a possible scenario of proton-gamma competition in a deformed proton emitter. Of course, the energy window for such a process is expected to be fairly narrow.

Recently, a method of calculating proton resonances by means of the coupled-channel technique with Gamow states has been proposed [42,59]. In another work, half-lives of deformed proton emitters were analyzed by means of the time-dependent Schrödinger equation [60]. In this context it should be noted that while in very deformed nuclei proton resonances can be treated by means of the strong coupling approach, to investigate the influence of the angular momentum dependence of the proton decay width, the Coriolis coupling should be considered.

Another exciting avenue is the competition between gamma-radiation and the emission of prompt protons. Here, spectacular examples are proton-emitting intruder bands in ^{58}Cu [61] and ^{56}Ni [62]. In ^{56}Ni , where two intruder bands have been observed, the lower rotational band can be explained by large-scale shell-model calculations in the pf shell. Also the results of cranked mean-field calculations indicate that this band is built upon a $4p\text{-}4h$ excitation within the pf shell (see Fig. 8, 4^04^0 band). The second band, however, is expected to involve particles in the $1g_{9/2}$ orbit, which is supported by its nearly identical behavior to the band in ^{58}Cu . However, the best scenario for this band [62] is based on *one* proton promoted to the $1g_{9/2}$ orbit (4^04^1 band in Fig. 8), while a neutron *and* a proton occupies this orbit in ^{58}Cu . Radioactive medium-mass nuclei such as ^{56}Ni are fantastic territories where various theoretical approaches can be confronted: state-of-the-art shell model, mean-field models, and cluster models. The spherical structures in ^{56}Ni are well described by the large-scale shell model, the collective 4^04^1 band can be understood in terms of the self-consistent mean-field theory, and

FIGURE 8. Excitation energy versus angular momentum for experimental and calculated intruder bands in ^{56}Ni . Lines indicate the $4^0 4^0$, $4^0 4^1$, and $4^1 4^1$ bands calculated in the cranked HF+SLy4 model, while the KBF shell-model calculations (SM) are indicated by crosses.

the $4^0 4^0$ band can be described by both methods (see also Refs. [63–65]).

CONCLUSIONS

In trying to see the phenomena of a “new physics”, one should ask the fundamental question of “how far is far” (see Fig. 9)? There is very little doubt that progress in the RNB research is not going to be rapid. Especially for the neutron-rich heavy elements, it will be a real struggle to obtain basic spectroscopic information. To put things in perspective, it is instructive to recall the discovery of polonium by Maria and Pierre Curie at the end of June 1898. The longest-lived isotope of polonium is ^{209}Po with a half-life of 102 y. The isotope ^{218}Po was studied by Rutherford already in 1904 [66]; its half-life is 3.1 min [67]. Amazingly, it took ninety-four years to add one more neutron to ^{218}Po ; only recently have the neutron-rich isotopes, $^{219,220}\text{Po}$, been produced at GSI by the international collaboration led by M. Pfützner [68]. It has been much easier to approach the neutron-poor side. The lightest polonium known, ^{190}Po , was found in 1988 at GSI [69]; its half-life, 2.4 ms [70], is long enough to enable detailed spectroscopic studies.

The doubly magic $N=Z=50$ nucleus ^{100}Sn is a paradigm of RNB physics at the proton-rich side. Although it was found experimentally three years ago [71,72], it took more than two years to roughly determine its mass [73], and it will still take quite a few years to find its first excited state. On an optimistic note, many nuclei very close to the $N=Z=50$ corner have already been approached spectroscopically in recent years [74], so the prospects for more spectroscopic news on ^{100}Sn are good. It will be much harder to approach another doubly magic nucleus, the neutron-rich ^{78}Ni . It was produced in 1995 [75], but our knowledge about this system and its neighbors is very scarce. Indeed, the heaviest nickel isotope known spectroscopically is ^{70}Ni [76], which is as far as eight neutrons away!

An experimental excursion into uncharted territories of the chart of the nuclides, exploring new combinations of Z and N , will offer many excellent opportunities for nuclear structure research. What is most exciting,

FIGURE 9. "Fishing expedition" to terra incognita far from stability.

however, is that 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. We are only at the beginning of a most exciting journey.

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