Physics at the Rare Isotope Accelerator (RIA): Exploring the Nuclear Landscape

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Life in nuclear “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 presentation is to discuss some of the challenges and opportunities for nuclear structure research with radioactive nuclear beams.

1. Introduction

There are less than 300 stable nuclei; they are surrounded by radioactive ones. Some of the unstable nuclei are long-lived and can be found on Earth, some are man-made, and several thousand nuclei are the yet-unexplored exotic species. The decay characteristics of most radioactive nuclei are determined by weak interactions. For heavier nuclei, where the Coulomb force plays a more important role, other decay channels, such as emission of alpha particles or spontaneous fission, dominate. Moving away from stable nuclei by adding either protons or neutrons, one finally reaches the particle drip lines. The nuclei beyond the drip lines are unbound to nucleon emission; that is, for these systems the strong interaction is unable to bind all nucleons into one nucleus.

The uncharted regions of the (N,Z) plane contain information that can answer many questions of fundamental importance for nuclear physics: How many protons and neutrons can be clustered together by the strong interaction to form a bound nucleus? What are the proton and neutron magic numbers in the neutron-rich environment? What is the effective nucleon-nucleon interaction in a weakly bound nucleus? 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 to the understanding of the underlying processes. Today, the physics associated with radioactive nuclear beams

(RNB) is one of the major thrusts of nuclear science worldwide.

Exotic beam facilities fall into two generic, and complementary, types - the fast beam (or in-flight method) and the ISOL (or re-accelerated beam) approach. The Rare Isotope Accelerator (RIA) is an innovative concept [1] embodying the best features of both in-flight and ISOL techniques and providing both reaccelerated and fast beams, as well as intense sources of stopped nuclei. The RIA physics case is well documented [2–7]. It addresses fundamental questions of nuclear structure, nuclear astrophysics, and fundamental interaction physics. It is useful to summarize the main thrusts of RIA physics as formulated at the recent workshop in Raleigh-Durham [7]:

The Nature of Nucleonic Matter: The limits of nuclear existence; the dependence of nuclear structure and dynamics on the asymmetry in neutron-proton composition, and new forms of nucleonic matter at extremes of N/Z ratio; effective interactions in proton-neutron asymmetric media.

The Origin of the Elements and Energy Generation in Stars: The astrophysical r- and rp-processes.

Tests of the Standard Model and of Fundamental Conservation Laws: Search for an atomic electric dipole moment; parity violation in Fr atoms; non-unitarity tests of the CKM matrix; search for non V-A contributions to the weak interaction.

In this short paper, we shall address some questions mainly related to nuclear structure aspects of the RNB program.

Figure 1 shows the role played by radioactive nuclear beams in our quest for understanding the nucleus. Studies at relativistic energies probe the domain of QCD; they reveal the nature of quark and gluon dynamics. Studies at lower energies probe the structure and dynamics of nuclei. The bridges illustrate major physics challenges: the mechanism of quark confinement, the nature of hadrons, the understanding of the bare nucleon-nucleon interaction in terms of the quark-gluon dynamics, and the understanding of the effective interactions in heavy nuclei in terms of the bare force.

The range of unstable nuclei accessible with RNB facilities opens up enormous opportunities for the study of nuclear structure and exotic new phenomena. Intriguing possibilities occur both at the drip lines and in the long iso-chains of nuclei between the valley of stability and the extremes of nuclear existence.

Exotica in the latter region are almost sure to appear since the mean field in weakly bound neutron-rich nuclei is likely to be modified relative to nuclei near stability, and since reduced nuclear densities and the large reservoir of continuum scattering states should modify residual interactions among the outermost nucleons. Together, these effects may modify the microscopic foundations of nuclei to the extent that the concept of single-particle motion itself loses validity. Halo nuclei are the best known examples of possible exotica. They are examples of physics on the threshold of nuclear binding. The predicted phenomena of low-density neutron skins is another, which is topologically similar to a halo, but quite different in microscopic origin [9]. Between the regions of known and near-dripline nuclei lies an extensive zone (typically, 20-40 neutrons wide in medium mass and heavy nuclei) where studies will reveal much about the microscopy of structural evolution

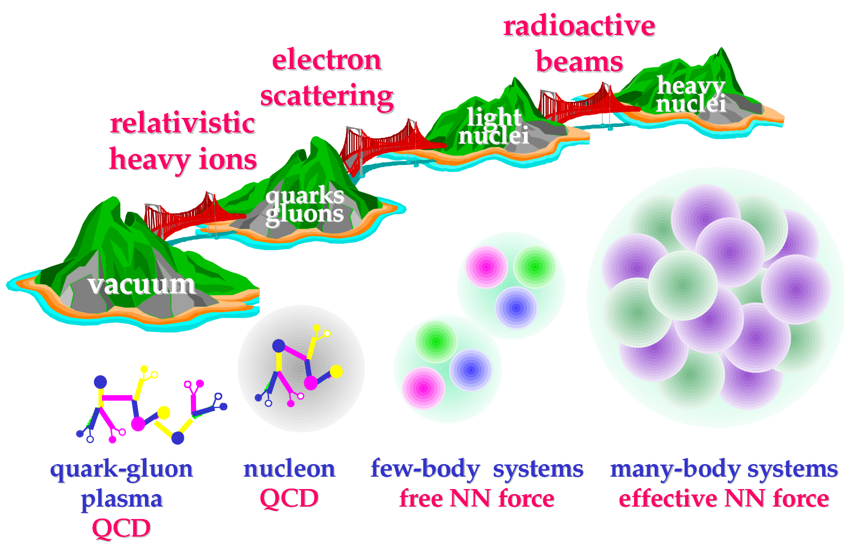

Figure 1. From the QCD vacuum to heavy nuclei: the intellectual connection between the hadronic many-body problem (quark-gluon description of a nucleon) and the nucleonic many-body problem (nucleus as a system of Z protons and N neutrons). Based on Refs. [8,6].

and will undoubtedly disclose new types of correlations, collectivity, and shape/phase transitional behavior.

This enterprise can be usefully compared with another major scientific development of our time. The full span of nuclei that can exist presents a kind of "nuclear genome" that we now possess the technology to probe in ways never before imaginable. Of course, we do not propose or hope to map every corner of the nuclear landscape, but rather to exploit the nuclear "gene pool" made available by advanced exotic beam facilities to select specific nuclei or nuclear reactions that isolate, amplify, or reveal new phenomena, new types of nucleonic aggregations, or key nuclear interactions in ways that access to stable nuclei cannot do.

2. RNB territory

The nuclear landscape, the territory of RNB physics, is shown in Fig. 2. 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;

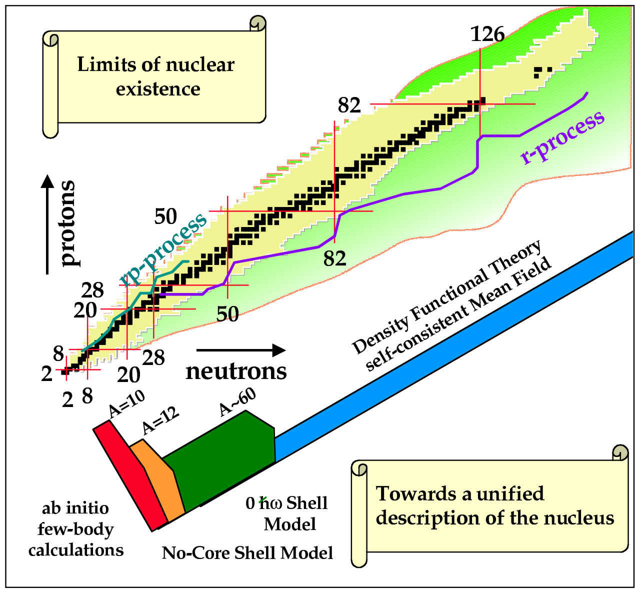

Figure 2. Top: Nuclear landscape. Bottom: Various theoretical approaches to the nuclear many-body problem.

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 such island is, of course, a neutron star which exists – thanks to gravitation. So far, calculations for light neutron drops have not produced permanent binding [10,11]. However, it has been suggested recently [12] that areas of stability can appear in heavier nuclei as a result of shape coexistence/isomerism.

Figure 3 shows various domains of nuclear matter, important in the context of the RNB program. The range of neutron excess, $(N-Z)/A$, in finite nuclei is from about –0.2 (proton drip line) to 0.5 (neutron drip line). RIA 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.

3. Unified description of the nucleus

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. Figures 1 and 2 illustrate, schematically, our main strategy in the quest for understanding the nucleus 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. Experimen-

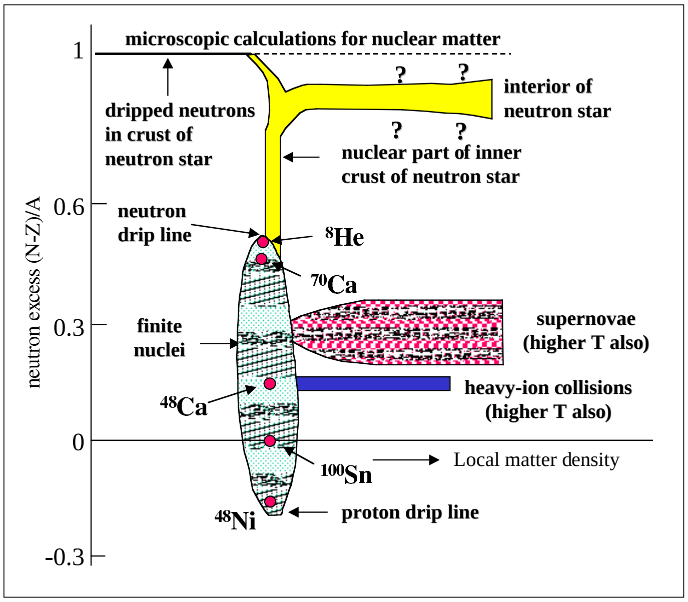

Figure 3. Diagram illustrating the range of densities and neutron excess of importance in various contexts. (Based on Ref. [13].)

tally, the NN force can be studied by means of NN scattering experiments. The best NN force parameterizations not only describe the two-body on-shell properties but have been used in few-body and many-body calculations. The very light nuclei can nowadays be described as A-body clusters bound by a free NN force (including higher-order interactions, such as a three-body force). The ab initio Green's Function Monte Carlo calculations [14,15] have recently reached A=10. The variational Monte Carlo calculations with a free NN force have been carried out for relatively heavy systems such as ^{16}O [16].

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 (Brückner renormalization). The recently developed no-core shell model, employing the effective interaction calculated (in the large configuration space) from the NN force, has recently reached ^{12}C [17]. In a parallel development, Bloch-Horowitz equations have been solved for very light systems [18].

What about the shell-model treatment of heavier nuclei? In the past, shell-model calculations utilizing the concept of valence nucleons interacting in a restricted configuration space were limited to medium-mass nuclei owing to the rapid growth of the size of the model space. Today, this is still the case, although the conventional shell-model calculations employing realistic NN interactions [19,20] are becoming more and more efficient in handling large configuration spaces. The state-of-the-art shell-model studies of ^{56}Ni [21] or Gamow-Teller distributions of A=45-65 nuclei [22] set the new standard in this area, although future progress is strongly limited by present-day computer resources.

Despite the exciting progress in shell-model approaches, applications to very heavy systems are still beyond our reach. But just as exact techniques in the lightest nuclei provide a bridge to the intermediate mass nuclei studied in the shell model, the shell model provides another bridge to the heavy nuclei where other techniques are used. The effective interaction derived in shell-model studies can be employed in mean-field studies of heavy nuclei based on the density functional theory.

To carry out the microscopic, consistent in-medium renormalization for heavy nuclei is a difficult task. Consequently, theories and methods have been developed which use effective interactions or effective Lagrangians. Among them are the self-consistent methods based on the density-dependent effective interactions, which by now have achieved a mature state of development, as well as those based on relativistic meson-nucleon Lagrangians which have reached the state where detailed studies of results and readjustment of basic parameters are now possible. These approaches 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 mass table has been recently developed [23] based on the Skyrme energy 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.

Figure 2, bottom, includes a schematic illustration of this hierarchy of theoretical models spanning the chart of the nuclides. By exploring connections between these models, nuclear theory aims to develop a unified description of the nucleus. 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. 1 will make this goal qualitatively possible.

4. Theoretical challenges far from stability

From a theoretical point of view, exotic nuclei far from stability offers a unique test of those components of effective interactions that depend on the isospin degrees of freedom. Since the effective interaction in heavy nuclei has been adjusted to stable nuclei and to selected properties of infinite nuclear matter, it is by no means obvious that the isotopic trends far from stability, predicted by commonly used effective interactions, are correct. In models aiming at such an extrapolation, the important questions asked are: What is the density dependence of the two-body central force? What is the N/Z dependence of the one-body spin-orbit force? What is the form of pairing interaction in weakly bound nuclei? What is the importance of the effective mass (i.e., the non-locality of the force) for isotopic trends? What is the role of the medium effects and of the core polarization in the nuclear exterior (halo or skin region) where the nucleonic density is small? Similar questions are asked in connection with properties of nuclear matter, neutron droplets, and the physics of the neutron-star crust.

In many respects, weakly bound nuclei are much more difficult to treat theoretically than well-bound systems [24]. Hence, before tackling the problem of force parametrization

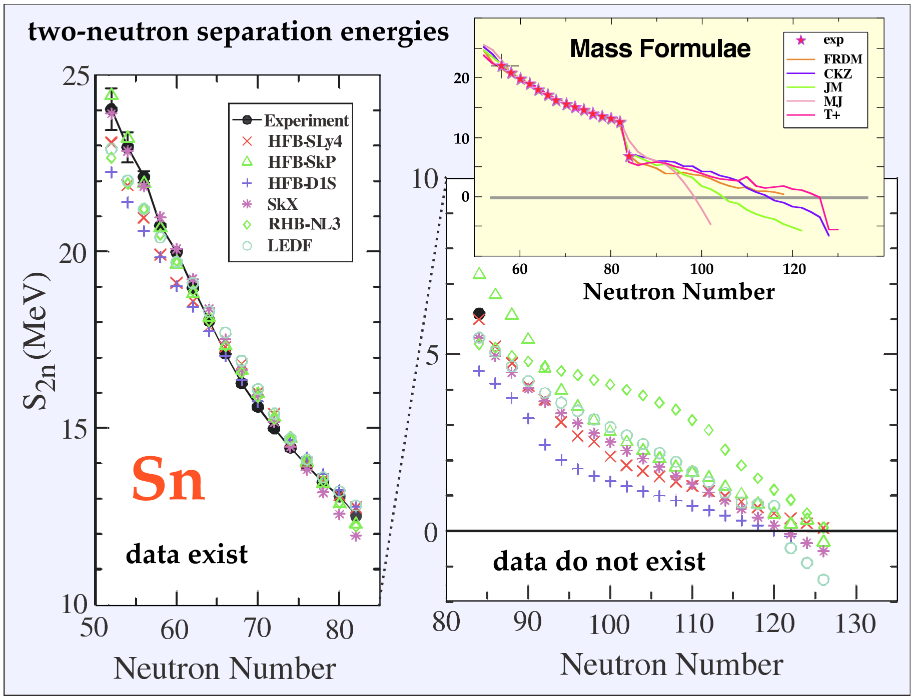

Figure 4. Predicted two-neutron separation energies for the even-even Sn isotopes using several microscopic models based on effective nucleon-nucleon interactions and obtained with phenomenological mass formulas (shown in the inset at top right). Taken from Refs. [4,6] and references quoted therein.

at the extremes, one should be sure that the applied theoretical tools of the nuclear many-body problem are appropriate. 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, the pairing theory, or the macroscopic-microscopic approach must be modified. 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. 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 description of the ^{16}O(p,γ)^{17}F capture reaction [25].

Experimentation with radioactive nuclear beams is expected to expand the range of known nuclei. That is, by going to nuclei with extreme N/Z ratios, one can magnify the isospin-dependent terms of the effective interaction (which are small in “normal” nuclei). The hope is that after probing these terms at the limits of extreme isospin, we can later go back to the valley of stability and improve the description of normal nuclei. In addition to nuclear structure interest, the understanding of effective interactions in the neutron-rich

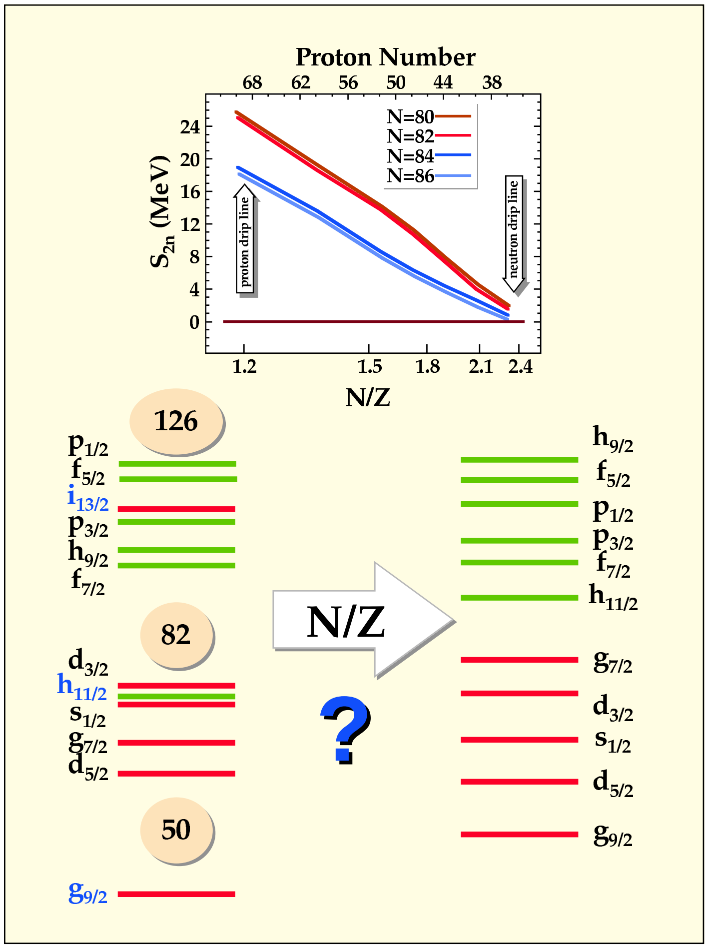

Figure 5. Left: Spherical shell structure characteristic of nuclei close to the valley of stability. Nuclear shells, the bunches of close-lying single-particle levels, are separated by magic gaps. Right: Neutron shell structure predicted for neutron-rich nuclei, corresponding to a shallow mean-field potential and significantly reduced spin-orbit coupling. The inset shows two-neutron separation energies for the N=80, 82, 84, and 86 spherical even-even isotones calculated in the HFB+SkP model as functions of the proton number [26]. The arrows indicate the proximity of neutron and proton drip lines for small and large proton numbers, respectively.

and proton-rich environment is important for astrophysics and cosmology.

Figure 4 illustrates difficulties with making theoretical extrapolations into neutron-rich territory. It shows the two-neutron separation energies for the even-even Sn isotopes calculated in several microscopic models based on different effective interactions and, in the inset, those obtained with phenomenological mass formulae. Clearly, the differences between forces and mass formulae 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 depends on the model used. 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 preferred 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.

A significant new theme concerns shell structure near the particle drip lines. Since the isospin dependence of the effective NN 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 (see Fig. 4 and related discussion). For instance, some calculations predict [24,27,28,26] that the shell structure of neutron drip-line nuclei is different from what is known around the beta-stability valley (see Fig. 5). According to other calculations [29], a reduction of the spin-orbit splitting in neutron-rich nuclei is expected.

Quenching of shell effects manifests itself in the behavior of two-neutron separation energies S_{2n}. This is illustrated in Fig. 5 which displays the two-neutron separation energies for the N=80, 82, 84, and 86 spherical even-even isotones calculated in the HFB model with the SkP [30] effective interactions. The large N=82 magic gap, clearly seen in nuclei close to the stability valley and to the proton drip line, gradually closes down when approaching the neutron drip line. As discussed in Ref. [24], this result can be attributed to two effects: (i) a gradual increase of the neutron surface diffuseness across the stability valley related to an increase of the neutron excess, and (ii) the influence of the continuum, which results in closing the shell gap near the neutron drip line down to zero.

5. Correlations

Correlations due to pairing, core polarization, and clustering are crucial in weakly bound nuclei. In a drip-line system, the pairing interaction and the presence of skin excitations (soft modes) could invalidate the picture of a nucleon moving in a single-particle orbit [26,31,32]. It is expected that the low-l spectroscopic strength is dramatically broadened when approaching the neutron drip line. In addition, since the energy of the pigmy 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 [33].

As shown in Fig. 6, the neutron drip line has been reached only up to ^{24}O (N=16). Interestingly, the heaviest isotope of fluorine known, ^{31}F, has 22 neutrons. That is, one additional proton binds at least six neutrons. This single experimental observation beautifully demonstrates the crucial role of the proton-neutron interaction in producing nuclear binding.

A fascinating aspect of halos and skins is the presence of clustering at the nuclear ground state. It is worth noting that all known neutron halo nuclei can be described in terms of cluster structures consisting of alpha particles surrounded by neutrons. The nuclear matter calculations indicate (see, e.g., Refs. [34,35]) the presence of deuteron

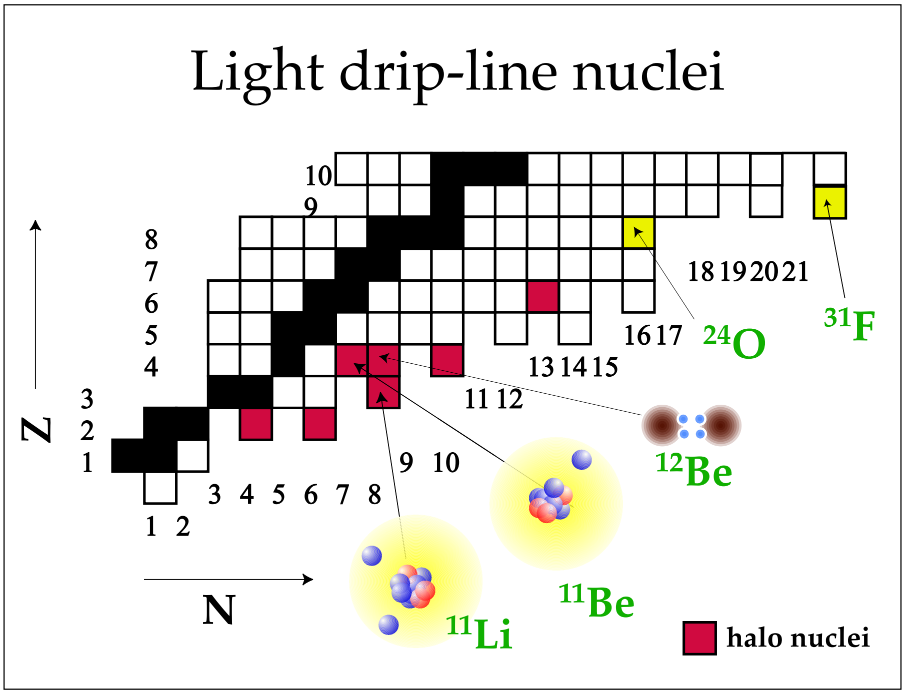

Figure 6. The part of the (N, Z) chart for the lightest nuclei. The halo nuclei, such as one-neutron halo ^{11}Be or two-neutron halo ^{11}Li are marked. A very elongated molecular "dimer" configuration in ^{12}Be has recently been found [36] at higher excitation energies.

and alpha condensates at low densities. This suggests that transition from a mean-field regime, corresponding to the two-fluid proton-neutron system, to the limit of weak binding, characteristic of drip-line nuclei, does not have to be smooth. Most likely, one will encounter an intermediate phase corresponding to the presence of granularities (i.e., cluster structures) in the skin region.

6. Signature efficiency

We have discussed a number of thoeretical issues in the study of exotic nuclei. Clearly, research in the new "terra incognita" will involve significant experimental challenges as well. In this section we focus on a number of important issues relating to RNB experiments and the interpretation of the resulting data.

It is important to recognize a key feature of any "next-generation" facility such as RIA. The idea is illustrated in Fig. 7, where in the top panel we show a typical isotopic chain extending from the valley of stability to the extremes of accessibility. The numbers along the chain indicate typical exotic beam (or, for stopped nuclei, source) intensities one might encounter. The lower left panel gives a very rough (and time-dependent) guide to typical lower limits of beam intensity at which different classes of experiments become feasible.

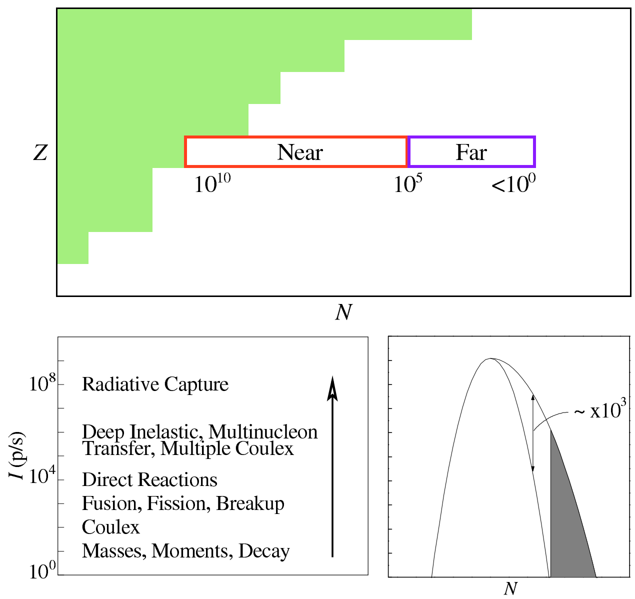

Figure 7. Top: Beam intensities along a typical isotopic chain. Bottom left: Guide to typical lower limits of beam intensity at which different classes of experiments are feasible. Bottom right: Schematic illustration of the higher beam intensities available with a new-generation RNB facility compared with previous facilities, illustrating both the regions of new nuclei accessible and the greater beam intensities for many other nuclei as well.

We see that at every step along the trajectory at the top of the figure, certain experiments will be possible. Obviously, though, the higher the beam intensity, the greater the variety of possible studies, varying from full spectroscopy "near" stability to measuring basic properties (existence, mass, lifetimes) in the extreme "far" region.

When a next-generation facility comes on line, it invariably gives a large boost in available intensities. A typical scenario is shown in the lower right panel of Fig. 7. Clearly, a major goal of any new facility is to extend the realm of nuclei that can be studied. Such nuclei are indicated by the shaded area at the most neutron-rich limit. But, all along the range of unstable isotopes, such a facility will give substantially greater intensities and, therefore, enable new classes of experiments to be carried out. Thus, the benefits of technological advances in exotic beam facilities extend far beyond merely the new nuclei made accessible.

Figure 8 highlights another essential aspect of experiments in newly accessible nuclei. As one goes further from stability, beam intensity will invariably drop. To maintain the physics output, one must therefore either increase the efficiency with which experiments are performed or the "efficiency" with which physics is extracted from a given amount of data.

Much effort has already gone into the former direction. For example, as shown in Fig. 8

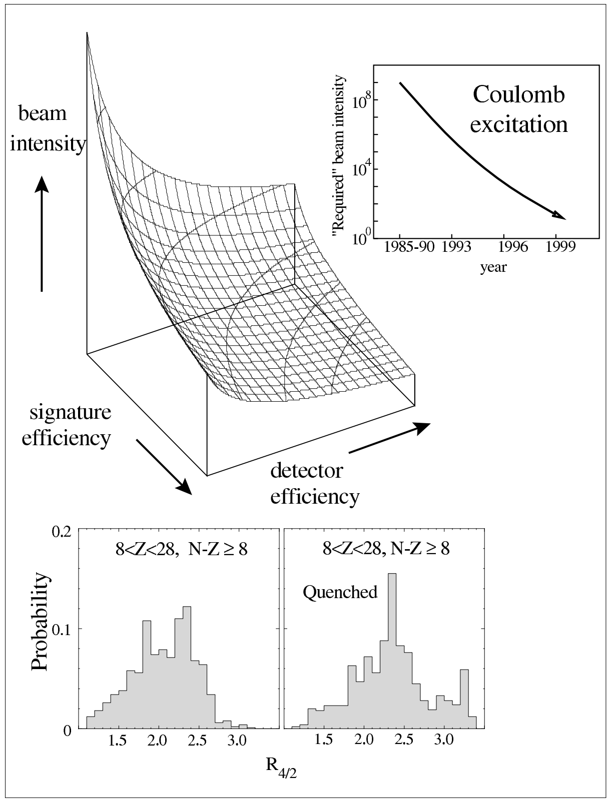

Figure 8. Top left: Illustration of the concept of "signature efficiency" and its relation to detector efficiency and beam intensity in extracting physics from RNB experiments. Top right: Indication of the reduction over the last 15 years in the minimum required beam intensity (in ions/sec) for simple Coulomb excitation experiments due to improvements in detector design. Bottom: An example of a simple signature of rather subtle physics: semi-empirical distributions of $R_{4/2}$ values for neutron-rich nuclei asssuming normal (left) and quenched (right) shell structure.

(top insert), fifteen years ago a typical Coulomb excitation experiment was done with 100 pA or more of beam, whereas nowadays experiments are possible at $\sim$100 particles/s in many cases and even at <1 particle/s in certain situations. A similar story can be written for mass measurements where traps and storage rings have greatly advanced our capabilities. Finally, in probing the drip line, nuclear "existence" is ascertainable at production totals (not rates) of just a handful of the nuclei of interest.

The second efficiency axis in Fig. 8, though, has not been as thoroughly exploited, and yet early work suggests that improvements in the "signature efficiency" can be just as potent a new tool as improvements in detectors. This has been discussed recently, and we will only summarize the results here and illustrate one example.

Consider a region of even-even nuclei where only the mass (S_{2n}, say), $E(2_1^+)$, $E(4_1^+)$,

$B(E2:2_1^+ \to 0_1^+)$, and $B(E2:4_1^+ \to 2_1^+)$ values are known. Simple N_pN_n plots [37] can reveal if any of these nuclei are anomalous, in the sense of deviating from the typically smooth N_pN_n trajectories. An isolated anomaly can signal special structure, such as shape coexistence. A region of scattered points (instead of a compact trajectory) would usually suggest an incorrect choice of local magic numbers, leading to inappropriate choices of N_n and N_p values, and would therefore hint at effects such as shell quenching.

Further hints along the same lines can be obtained from a frequency destination of $R_{4/2} = E(4_1^+)/E(2_1^+)$ values. Deviation from distributions characterizing known nuclei point either to altered shell structure, altered residual interactions, or both. This is illustrated in the lower inset of Fig. 8 for neutron-rich $N-Z{\geq}8$ nuclei where predicted distributions, based on a semi-empirical database of known $R_{4/2}$ values, [38] are shown for normal shells and for the case where the last neutron magic number is assumed to be quenched. Clearly, if a region of nuclei in this range of elements shows significant numbers of nuclei with $R_{4/2}{>}3$, it suggests underlying changes in shell structure or residual interactions.

Simple data offer sometimes clues on nuclear dynamics and collectivity. For instance, γ softness shows up in correlations of $B(E2:2_1^+ \to 0_1^+)$ values with $R_{4/2}$ where different trajectories characterize vibrator-to-axial-rotor from vibrator-to-γ-soft-rotor transition regions. (If more data are available, γ-band energy staggering also distinguishes γ-soft from rigid triaxial nuclei.)

Further work on the improvement of signature efficiency, concomitant with improvements in measuring efficiency, will reap highly leveraged dividends in the interpretation of structure and structural evolution far from stability [39]. Such an effort goes hand-in-hand with advances in nuclear theory and computational enhancements in pursuing the goal of a comprehensive unified theory of nuclear structure spanning the nuclear chart from drip line to drip line and from the lightest to the heaviest nuclei that can exist.

7. Conclusions

The main objective of this brief review was to discuss various facets of RNB physics. The list of topics covered is by no means complete due to time and space constraints.

In years to come, we shall see substantial progress in our understanding of nuclear structure – a rich and many-faceted field. An important element in this task will be to extend the study of nuclei into new domains. The journey to "the limits" of nuclear existence is a quest for new and unexpected phenomena which await us in the uncharted territory. However, the new data are also expected to bring qualitatively new information about the effective NN interaction and hence about the fundamental properties of the nucleonic many-body system. New RNB facilities, such as RIA, together with advanced multi-detector arrays and mass/charge separators, will be essential in probing nuclei in new domains. The field is extremely rich and has a truly multidisciplinary character.

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, 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 this most exciting journey.

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