FRONTIERS IN NUCLEAR STRUCTURE

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Current developments in nuclear structure are discussed from a theoretical perspective.

1 Introduction

The atomic nucleus is a fascinating many-body system bound by strong interaction. The building blocks of a nucleus – protons and neutrons – are themselves composite aggregations of quarks and gluons governed by quantum chromodynamics (QCD) – the fundamental theory of strong interaction. 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. Figure 1 shows the main challenges 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 questions: 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.

In this talk, I intend to review – rather briefly – the enormous progress that has happened in nuclear structure during recent years. For a general overview of nuclear science, the reader is encouraged to study the recent report [3].

2 The Territory

The nuclear landscape, the territory of nuclear structure, is shown in Fig. 2. 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. Examples of such systems are proton emitters – narrow resonances beyond the proton drip line which exist due to the confining effect of the Coulomb barrier [4]. An exciting question is whether there can possibly exist *islands* of stability beyond the neutron drip

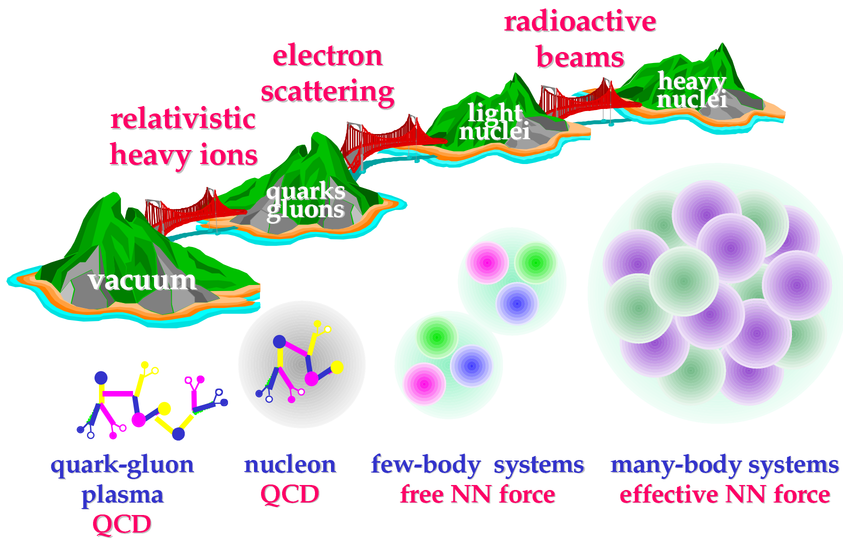

Figure 1: From the QCD vacuum to heavy nuclei: the intellectual connection between the hadronic many-body problem (quark-gluon description of a nucleon) and the nucleonic many-body problem (nucleus as a system of Z protons and N neutrons). Based on Refs. [1,2].

line. One such island is, of course, a neutron star which exists due to gravitation. So far, calculations for light neutron drops have not produced permanent binding [5,6]. However, it has been suggested recently [7] that areas of stability can appear in heavier nuclei as a result of shape coexistence/isomerism.

The vast territory of nucleonic matter is shown in Figure 2 which illustrates various domains of nuclear matter. 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). The new-generation radioactive beam 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.

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

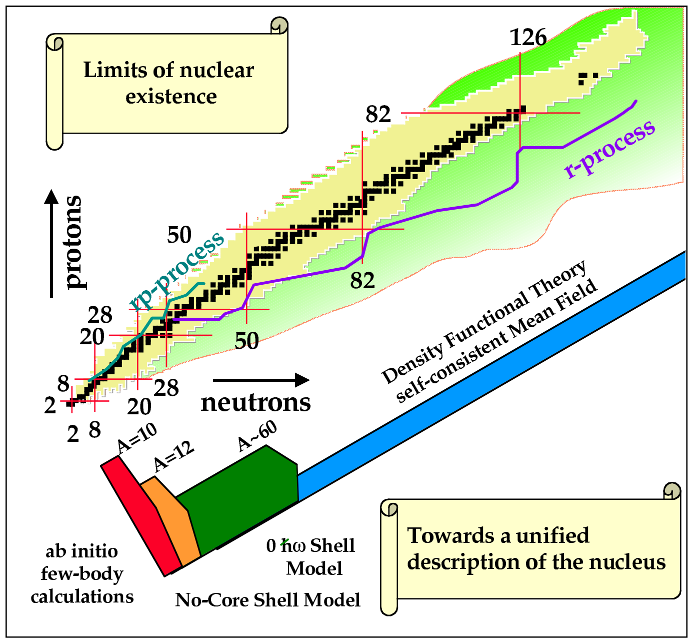

Figure 2: Top: Nuclear landscape. Bottom: Various theoretical approaches to the nuclear many-body problem.

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. Experimentally, 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[9,10] have recently reached A=10. In the parallel development[11,12,13], ab

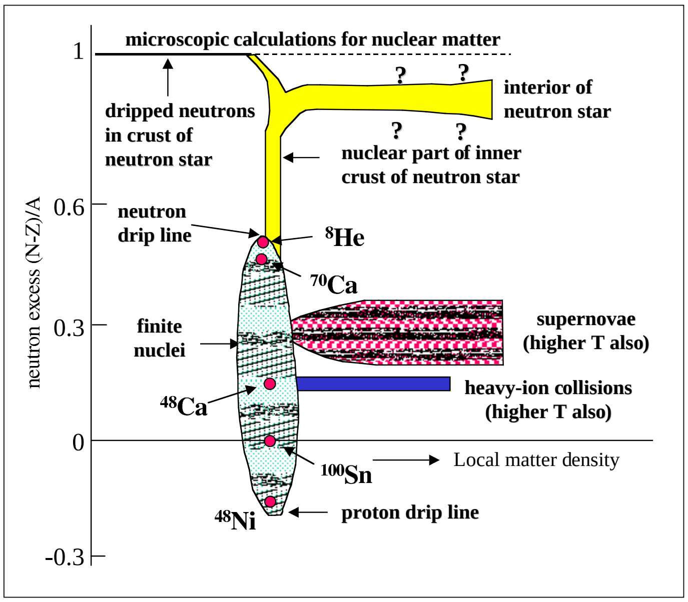

Figure 3: Diagram illustrating the range of densities and neutron excess of importance in various contexts. (Based on Ref.[8].)

initio calculations describing the scattering of few-body systems have brought new insights into the nature of the three-nucleon force.

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. 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 (see Ref.[14]). In a parallel development, Bloch-Horowitz equations have been solved for very light systems[15], and an effort has been underway[17] to marry the numerical methods of the shell model with the tools of effective theory[16] to generate effective interactions and effective operators. (In this approach the hard-core contribution is summed to all orders analytically.)

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 [18,19] are becoming more and more efficient in handling large configuration spaces. The state-of-the-art shell-model studies of ^{56}Ni [20,21], Gamow-Teller distributions of A=45-65 nuclei [22], electron capture and beta-decay rates in the pf nuclei [23], and spectroscopic studies of A=50-52 isobaric chains [24] set the new standard in this area, although future progress is strongly limited by present-day computer resources.

That the conventional shell model fails at short distances, due to the presence of short-range correlations, has been known for quite some time. Recently, ^{16}O(e,e$'$pp)^{14}C two-proton knock-out data [25,26] offered an opportunity to study one- and two-body currents and to discriminate between long-range and short-range correlations [27]. Such studies are extremely important for understanding in-medium effects in nuclear matter. Another complementary piece of data coming from the decay studies, relevant to the question of two-nucleon correlations, was the recent observation [28] of the simultaneous emission of two protons from a resonance of ^{18}Ne. This new mode of nuclear decay was predicted in the 1960s, but until recently experimental efforts have found sequential emission of single protons though an intermediate state. A key remaining question is whether the two protons, as they leave the nucleus, are closely coupled together to form ^{2}He, or are emitted almost independently in a direct three-body breakup ("democratic" decay). Further studies of this phenomenon will shed new light on the nature of nucleonic superconductivity. (See Ref. [29] for the recent theoretical developments.)

Despite the exciting progress in shell-model approaches, their applications to very heavy systems are still beyond our reach. Moreover, 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 [30,31]. For instance, a self-consistent mass table has been recently developed [32] 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 Far From Stability

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? What are the phases of nucleonic matter? 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 is one of the major thrusts of nuclear science worldwide.

From a theoretical point of view, exotic nuclei far from stability offer 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 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 [33]. Hence, before tackling the problem of force parametrization 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 [34].

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. For instance, some calculations predict [33] that the shell structure of neutron drip-line nuclei is different from what is known around the beta-stability valley. According to other calculations[35], a reduction of the spin-orbit splitting in neutron-rich nuclei is expected.

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 [36,37,38,39,40]. It is expected that the low-l spectroscopic strength is dramatically broadened when approaching the neutron drip line [41,42]. 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 [43].

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. [44,45]) the presence of deuteron and alpha condensates at low densities. This suggests that the 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.

On the proton-rich side, recent highlights are the discovery [46] of the two-proton unbound doubly magic nucleus ^{48}Ni, the first (indirect) data on the core-breaking excitations in ^{100}Sn through the high-spin studies of ^{99}Cd (Ref. [47]), and studies of deformed proton emitters [48,49]. For a comprehensive review of challenges and opportunities in nuclear structure far from stability, I would like to refer the reader to the recent RIA White Paper [50] where many delightful examples can be found.

5 Nuclear Collective Modes

In spite of the fact that the time scale of nuclear collective excitations is comparable to the single-particle time scale ($\sim 3\cdot 10^{-22}$s), the nucleus exhibits a variety of collective modes such as vibrations and rotations in which nucleons move in unison. The understanding of collective modes of nuclear matter is one of the main goals of nuclear structure research. By studying nuclear rotations and vibrations, nuclear physicists can probe the nuclear force in the strongly interacting medium and investigate the many-body dynamics.

We have already learned a lot about the basic mechanisms governing the behavior of fast nuclear rotation, especially the interplay between collective and non-collective degrees of freedom, competition between rotation, deformation, and nuclear superconductivity, and many global and detailed aspects of high-spin gamma-ray spectroscopy. However, a lot of surprises are still being encountered. The new-generation experimental tools, such as multidetector arrays EUROBALL and GAMMASPHERE, combined with the new-generation particle detectors and mass/charge separators, enable us to study discrete nuclear states up to the fission limit, as well as a high-spin quasi-continuum, and explore new limits of excitation energy, angular momentum, and energy resolution.

A spectacular example of today's high-spin spectroscopy is the investigation of superdeformation in the light $N{=}Z$ nucleus ^{36}Ar [51]. The observed superdeformed band, seen up to its high-spin termination at $I^{\pi}{=}16^{+}$, contains four pf-shell nucleons. Probably the best "molecular" rotational-vibrational nuclear spectrum is that of ^{240}Pu in its superdeformed minimum [52]. This beautiful and rich structure, observed in a ^{238}U(α,2n) reaction, shows one- and two-phonon deformed quadrupole and octupole vibrational states, as well as the rotational bands built upon them. Other magnificent examples include the spectroscopic studies far from stability [53,54] (including high-spin structures in proton emitters and medium-mass $N{=}Z$ nuclei, as well as spectroscopy of light neutron-rich nuclei), observation of wobbling bands in triaxial superdeformed nuclei [55], studies of hyperdeformed minimum in ^{234}U [56], and investigations of hot rotating nuclei [57].

A transition from qualitative to quantitative description is taking place in nuclear theory of high spins. In the presence of large angular momentum, the intrinsic density is strongly polarized, i.e., the nucleus shows phenomena and behaviors characteristic of condensed matter in the magnetic field: ferromagnetism, Meissner effect, and Josephson effect. The nuclear magnetism is caused by the time-odd components in the average mean-field potential. The understanding of the structure of the time-odd fields, which are dramatically amplified by the huge Coriolis interaction, is a major challenge for nuclear structure theory [58,59].

There has been significant progress in our understanding of nuclear vibrations, both at low and high energy (Gammow-Teller modes, spin-dipole excitations, multiphonon states), and of transitional systems. These topics have been covered in a number of talks, cf. Refs. [60,61,62].

6 The Limit of Mass and Charge

The stability of the heaviest and superheavy elements (SHE), stabilized by shell effects, has been a long-standing fundamental question in nuclear science. In spite of tremendous experimental effort, after about thirty years of the quest for superheavy elements, the borders of the upper-right end of the nuclear chart are still unknown [63]. Recent years have brought significant progress in the production of the heaviest nuclei [63]. During 1995-96, three new elements, Z=110, 111, and 112, were synthesized by means of both cold and hot fusion reactions. Recently, in hot fusion experiments performed in Dubna [64,65], the synthesis of three isotopes (A=287-289) of the element Z=114 has been reported, and, utilizing the cold fusion reaction, the Berkeley-Oregon group reported three α-chains attributed to the decay of the new element Z=118, A=293 [66]. While some of these discoveries still need to be confirmed by independent measurements (cf. critical discussion in Ref. [67]), there is very little doubt that the new experimental advances will take us deeper into the territory of superheavies, closer to the center of shell-stability. In another exciting development, the nuclei around ^{254}No have been reached spectroscopically [68,69,70]. Remarkably, these nuclei turned out to be stable against fusion up to angular momenta as high as $22\hbar$.

Parallel with experimental work, there has been significant progress in theoretical modeling of SHE. In particular, a number of self-consistent calculations, based on realistic effective interactions, have been carried out [71,72]. However, in spite of an impressive agreement with experimental data for the heaviest elements, theoretical uncertainties are large when extrapolating to unknown nuclei with greater atomic numbers. Since in the region of SHE the single-particle level density is relatively large, small shifts in positions of single-particle levels can influence the strength of single-particle gaps and be crucial for determining the shell stability of a nucleus. According to a self-consistent study [73], the non-relativistic Skyrme models predict the strongest spherical shell effect at N=184 and Z=124,126, while the relativistic mean-field models yield the strongest shell effect at N=172 and Z=120. It is very likely that the main factor contributing to this difference is the spin-orbit interaction, or rather its isospin dependence. Hence, the experimental determination of the centre of shell-stability in the region of SHE will be of extreme importance for pinning down the fundamental question of the spin-orbit force.

7 Nucleus as a Finite Many-Fermion System

The atomic nucleus is a complex, finite many-fermion system of particles interacting via a complicated effective force which is strongly affected by the medium. As such, it shows many similarities to other many-body systems involving many degrees of freedom, such as molecules, clusters, grains, mesoscopic rings, quantum dots, atom condensates, and others. There are many topics that are common to all these aggregations: existence of shell structure and collective modes (e.g., vibrations in nuclei, molecules, and clusters; superconductivity in nuclei and grains), various manifestations of the large-amplitude collective motion (such as multidimensional tunneling, coexistence, and phase transitions) and nonlinear phenomena (many-fermion systems are wonderful laboratories to study chaos), and the presence of dynamical symmetries.

Historically, many concepts and tools of nuclear structure theory were brought to nuclear physics from other fields. Today, thanks to the wide arsenal of methods, many ideas from nuclear physics have been applied to studies of other complex systems. There are many splendid examples of such interdisciplinary research: studies of the multidimensional tunneling and of the large-amplitude collective motion and symmetry-breaking in many-body systems, applications of the nuclear mean-field theory and its extensions to studies of static and dynamical properties of metal clusters [74,75], treatment of finite-size effects in the description of superconductivity of ultrasmall grains and fullerenes [76,77,78], use of symmetry-dictated approaches to describe collective excitations of complex molecules [79], studies of supersymmetries in many-body systems [80,81,82], applications of the nuclear random matrix theory to various phenomena in mesoscopic systems [83,84,85], studies of Bose condensates [86,87], and the description of correlations in many-fermion systems [88].

A topic of great interest is the signatures of classical chaos in the associated quantum system, a sub-field known as quantum chaos. A nuclear physics theory (random matrix theory), developed in the 1950s and 60s to explain the statistical properties of the compound nucleus in the regime of neutron resonances[89], is now used to describe the universality of quantum chaos. Today, the random matrix theory is the basic tool of the interdisciplinary field of quantum chaos, and the atomic nucleus is still a wonderful laboratory of chaotic phenomena. Other excellent examples of interplay between chaotic and ordered motion in nuclei are parity-violation effects amplified by the chaotic environment [90], the appearance of very excited nuclear states (symmetry scars) well characterized by quantum numbers [91], and the appearance of collectivity in the many-body system governed by random two-body interactions [92,93,94,95].

The study of collective behavior, of its regular and chaotic aspects, is the domain where the unity and universality of all finite many-body systems is beautifully manifested.

8 Conclusions

The main objective of this brief review was to discuss various facets of nuclear structure 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 interdisciplinary field. An important element in this task will be to extend the study of nuclei into new domains. New radioactive beam facilities, together with advanced multi-detector arrays and mass/charge separators, will be essential in probing nuclei in new domains where new phenomena, likely to be different from anything we have observed to date, will occur. The new data are expected to bring qualitatively new information about the fundamental properties of the nucleonic many-body system and will be crucial for developing a unified description of the nucleus.

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