Exotic Nuclei and the Evolution of Structure across the Nuclear Chart

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Abstract. Nuclear Structure physics is entering a new era, associated with three major technological developments and the physics they enable: facilities that give access to large numbers of exotic nuclei far from the valley of stability, new generations of detector systems and particle separators, and advanced computing capabilities both for data acquisition and analysis, and for theory. This talk will discuss the physics of exotic nuclei, focusing on new phenomena in the weakly bound, strongly interacting, quantal systems that nuclei near the drip lines provide, and on the opportunities to study the evolution of structure, shell structure, collective modes, many-body symmetries, and quantum phase transitional behavior and critical point symmetries across long chains of nuclei. A brief worldwide perspective on next generation exotic beam facilities will also be presented.

1 Introduction

The simultaneous advent of three hugely important technological advances have converged to produce a truly revolutionary transformation in low energy nuclear physics - nuclear structure and nuclear astrophysics—that is ushering in a renaissance of activity and interest in this field and which promises an extremely bright future. The most prominent of these advances is the ability to construct major facilities for the production, extraction, and exploitation of exotic nuclei far from the valley of stability. But this advance alone would not have led to the present situation.

Equally crucial are the development of new generations of both detector systems and beam separation and purification devices, and the rapid development of advanced computing capabilities. Exotic nuclei are produced in beams with extremely weak intensities. Instead of the traditional experience of experiments with 10^8 to 10^{10} particles/sec, studies with exotic nuclei will often range down from intensities of, say, 10^6 particles/sec to as low as one particle/hour or even less. Moreover, frequently, these beams are accompanied by other contaminant beams, often many orders of magnitude stronger. Clearly, traditional methods of beam separation and radiation ($e.g.$, γ-ray spectroscopy) detection will need to be significantly upgraded. Fortunately, this is occurring rapidly. New generations of γ-ray tracking instruments, such as GRETINA, and then GRETA, or AGATA, and new electromagnetic separation devices such as DRAGON at TRIUMF or the S1900 at MSU, are revolutionizing experimental capabilities. Beams of exotic nuclei do provide one gain in efficiency: most experiments are done in inverse kinematics so that all the reaction products go forward in a narrow cone and it is easier for detectors to subtend a larger fraction of 4π solid angle.

Two examples of the improvements in capabilities are Coulomb excitation with medium energy beams and mass measurements, where, today, experiments are commonly done with beam intensities on the order of 10^2 particles/sec or less [1–4]. The Coulomb excitation work exploits the extreme forward peaking to capture nearly all the reaction cross section, and the single-step simplicity of the excitation process at beam energies of 50-200 MeV/particle. The mass measurements take advantage of the precision and efficiency of modern Penning trap systems.

Advanced high speed computing comes into play in two ways—experimental and theoretical. Experimentally, it is often key to track each beam particle as it traverses the target and interacts with it. This implies the need for fast multi-level triggering and coincidence gating with on-line computer processing of each event. (Of course, the same also applies to current experiments with stronger beams such as in γ-ray spectroscopy.) Theoretically, advanced computing is increasingly needed as the nuclear systems that can be attacked by modern microscopic models become heavier and heavier with more and more active nucleons and larger Hilbert spaces and as the forces used to calculate nuclear properties become more and more complex.

The temporal confluence of these three technological advances has spurred an increase of activity and excitement in low energy nuclear structure (analogous to the revolution induced in atomic and condensed matter systems by the laser) unlike anything seen since the advent of the first arrays of Ge γ-ray detectors in the 1970s. The purpose of the rest of this short paper is to discuss some of the new physics that these advances offer. We will first very briefly discuss physics near the drip lines and then turn to the so-called "fourth" frontier, the internal one of structural evolution and the emergence of collectivity and coherence across spans of, say, isotopes, from near the proton drip line to very neutron rich. Finally, we will end with a short world-perspective on recent and upcoming facility development activities in this area.

2 Physics of weakly-bound nuclear systems

One of the most important and intriguing aspects of exotic nuclei includes the effects and phenomena that occur for weakly bound nuclei near the drip lines. The idea is encapsulated in the sketch in Fig. 1. In normal nuclei, nucleons are typically bound by the nucleon separation energy of 5-15 MeV. Their wave functions are well contained within the normal nuclear volume. In exotic nuclei near the drip lines, say, the neutron drip line, the last neutrons are very weakly bound. This has at least four significant consequences.

First, from trivial quantum binding effects, their wave functions will extend to large distances, well outside the radius of a well-bound nucleus of the same A value. This creates, especially if it applies to many nucleons, an outer region of low density, diffuse, spatially extended, nearly pure neutron matter. This is the origin of the famous phenomenon of halo nuclei [5]. With many weakly bound nucleons, this is

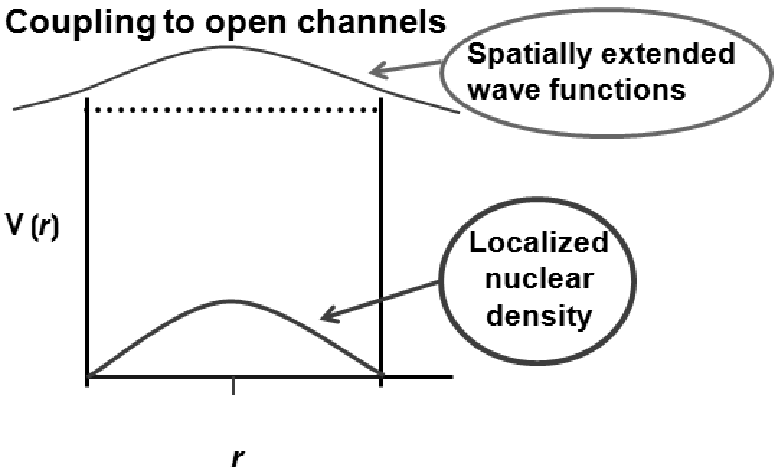

Figure 1. New Features in Exotic Nuclei

expected to give rise to a neutron skin and to intriguing relations with the crusts of neutron stars.

Secondly, since it is the nucleons themselves whose densities create the mean field of single nucleon potential models, the shapes of those potentials may change in weakly bound, exotic, regions. Shell changes due to weak binding/spatial extension can alter the high-j-low-j ordering of single particle levels and the magnitude of the spin-orbit force which is surface-peaked. This is one of two well-known origins of the changes in shell structure that occur far from stability. The other mechanism is usually attributed to the monopole component of the p-n interaction that shifts single particle energies due to a self-energy contribution [6, 7]. Sorting out which mechanism is relevant in any given mass region is an interesting challenge and one whose understanding will help in approaching the goal of a unified theory of atomic nuclei. Examples of changes in shell or subshell gaps have been much discussed. Early references are [1, 6–8], and recent experimental work includes Refs. [9–11].

Thirdly, scattering to the continuum of unbound resonances [12,13] will become important and needs to be taken into account. Fourthly, and related to the third, the relative effects of residual interactions might be altered since these interactions are density-dependent. In particular, scattering of pairs of nucleons into the continuum may increase the strength of the pairing interaction. In extreme cases, this effect could be strong enough to vitiate the viability of the single particle mean field and raise the pairing interaction to such a level that single particle motion as a dominant ansatz is seriously altered.

3 Structural evolution—the fourth frontier

Studies of weakly bound nuclei are only one of the many fascinating and critical aspects of the study of exotic nuclei. Access to much larger ranges of isotopes provides a unique opportunity to study the evolution of structure between the neutron-poor and neutron-rich limits of accessibility. The Ni isotopes, for example, will be accessible for isotopes spanning portions of up to four major shells.

Simple considerations of the nature of residual interactions show that the physics in heavy nuclei can be qualitatively different, and much richer, than in light nuclei, in particular concerning the emergence and types of collectivity, and thus access to long isochains in medium and heavy nuclei offers a completely new vista in nuclear structure. The reason the physics of heavy nuclei can be qualitatively different can be encapsulated simply. The number of spherical-driving valence residual interactions, such as pairing, scales with the total number of valence nucleons, since each valence nucleon interacts with only one other—that in the time reversed orbit. In contrast, the number of collectivity-driving interactions such as the p-n interaction scales with the product of the number of valence protons and neutrons since all valence nucleons participate. Thus the competition of spherical-driving and collectivity-driving interactions depends, at least in the crudest model of all-equal interactions strengths, as $N_pN_n/(N_p + N_n)$ [14]. It is well known that many aspects of collectivity, from equilibrium structure, to collective modes and even to rotational spectra [15], are sensitive to this quantity, called the P-factor. Since shell size increases in heavy nuclei, P can take on much larger values near mid-shell in heavy nuclei. This gives much more free-reign to the development of collectivity and deformation in nuclei. Since $P \sim 5$ is, roughly speaking, the borderline between spherical or transitional and deformed nuclei, it can easily happen that P never attains such values in light nuclei, or does so only for a small subset of nuclei, whereas, in heavy nuclei, many nuclei with $P > 5$ exist and can exhibit strong collective effects. In addition, in heavy nuclei, typically, the major shells contain a large number, and significant variety, of single particle levels, giving rise to a richer diversity of interactions and interaction strengths. Thus, heavy nuclei are not just more massive siblings of their lighter brethren—they can and do exhibit different manifestations and systematics of emergent collectivity.

One of the most interesting recently studied phenomena in the development of collectivity and deformation in nuclei is that of quantum phase transitions(QPTs). These are rapid changes in the ground state equilibrium structure, induced by changes in the number of nucleons and their interactions. In this view, nucleon number is the control parameter for the phase transition, and the deformation (or some suitable observable experimental proxy for it) is the order parameter. In the $A \sim 150$ and other regions, evidence for such QPTs was discussed a number of years ago [16, 17]. This discovery in turn inspired Iachello to develop the concept of Critical Point Symmetries (CPSs) to describe nuclei at the phase transitional point [18, 19]. Immediately upon their proposal, empirical manifestations were discovered [20, 21]—in ^{134}Ba for the case of a second order phase transition and the CPS E(5) and in ^{152}Sm for a first order phase transition and the CPS X(5). Soon thereafter, other examples of X(5) were proposed [22, 23] in the N=90 region. Using the criterion of $P \sim$5, Ref. [24] identified the potential locus of candidates for X(5)-like nuclei. Many of these lie far off stability and thus provide an additional incentive for the study of structural evolution far from stability.

Of course the idea of structural evolution and that of changes in shell structure discussed earlier are closely linked. An important question is whether structure will evolve in similar ways off stability as it does in the nuclei we currently know. Will we see the same manifestations of shape/phase transitional regions? There are many reasons one may expect different behavior and identifying it will again help in delineating a comprehensive theory of all nuclei.

Far off stability the combinations of valence neutron and proton orbits will be different than those near stability. Residual interactions, even well within the drip lines, may then well be different. An example of this is illustrated by studies of empirical valence proton-neutron interactions [25–31]. These vary considerably depending on the outermost proton and neutron orbits being filled—both near closed shells [25] and throughout major shell regions [27, 28]. (See talks by Mario Stoitsov [30] and R.B. Cakirli [31], this conference). If shell structure varies far from stability, such effects may be further exacerbated. Changes in the p-n interaction, or in pairing interactions, may well determine how structure depends on N, Z, and A.

Another reason to expect different behavior far from stability has to do with the proton-neutron asymmetry in such regions. The low lying states of nuclei near stability are, to a high degree of accuracy, proton-neutron symmetric. This is evidenced by the success of the phenomenological IBA-1 model [32] which makes no distinction between proton and neutron degrees of freedom. If the proton and neutron degrees of freedom are decoupled or partially so, as would likely occur in neutron-rich nuclei, different symmetries appear [32] and the nuclear equilibrium phase diagram changes from a triangle [33] to a tetrahedron [34]. In addition, prolate-oblate shape/phase transitions may be more abundant than the rare examples currently known [35].

4 World perspective on exotic beam facilities

This is, of course, not the place for a thorough review of current and next-generation facilities of exotic beam physics. However, it should be clear from the above discussion that this area offers a new and unique opportunity for a renaissance in nuclear structure physics that has generated worldwide enthusiasm and activity. Currently, significant activity in the field of exotic nuclei is on-going in North America (NSCL at MSU, HRIBF at ORNL, and ISAC-II at TRIUMF, along with active niche research at ATLAS at ANL), in Europe (especially at GSI, GANIL, ISOLDE at CERN, Catania, and elsewhere) and in Japan (RIKEN). Major next-generation facilities have just been built (RIKEN RIBF in Japan), are under construction (FAIR at GSI and SPIRAL II at GANIL), or about to be authorized and constructed (FRIB in the US). In the longer term, EURISOL is on the horizon in Europe as well. These facilities use a variety of techniques, ranging from ISOL, gas-catcher stopping, in both cases, accompanied by re-acceleration, to in-flight methods that use higher energy beams directly.

Table 1. Rough qualitative guide to classes of experiments that can be done at different exotic beam intensities.

Particles/sec	Physics of Nuclei
10^{-5}	Existence; perhaps half life, decay modes
10^{-4} to 10^{-3}	Half life, mass, min. structural information
10^{-2} to 10^{-1}	Some detailed structural information
10^{3}	Full details of structure
$>10^{5}$	Astrophysical reaction rates
10^{6}	Weak interaction strengths
10^{8} to 10^{12}	Production of superheavy elements

Perhaps the most important single criterion for assessing these facilities is the beam intensities of the exotic isotopes produced. While this is far from the only criterion (beam energy, beam purity and quality, associated beam separation devices and end-station instruments are also vitally important), it is useful to end with a schematic survey of the kind of nuclear structure physics that can be extracted at different beam intensity levels. This is shown, with some trepidation, in Table 1. These numbers are rough guides only, and the complexity of different classes of experiments cannot be captured by a single or pair of intensity numbers. Moreover, as time passes, experimental techniques will surely improve, as they have dramatically in the last decade, and it is likely that many of these techniques will be usable with orders of magnitudes lower beam intensities in the next decade. Nevertheless, the Table is useful in showing that, at any given intensity, certain classes of experiments are doable, and that more spectroscopic information becomes available with increasing intensity. An important corollary is that, in comparing a facility with higher beam intensities that give access to new nuclei further from stability, it is not only the newly accessible nuclei that represent the step forward, but also the typically orders of magnitude higher intensities at which already accessible nuclei will then be available and the greater structural information that that will provide.

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