The Scientific Basis of the RIA Specifications

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Preface

The field of nuclear physics with rare isotopes from RIA is both rich and diverse. While there are many critical scientific questions that can be addressed with these isotopes, it is useful to classify the scientific purview of RIA science according to the following four themes:

- **The Nature of Nucleonic Matter and the Understanding of Complex Systems**
- **The Origin of the Elements and Energy Generation in Stars**
- **Tests of the Standard Model and of Fundamental Conservation Laws**
- **New Isotopes to Meet Societal Needs**

The scientific justification has been thoroughly documented in a number of white papers, which are available at the RIA User's group website (http://www.orau.org/ria/). Some of the more complete and recent are:

- The Isospin Laboratory (1991)
- Concept for an Advanced Exotic Beam Facility (ANL 1995)
- Scientific Opportunities with an Advanced ISOL Facility (Columbus 1997)
- Scientific Opportunities in Nuclear Astrophysics (Notre Dame 1999)
- Scientific Opportunities with Fast Fragmentation Beams from the Rare Isotope Accelerator (MSU 2000)
- RIA Physics White Paper (Durham 2000)
- RIA Applications Workshop (Los Alamos 2000)
- The Intellectual Challenges of RIA (RIA Steering Committee 2002)

These documents provide a detailed description of the nuclear science that RIA will address including a discussion of key experiments. The last of these documents, *The Intellectual Challenges of RIA*, is included below. It provides a comprehensive view of the issues to be addressed with RIA in the context of science in general. The science goals are mapped into the machine requirements in the final section where we discuss which rare-isotope beams and what energies are necessary.

To achieve the scientific goals envisioned in these documents, RIA must provide a wide range of rare isotopes with the necessary intensities. This is only possible by employing a variety of production methods, e.g., fragmentation, fission, fusion and spallation that allow the optimum production of a given nuclide for the desired energy. The facility will require innovative ideas in isotope separation to provide beams of all elements, which is critical to the science, with little dependence on half-life or chemistry. The desire to use multiple production mechanisms and have efficient collection and separation of the nuclides produced determines the characteristics of the driver LINAC. These considerations dictate a primary beam energy of at least 400 MeV/u for all beams including uranium, and beams of nearly all elements from hydrogen to uranium at a beam power of at least 100 kW and preferably at 400 kW.

I. Introduction

RIA-based science is extremely broad and diverse. It spans the gamut from nuclear structure to astrophysics, tests of fundamental laws of nature, and myriad applications. Nevertheless, it is characterized by several encompassing themes that reflect the major challenges facing modern science today, and it has deep links to many other fields. In this Introduction, we will briefly touch on these themes and relate them to specific areas of RIA research. The sections that follow will be couched in terms of this framework.

The study of exotic nuclei opens new opportunities, excitement, and challenges. The opportunities arise because we now (with RIA) will have the ability to select specific nuclei from a greatly enhanced "gene pool" in order to isolate and/or amplify specific interactions, nucleonic correlations, excitation modes, and symmetries. The challenges and the excitement arise because exotic nuclei will present new and radically different manifestations of nucleonic matter that arise near the bounds of nuclear existence, where the special features of weakly bound, quantal systems come into prominence, and because these nuclei are key to understanding the cosmos. We already see glimpses of the exciting physics, for example, in the appearance of Borromean halo nuclei, and in the breakdown of the long cherished magic numbers as benchmarks for structural evolution, but a much broader range of new phenomena is expected to emerge beyond the present limits of experimental accessibility.

How Complex Systems Emerge from Simple Ingredients

The world around us, ranging from microscopic matter to the cosmos, seems, and often is, incredibly complex. Yet it is constructed from a small number of entities that obey simple physical laws and interact with only a small number of forces. It is a remarkable achievement and an on-going challenge of modern science to understand the immense diversity of nature in terms of elemental particles, a set of conservation laws (energy, angular momentum, and the like), four forces and a framework of fundamental physical Principles (the laws of quantum mechanics, quantum statistics, and the like).

The atomic nucleus is a finite, 2-fluid (protons and neutrons) many-body laboratory that manifests this challenge in unique ways. With RIA, we will have the capability to specify, control, and vary precisely the number of nucleonic bodies over wide ranges so that we can study, not only the structure of individual nuclei, but the evolution of that structure across the nuclear chart. The goal of nuclear physics with RIA is to achieve a comprehensive, unified theory of nuclear structure across the entire nuclear landscape.

Simplicities and Regularities in Complex Systems

Despite the complexity of nucleonic matter, the nuclear systems that emerge display astonishing regularities and simple excitation patterns, at least in those systems near stability that have been accessible to date.

This brings us to the second principle theme and challenge, namely, understanding how such complex nuclear systems, with up to hundreds of interacting nucleons, can display these elegant simplicities. This challenge is nothing less than the elucidation of paradigms of structure that allow the classification of wide varieties of nuclei under the umbrella of a single unified conceptual framework. These paradigms often involve a geometrical perspective on structure and therefore lend themselves to the concept of symmetries and, especially, dynamical symmetries, and even supersymmetries. In weakly bound systems the dramatic changes in nuclear structure may lead to entirely different manifestations of symmetries in nuclei and possibly to the emergence of new symmetries and new structural paradigms. With RIA we will, for the first time, have broad access to this physics.

Note that these first two themes are beautifully complementary near-mirror images of each other: how can complex systems be constructed from basic ingredients, and how can the resulting complex many-body systems display such elegant regularities and symmetries.

Understanding the Nature of the Physical Universe

Clearly, one of the goals of modern science is to understand the nature of the physical universe. Here, nuclear physics, and in particular nuclear structure, plays an especially central role, since so much of the energy generation in stars involves the release of nuclear energy, either through fusion or fission processes, or in radioactive decay. All of the nucleosynthesis of the elements in our world (and ourselves) involves nuclear reactions. Given the temperatures and particle densities in stellar objects and in cataclysmic stellar explosions, these reactions often occur in unstable nuclei. This makes a facility such as RIA critical to advancing our understanding in this field. This is also an area of optimal cross fertilization between disciplines—optical (especially modern satellite) observational astronomy on the one hand, provides windows of observation for celestial phenomena originating in nuclear processes, while RIA provides the tool for the terrestrial study of the nuclear reactions that drive these events. The link between RIA physics and astrophysics runs even deeper than this since the study of neutron rich nuclei provides the tools for understanding the properties of such important objects as neutron stars, and the physics of nuclear phase evolution in the realm of extreme densities.

Testing Fundamental Laws of Physics

The idea of being able to select specific nuclei to isolate and enhance particular effects is central to the role RIA will play in testing fundamental laws of physics. The ability to access long sequences of isotopes is crucial to eliminating sources of theoretical uncertainty in carrying out these tests. Moreover, often specific nuclei, such as the rare examples with octupole deformed (pear) shapes, enhance certain sought-after effects, such as violations of time reversal symmetry.

It is interesting that two such very different frontiers of RIA research as the stability of the heavy elements and tests of fundamental symmetries both depend on inherently nuclear structure effects, specifically, the non-uniform distribution of single particle levels which has its origin in geometric symmetries of classical orbits.

Interdisciplinary Aspects

In the past, nuclear physics has often borrowed from other fields of physics. The concepts of the mean field and the importance of pairing are two examples, as are techniques such as the BCS formalism and the RPA approach to the microscopic understanding of collective modes. Now the flow of interdisciplinary cross fertilization proceeds actively in both directions. In recent years, ideas from nuclear physics have found applications in other mesoscopic systems such as quantum dots, metallic clusters, and molecular systems, in astrophysical environments such as neutron stars, and in the exploitation of the concepts of dynamical symmetries and supersymmetries. After decades in which the disciplines of physics (and of science) have tended to diverge, there is a growing interlinkage between fields. Exploitation of this will surely enhance all disciplines. Discussions of interdisciplinary aspects of RIA science permeate this White Paper.

Science for the Betterment of Mankind

Finally, although not the focus of this particular White Paper, RIA will provide huge opportunities for potential applications of nuclear physics. Often, these applications rely, as above, on our ability to select specific nuclei with particular decay modes, half-lives, and energies. This is especially true in medical (diagnostic and therapeutic) applications, in waste management, and for National Security. In other fields (e.g., in condensed matter research) the availability of time-delayed (by radioactive decay) chemical changes in an implanted atom may be critical to enhancing the performance of electronic devices, or of rendering them feasible to begin with. A broad range of applications and numerous opportunities for future technical developments with RIA have been described in previous White Papers. Perhaps most importantly, RIA will also provide a superb venue for the important mission to educate and train the next generation of nuclear scientists, who will play key roles not only in basic research itself but in myriad allied fields.

Worldwide, the study of exotic nuclei is in rapid advance. Major projects are planned or already underway in Europe and Japan. The field is vital and intensely active. Progress can be made, at a reduced level, of course, without RIA, but RIA stands alone, 1 – 2 orders of magnitude better than any existing, or ever envisioned, facility. RIA is, simply put, second to none. With RIA, the U.S. will maintain a world leadership position in nuclear physics for decades.

Today nuclear structure and astrophysics find themselves on the threshold of the most exciting era in decades, perhaps ever. We are poised to make extraordinary advances and to achieve a perspective so much broader than we have today. To realize such progress, RIA is essential.

II. Towards a Global Theory of the Nucleus—Understanding Complex Nuclear Systems

Significant advances in microscopic modeling of nuclear structure have been made in recent years, due to both new algorithms and to the tremendous increase in computational power. The "*ab initio*" work on few-nucleon systems, based on the bare nucleon-nucleon interaction, augmented by a three-body force, already allows us to calculate the properties of nuclei with $A \leq 12$. For heavier nuclei, various shell model methods utilizing sophisticated truncation schemes have been very successful in predicting nuclear properties. The effective interactions developed in shell model studies can be used to understand the forces employed by the mean-field methods based on the density functional theory applied to heavy nuclei. By exploring connections between these models, nuclear theory aims to develop a unified description of the nucleus.

This theory program is an ambitious one, and it cannot be carried out without the stimulation of RIA. RIA will extend the knowledge of nuclear properties beyond the known chart of the nuclides toward the limits of existence of bound nuclei. The challenge to microscopic theory is to develop methodologies to reliably calculate and understand the origins of unknown properties of new physical systems, physical systems with the same ingredients as familiar ones but with totally new and different properties. Only with RIA will we have the new data to test theoretical predictions. Only with such data do we have a chance to develop a comprehensive nuclear theory.

In this White Paper, we will focus on just a few topics that have deep links to other areas of mesoscopic physics and, therefore, where advances in nuclear physics will have wide impact. The microscopic framework for understanding the structure of all but the lightest nuclei is the twin concept of the mean field and residual interactions. The former leads to the shell structure which is the cornerstone of nuclear structure, while the latter generates the correlations and collectivity that give such richness to nuclear phenomena. Research on exotic nuclei already in hand suggests that both concepts may face radical alteration far from stability and, therefore, that any global theory of the nucleus must embody this flexibility. Both concepts are also pervasive in many-body physics and therefore advances in one area contribute to those in others.

RIA as a Laboratory of Mesoscopic Physics

The atomic nucleus is a complex fermionic system of particles interacting via an effective force strongly influenced by in-medium effects. It is small enough that the quantum nature of its constituents determines its properties but large enough that macroscopic features begin to evolve. Nuclei have been the traditional objects for studying mesoscopic phenomena. Now, additional mesoscopic systems have become available for study, such as clusters, grains, mesoscopic rings, quantum dots, atom condensates, and others. There are many topics common to these small aggregations: existence of shell structure and collective modes [*e.g.*, vibrations in nuclei, molecules, and clusters; superconductivity in nuclei and grains, manifestations of large-amplitude collective motion (such as multidimensional tunneling, coexistence, and phase transitions), nonlinear phenomena and chaos, and dynamical symmetries].

Femtostructures and Nanostructures

There is intense research today on quantum nanostructures. These are grains, droplets or surface structures, which confine a number of electrons within a nanometer-size scale. Nuclei are femtostructures. All these small systems share common phenomena which appear on very different energy scales, the nuclear MeV, the molecular eV, and the solid-state meV scales.

As compared to the other mesoscopic systems, research with nuclei offers a number of advantages. The temperature is zero; the number of constituents is known; the effect of strong magnetic fields can be simulated by setting the nucleus into rapid rotation. Moreover, recent advances and breakthroughs in detector technology, coupled with decades of experience, provide a unique technological basis for further research. Since certain properties that can easily be measured in nuclei are hardly or not accessible for non-nuclear mesoscopic systems and vice versa, complementary studies are essential for understanding the underlying physics governing such systems.

A central and very general question is how the structure of a mesoscopic system develops with the number of constituents. In nuclear physics, this evolution is strongly mediated by the beautiful concept of shell structure. In nuclei, shell structure arises from basic aspects of the mean field and the effects of the Pauli Principle. Shell structure has also now been found in metallic clusters and quantum dots, and is key to understanding the structure of these systems. Figure 1 illustrates shell structure in both nuclei and atomic clusters.

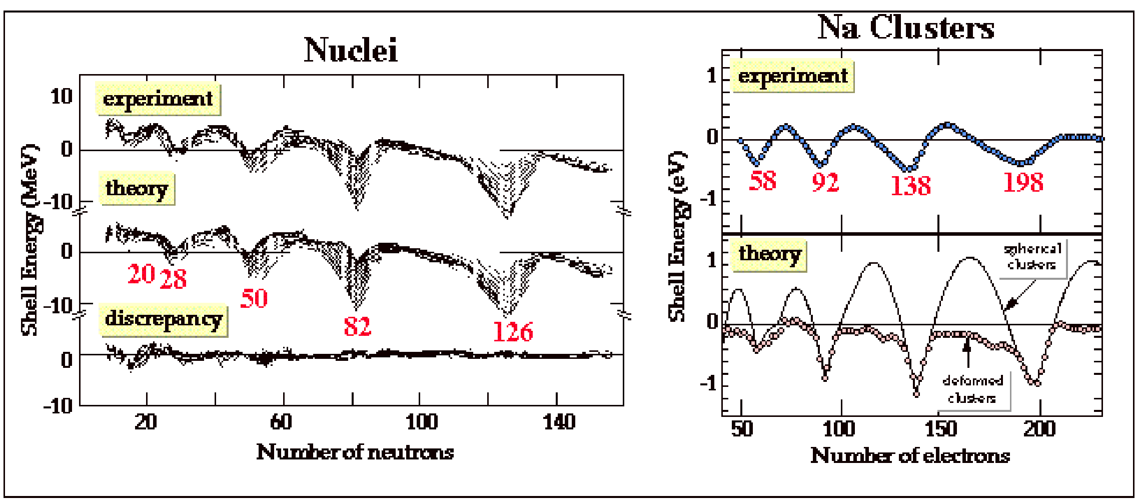

Fig. 1. Experimental and calculated shell energies for nuclei (left) and sodium clusters (right) as a function of particle number (neutrons for nuclei and electrons for clusters). The sharp minima can be attributed to the presence of magic gaps.

Shell structure, once conceived as a robust characteristic of all nuclei, is now being recognized as a more fluid concept. The weakly bound diffuse outer realm of an exotic nucleus, for example, cannot support the same sharp-edged mean field that characterizes nuclei near stability. *RIA will extend our knowledge of near-drip line nuclei far more than any other facility. It is the key to* *probing how shell structure, shell gaps, and magicity evolve and to study the impact of these changes on nuclear structure.* Such changes also have large effects on nucleosynthetic processes (*e.g.,* r-process), which pass through extremely neutron-rich nuclei.

The evolution of nuclear structure with the number of nucleons, angular momentum, and temperature exhibits rapid changes, which are the counterpart, in these small systems, *of phase transitions in macroscopic materials*. These critical phenomena pose a great intellectual challenge: we are just beginning to understand their nature. It is essential to characterize the transition by appropriate parameters that are reflected by experimental signatures. Nuclear structure physics has already contributed in a crucial way to this vigorous field. With RIA, one can expect further important contributions that reach far beyond nuclear structure. One example, the powerful classification scheme of nuclear phases in terms of dynamical symmetries is discussed in the next section.

Nuclear structure also provides perspectives on spontaneous symmetry breaking. The breaking of spherical symmetry to produce nuclei with axial deformation manifests itself in rotational bands. The breaking of intrinsic reflection symmetry manifests itself in parity doubling: that is, the appearance of nearly degenerate states of opposite parity. Phenomena similar to the Jahn-Teller effect observed in molecules can be seen in nuclei, where the addition of a proton or a neutron lowers the symmetry of the adjacent even-even nucleus. It has been suggested that the concept of "chirality" used in molecular physics can be applied to nuclei. *Many symmetry breaking modes are rare in nuclei near stability. Hence, these phenomena can be studied in much greater depth with RIA.*

Finally, another topic of great interest is the signatures of classical chaos in associated quantum systems. A nuclear physics theory (random matrix theory), developed in the 1950s and 1960s to explain the statistical properties of the compound nucleus in the regime of neutron resonances, is now used to describe the universality of quantum chaos. Other excellent examples of the interplay between chaotic and ordered motion in nuclei are the appearance of special excited nuclear states (symmetry scars) well characterized by specific quantum numbers, and the appearance of collectivity in the many-body system governed by random two-body interactions. The study of collective behavior, of its regular and chaotic aspects, is a domain where the unity and universality of all finite many-body systems are beautifully manifested.

Pairing

Any attractive interaction between fermions at low temperatures generally leads to fermion pairing analogous to the Cooper pairing of electrons in superconducting metals. It is not surprising, therefore, that pairing lies at the heart of nuclear physics. It is present in finite nuclei and in the nuclear matter of neutron stars (nucleonic pairing), and it is believed to exist in the quark-gluon plasma (color superconductivity).

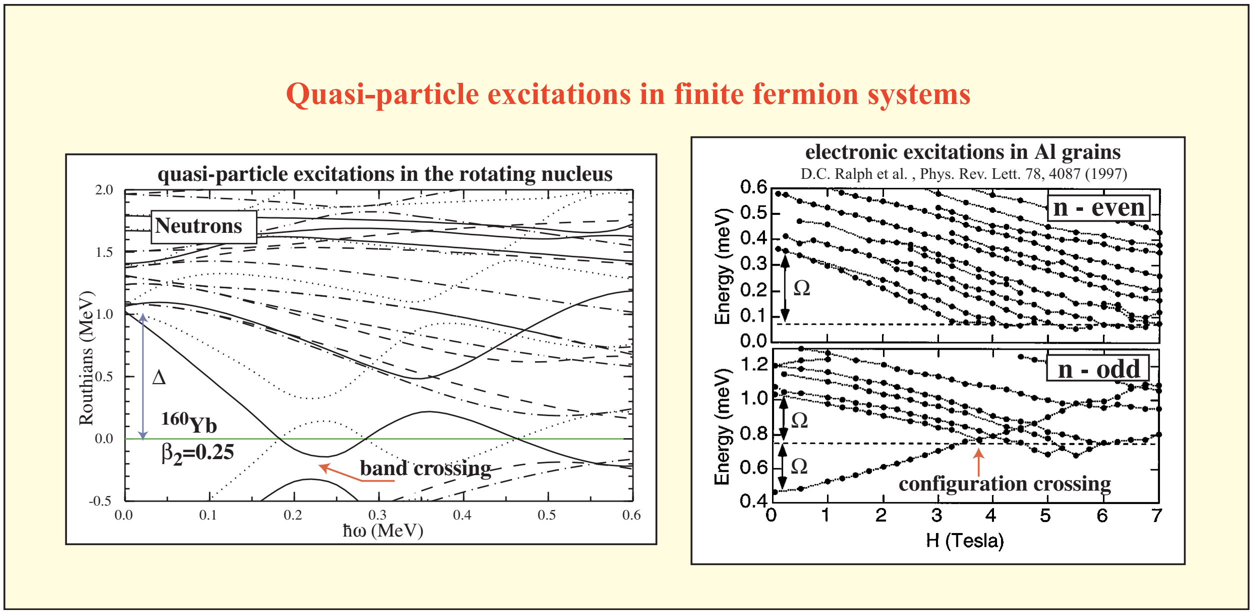

Fig. 2. Quasi-particle excitations in femto-and nano-structures. Left: Quasi-particle neutron spectrum of rotating ^{160}Yb as a function of rotational frequency $\hbar\omega$ calculated assuming neutron pairing gap Δ_n=1 MeV and quadrupole shape deformation β=0.25. Right: Measured electronic excitations in Al grains as functions of the external magnetic field.

While the concept of pairing was introduced to the study of atomic nuclei at a very early stage, there are many basic questions regarding this fundamental many-body mode which have not yet been answered, such as the microscopic origin of many-body pairing in finite nuclei (e.g., what part of the effective pairing interaction comes directly from the bare force and what part is induced).

Exotic nuclei accessible with RIA will offer many new opportunities to study pairing, especially in systems with strong density variations. Since the number of nucleons can be precisely controlled, nuclei are wonderful laboratories of many-body pairing at various regimes of the strength (one can probe dynamic and static aspects of pairing in different isotopes of the same element). Extremely neutron or proton rich nuclei can have different superconducting phases, characterized by nucleonic Cooper pairs carrying different isospin, spin, and total angular momentum. For example, while neutron and proton pairing fields are essentially independent in nuclei near stability, in proton rich nuclei, they may be coupled, leading to deuteron-like spin 1 pairs. The idea of such correlations between non-identical fermions may be special to nuclear physics, but spatially anisotropic (non-zero angular momentum) pairing fields are also discussed in the context of high-T_c superconductivity.

The coherence length (the size of the Cooper pair) in atomic nuclei is much larger than the nuclear size. Nuclei used to be the only example of such a situation until very recently, when it became possible to study ultrasmall, nano-size Al grains. As in nuclei, superconducting grains exhibit the presence of the energy gap in the spectrum and they show the odd-even staggering of binding energies. Also, as seen in Fig. 2, in the presence of an external magnetic field, quasi-particle spectra of grains strongly resemble those of rotating nuclei.

Pairing can determine even the existence of a nucleus. A classic example is the chain of helium isotopes: the N-even nuclei $^{4,6,8}He$ are bound while the odd-N isotopes $^{5,7}He$ are not. Such an odd-even effect in nuclear binding energies is well known, but it is particularly important in drip line nuclei. Indeed, pairing in near-drip-line nuclei may take on such importance that single particle motion in a mean field is no longer a viable ansatz.

Another fascinating example of interplay between nuclear physics and other fields involves trapped cold Bose and Fermi gases. The relationship between Bose-Einstein condensation and superfluidity has been studied extensively in liquid helium, but it is only recently that it has been possible to examine it in condensates of dilute alkali metal vapors. A spectacular example is the so-called scissors mode in which the atomic cloud oscillates with respect to the symmetry axis of the confining potential (Fig. 3, right). Actually, this kind of angular oscillation was first introduced in the context of nuclear physics. If the nucleus is deformed, neutron and proton clouds can undergo orbital angular oscillations, which manifest themselves in characteristic collective magnetic excitations and their M1 decay (see Fig. 3, left). RIA will enable us to study a new form of scissors vibrations, namely, of the weakly bound neutron skin with respect to a well-bound deformed core in neutron-rich nuclei.

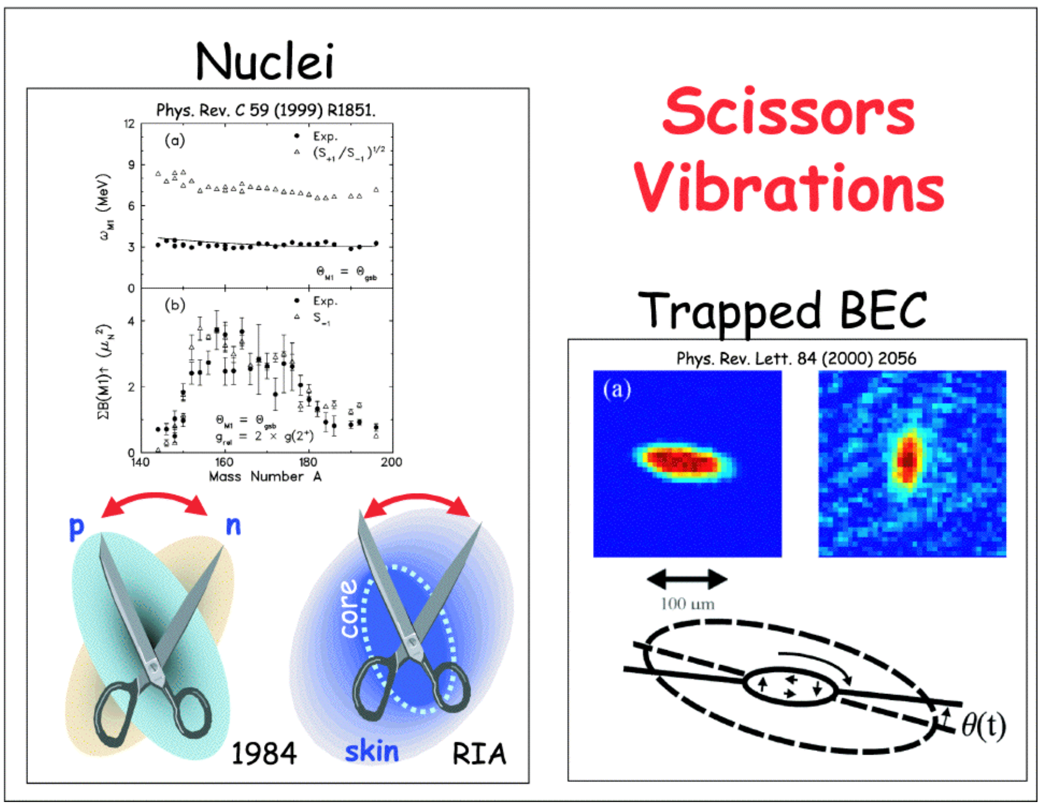

Fig. 3. Scissors modes in deformed superfluid nuclei (left), showing some of the energy and transition rate data supporting the concept, and a similar depiction of trapped Bose-Einstein condensate of ^{87}Rb atoms (right).

III. Simplicity and Regularity in Nuclei: Symmetry Structure of Nucleonic Matter

In science, as Einstein once said, "Everything should be made as simple as possible, but not simpler." In nuclear physics, while we hope to achieve a global microscopic theory of the nucleus (at least at the nucleonic level), it is important not only to be able to predict observables but also to understand as simply as possible the physical structure of nuclei that leads to the particular behavior of those observables. One very powerful approach is the concept of symmetries, in particular as manifested in the idea of dynamical symmetries, founded in a group theoretical basis. Often, solutions to physical problems originally obtained by numerical methods are later found to be obtainable almost by inspection once the underlying symmetry is recognized. Moreover, the concept of symmetry links diverse physical systems. Often, very disparate, seemingly unrelated, physical systems reveal deeply rooted similarities that are described by the same mathematical structure.

Symmetries have provided a remarkably simple and elegant understanding of the structure of atomic nuclei. However, the manifestations of such systems in nuclei have been limited to examples near the valley of stability. Since the physics of nuclei far from stability may be radically different (see previous section), completely new dynamical symmetries may occur or the manifestations and characteristic locus (in N, Z) of currently known dynamical symmetries may be greatly altered. *It will only be with the availability of the new nuclear species that can be accessed at RIA that we can hope to achieve a comprehensive understanding of the symmetry structure of atomic nuclei.* Moreover, as noted above, the ideas underlying these algebraic structures have wide applications throughout all of physics. Here we briefly comment on three classes of symmetries and their impact on our understanding of nuclei and other many-body systems.

Dynamical Symmetries

Dynamical symmetries, are symmetries of the interactions. One of the best examples is that already known to Pauli in 1926 of the Coulomb interaction (which has a dynamical symmetry associated with the group of rotations in an abstract four dimensional space generated by the angular momentum and the Runge-Lenz vectors). The dynamical symmetry of the Coulomb interaction, O(4), produces the Bohr formula that is the cornerstone of our understanding of the hydrogen atom and of atomic physics.

Dynamical symmetries play a key role in nuclear physics, especially within the framework of the Interacting Boson Model. In this model, the collective structure of nuclei with even numbers of protons and neutrons can be described in terms of angular momentum 0 and 2 bosons (s and d bosons), envisioned as correlated pairs of fermions analogous to the Cooper pairs in an electron gas. This structure gives rise to a U(6) parent group and to dynamical symmetries U(5), SU(3) and O(6) corresponding to spherical vibrator nuclei, ellipsoidally deformed axially symmetric rotational nuclei, and axially asymmetric nuclei, respectively. Remarkably, empirical examples of nuclei closely manifesting each of these idealizations have been found. These benchmarks provide guideposts to the structure of nearly all collective nuclei. The symmetry triangle, illustrated in Fig. 4, provides a structural framework for nuclei. The dynamical symmetries are shown at the vertices, and almost all even-even nuclei can be assigned a symmetry structure and placed somewhere within or on the triangle.

Critical Point Symmetries

The legs of the triangle in Fig. 4 represent transition regions from one symmetry to another. These transitional regions occur in real nuclei as a function of nucleon number, and theoretically, as a function of a coupling constant in the Hamiltonian rather than as a function of the temperature. (A simple example is the phase transition that occurs at zero temperature as a function of the strength of the magnetic field in materials that can be described by the Ising model.) Very recently, an astonishing result has been found in systems at the critical point of quantum phase transitions. Such phase transitions display a very simple behavior: their spectra appear to be well-described simply in terms of properties of special analytic functions. Such descriptions, called critical point symmetries [specifically labeled X(5) and E(5) in Fig. 4], are parameter free except for scale. This is particularly noteworthy in view of the fact that, at the critical point, fluctuations are at a maximum and thus one would expect maximal complexity in the spectrum due to the competition of different degrees of freedom (*e.g.,* spherical, deformed configurations in nuclei). Examples of critical point symmetries have now been found experimentally in atomic nuclei.

The concept of critical point symmetry is of interest to other fields of physics. In molecular physics, "shape" phase transitions similar to those observed in nuclei occur. Shapes of molecules are characterized by discrete groups. Examples of molecules sitting precisely at the critical point of "shape" phase transitions have actually been found. The best known is fulminic acid, HCNO, and its isotopic substitution, DCNO. In HCNO, the hydrogen atom sits in a very floppy configuration corresponding to the critical point of the linear to bent transition. Even more dramatic is the situation in a particular electronic state of methinophosphide, HCP. This state has been very recently found from analysis of Franck-Condon intensities to correspond to a quasi-bent configuration and to display all the characteristics of a critical point.

RIA will provide a fertile ground for the study of phase transitional behavior in nuclei, by giving access to new regions in which nuclear structure is rapidly evolving. Due to changes in the underlying structure in highly proton-neutron asymmetric nuclei, the character of their phase transitions is likely to be quite different, and offers the opportunity to enrich the study of critical point phenomena in finite systems.

Supersymmetries

This is a complex type of symmetry, originally introduced for particle physics, but which has been suggested as a classification scheme of nuclei as well. The search for supersymmetry is one of the main motivations of all present proposals for particle physics accelerators. Of course, supersymmetry in particle physics is quite different than in nuclear systems. The bosons in the former are fundamental entities, whereas, in nuclei and other many-body systems, the bosons are composite objects constructed from pairs of fermions. In this respect, the concept of supersymmetry in nuclei is closely allied to applications of this idea in condensed matter systems. Experimental study of the spectra of a quartet of nuclei near ^{196}Au has recently provided support for the actual existence of nuclear supersymmetry. Of course, with this first example, the study of supersymmetry in nuclei is only in its infancy. *RIA will offer an unequaled opportunity to test if this concept is manifested elsewhere and whether it provides a new route to understanding generally the relationships of "bosonic" and "fermionic" nuclear systems.* Finally, the discovery of supersymmetry in nuclei has stimulated searches for supersymmetry in cuprate materials (high-T_c superconductors) where bosonic (s and d) and fermionic excitations similar to those of nuclei seem to occur.

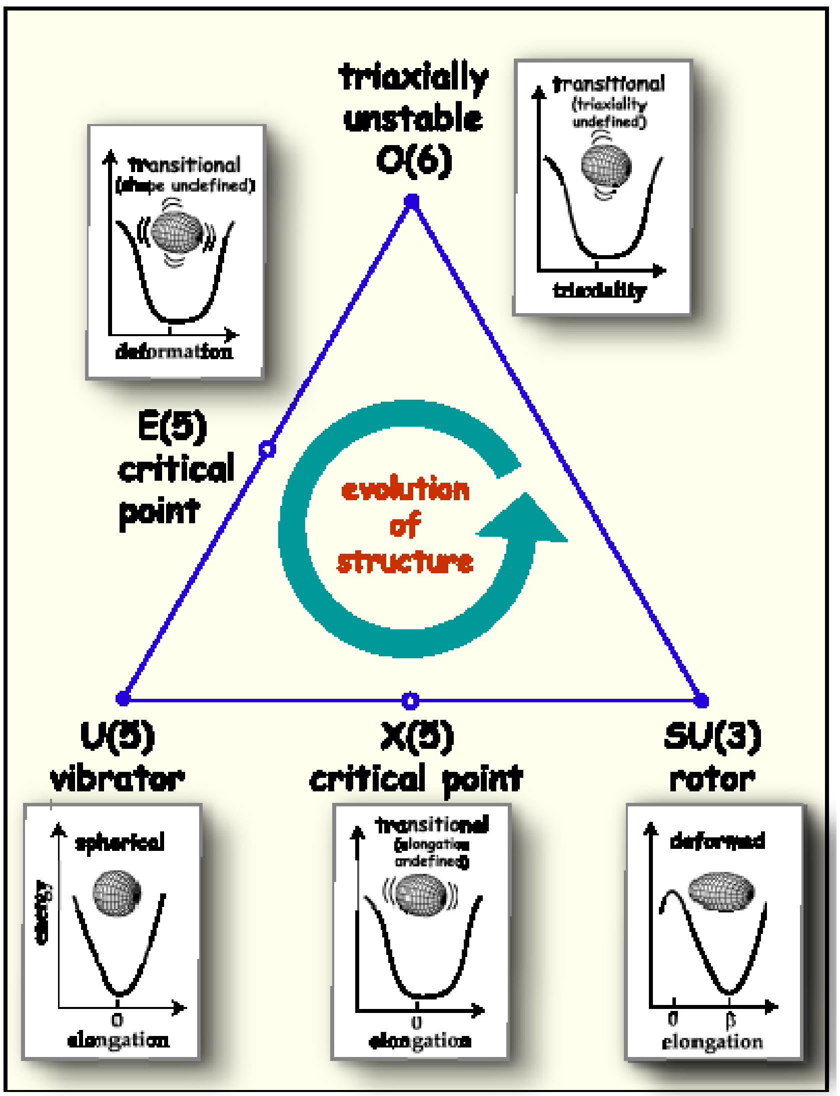

Fig. 4. Symmetry triangle for collective manifestations of nuclear structure showing the dynamical symmetries of the Interacting Boson Model at the vertices and critical point symmetries on the legs. The inserts show the nuclear energy surface as a function of appropriate shape parameters.

IV. Understanding the Physical Universe

Linking Femtophysics with the Cosmos

Mankind has wondered with awe at the cosmos since the beginning of our species. In our era, modern science complements that awe with growing comprehension. And nuclear physics plays an essential and deeply-rooted role in this quest. The structure of nuclei and their interactions control energy generation in stars. They also determine, in a cosmic battle with gravity, the evolution of stellar objects, the synthesis of the elements, and hence the appearance of life itself. As we outline below, data accessible only with RIA will allow us to make a real leap forward in our understanding of the origins and structure of the physical universe.

Throughout the history of the universe, from the third minute on, when the primordial nuclei ^{1}H and ^{4}He were formed, nuclei and nuclear structure have defined the development of matter formation. Indeed, already at this beginning era, the instability of nuclei with A = 5 and 8 inhibits nucleosynthesis much beyond A = 4. The subsequent evolution of the universe has been driven by the interplay between the long range gravitational force, the strong force and the Coulomb interaction. Gravitational forces lead to the clusterization of the primordial matter, creating localized regions of high density. These locations provide the "cauldrons of the cosmos" – the temperature and density conditions necessary for the nuclear reactions and decay processes leading to the formation of the elements, and the explosive hydrodynamic mechanisms for mixing these elements with the interstellar and intergalactic material.

The abundances of the elements are a unique reflection of the underlying nuclear structure. Stellar evolution provides a beautiful example of the evolution of matter channeled by nuclear structure. For two nuclei to fuse, they need enough energy to overcome (or tunnel through) the Coulomb barrier. This barrier increases very rapidly with Z. Hence, stellar energy generation proceeds in a sequence of hotter and hotter, and shorter time scale, nuclear "burning" cycles of reactions and decay processes, up to the iron region. Many of these cycles involve fusion reactions leading to alpha cluster nuclei such as carbon and oxygen. Indeed, the properties of these reactions establish a high carbon/oxygen ratio (and limit the formation of higher order clusters such as silicon), leading to the dominance of carbon-based organic matter within the universe. All these burning cycles are closely correlated to the structure of nuclei. Hence, the microscopy of nucleonic motion impacts the dynamical evolution of stars, and the composition of our universe.

Some of these burning stages already involve reactions with unstable nuclei. These kinds of reactions become even more important in late-stage explosive conditions. Yet, we do not actually know the structure or reaction processes of many of the key nuclei whose properties determine the resulting abundances. *RIA changes all this. We will now have laboratory access to key nuclear reactions involving unstable nuclei. This has every promise of boosting our understanding of the origins of the elements to a qualitatively new level.* There is a particular timeliness to this, since observational astronomy has broken through into a new era itself with sophisticated satellite-based observatories which are providing rich observational data heretofore only dreamt of. However, full exploitation of the opportunity offered by this wealth of new data is only possible if we understand the nuclear interactions that generate the radiations detected.

We know that the production of nuclei beyond Fe largely takes place in cataclysmic stellar explosions. Remarkably, we do not know what is the principal site. Among the likely candidates are supernova, which are among the most energetic explosions anywhere in the known universe, and they may be the site of the almost instantaneous production of many of the elements above Fe, via the r-process of rapid neutron capture in a very neutron rich environment.

In supernovae, the explosion and emerging shock conditions introduce a new, barely explored, environment for the evolution of nuclear matter and nuclear structure. This mirrors the slow formation of elements during the billions of years of evolution for the universe but on a time scale of seconds. Supernovae-sited nucleosynthesis, in particular the r-process path, is defined by the shell structure of heavy nuclei in neutron-rich regions of the nuclear chart still unknown to us. The effects of structure can be dramatic. For example, r-process calculations assuming normal shell structure reproduce many trends in the observed element abundances, but also exhibit significant discrepancies in specific mass regions. Calculations assuming shell quenching scenarios do much better. Also, fission of very neutron rich heavy nuclei represents the endpoint of the r-process, which is defined by the evolution of nuclear structure towards superheavy nuclei.

A particularly fascinating possible scenario is associated with the onset of the r-process itself. Neutron halo structure near the drip line may drive nucleosynthesis immediately towards the very neutron rich side of the line of stability, eventually controlling the reassembly of heavy elements through the enhanced pairing forces which are thought to govern and stabilize the structure of near-neutron drip line nuclei. Thus, quintessential nuclear structure questions such as quenching of shell structure, the nature of pairing, and possible clusterization within the neutron skin, may severely impact the origin and present distribution of elemental abundances.

It is clear that data on nuclei in the r-process path, accessible only with RIA, and the improved understanding of the nuclear quantum many-body problem that will follow, thus directly influences our knowledge of element production in the Universe. It is important to recognize that solving this problem also entails extensive use of modern parallel computing systems and the development of powerful new computational algorithms both for nuclear structure calculations and for modeling cataclysmic stellar explosions. Thus, a three-way synergy exists among the many-body problem, astrophysics, and computational science.

Another type of cataclysmic stellar explosion occurs in accreting binary systems in which a neutron star gathers material from a close companion star. Accretion feeds light hydrogen and helium isotopes into a high density temperature environment. Alpha clustering and rapid proton reactions produce nuclei up to A ~ 100. In addition, the process leads to truly exotic forms of bulk nuclear matter as the accreted matter sinks into the neutron star. For example, crystallization of heavy nuclei into a *bcc* lattice structure within a near superfluid neutron environment at extreme densities may lead to the disappearance of the deflecting Coulomb forces allowing pycno-nuclear fusion processes to emerge as a new heat source within the neutron star crust. The fate of the ashes, the neutronization and crystallization of matter, and the emergence of new energy sources at extreme conditions unlocks a new frontier in nuclear physics.

Linking Finite Nuclei with Stellar Matter

Neutron Stars

Neutron stars are of intense interest in nuclear physics for another reason. They are themselves a form of bulk nuclear matter -- the largest nuclei, as they have been called. Remarkably, though neutron stars are complex, multi-layered structures that are 18 orders of magnitude larger than nuclei, they share common features with the most neutron rich species. Indeed, the neutron skins in such nuclei simulate the liquid mantles of neutron stars that lie below a lower density, possibly crystalline, outer solid crust.

To put this into perspective, Fig. 5 surveys the phases of nuclear objects as a function of their proton-neutron asymmetry and the nucleonic density. The full panoply of bound nuclei comprises the vertical ellipse. Densities accessible with different reactions, and the properties of neutron star layers, are indicated.

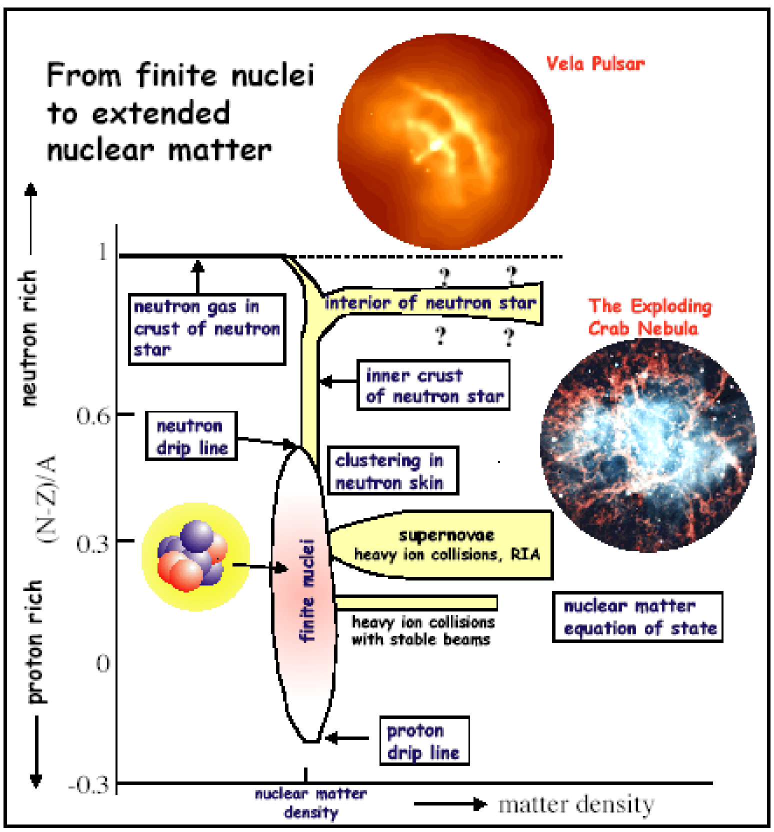

Fig. 5. The territory of various domains of nucleonic matter characterized by the neutron excess and the nucleonic density. RIA will provide a unique capability for accessing very neutron-rich nuclei -- our best experimentally accessible proxies for the bulk neutron rich matter in the neutron star crust. RIA will also enable us to compress neutron-rich matter in order to explore the nuclear matter equation of state -- essential for the understanding of supernovae and neutron stars. (Based on Pethick and Ravenhall, Annu. Rev. Nucl. Part. Sci. 45, 429 (1995).)

Neutron stars are exotic neutron-packed stars with large density variations from well below to well above nucleon densities. They are "laboratories" of extreme states of matter, perhaps containing (superfluid) neutrons and protons, hyperons, boson condensates, deconfined superconducting quarks, and strange matter, enveloped by a solid crust of nonuniform neutron-rich matter. The crust of a neutron star is believed to have a "pasta"-like structure, made of nuclei. The specific structure and properties of the crust are known qualitatively at best, due to the lack of a reliable nuclear density functional. Some authors claim that the structure of the crust is that of a crystal lattice, therefore rather stiff, others that that structure is amorphous, and still others claim that one is perhaps dealing with a new type of liquid crystal structure.

Here is where RIA will help. If nuclei with large neutron excesses are studied, in which the exterior "mantle" (skin) of the nucleus is essentially neutronic, we might be able to better extrapolate to the physics of neutron stars. The thickness of the nuclear skin depends on the pressure of neutron-rich matter. The same pressure supports a neutron star against gravity. Thus, models of nuclei with thicker neutron skins, when applied to neutron stars, often yield larger stellar radii. The phase transition from solid to liquid depends on the properties of neutron-rich matter. Indeed, a high pressure implies that the energy rises rapidly with density. Thus a high pressure typically implies that the solid-crust → liquid-mantle transition boundary occurs at a relatively low density. This in turn means that the crust itself is thinner. Qualitatively, at least, these same features are replicated in extremely neutron-rich nuclei. *Therefore, measurements of neutron skins and radii with RIA may have important implications for neutron-star properties. RIA will help us build an intellectual bridge between finite nuclei and bulk nucleonic matter.*

The nuclear equation of state (EOS) describes the possibility of compressing nuclear matter. It plays a central role in nuclear structure, and in heavy ion collisions. It also determines the static and dynamical behavior of stars, especially in supernova explosions and in neutron star stability and evolution. Unfortunately, our knowledge of the EOS, especially at high densities and/or temperatures, is very poor. In nuclear collisions at RIA induced by neutron-rich nuclei, a transient state of nuclear matter with an appreciable neutron-to-proton asymmetry, as well as large density, can be created. This will offer the unique opportunity to study the N/Z-dependence of the EOS, crucial for the supernova problem.

RIA will be the terrestrial proxy for normal stellar objects, supernovae and accreting neutron star crust environments, probing nuclear matter and nuclear phase conditions at and possibly beyond the boundaries of stability. RIA provides the intellectual link between the physics of the high temperature matter in the early universe, the physics of neutron stars, and the physics of nuclear matter at ideal gas phase conditions in the core of stars. Present facilities only scratch at the limits of stability; RIA will be the tool to reach beyond these limits.

It is via this theme and its challenge to understand the universe that the strongest possible links appear between femtophysics at the nuclear level and giga-physics at a universal scale. We cannot understand the universe without understanding the nucleus, in particular, the manifestations of nuclear species that only RIA will provide.

V. Testing Fundamental Laws of Physics

The persistence of the basic symmetries of the underlying Standard Model governing the constituents of nucleons should have observable consequences in even the most complex of nuclear systems. Exploring the limits of these symmetries is an adventure that could lead us to answer some of the most fundamental puzzles in nature.

By definition the most fundamental theory must be rigorous and applicable without exception. The most fundamental theory must confront relentless experimental attack, this is the only way to make progress. Numerical consistencies need to be tested with ever increasing experimental precision. The history of physics validates this approach with the lesson of previously superceded paradigms.

Tests of such ideas can be performed both at high and low energy. For example, at high energy, the discovery of new particles, such as supersymmetric partners of the known fundamental bosons and fermions, could possibly signal large enough CP-violations to account for the matter-antimatter asymmetry in the universe. Assuming CPT invariance holds, violations of CP invariance implies violation of T invariance and this can be tested at low energy by the discovery of electric dipole moments (EDM) of particles or atoms. Similarly, parity violation can be studied at low energy in both atomic and nuclear systems. Low and high energy tests of fundamental symmetries and of physics beyond the Standard Model are complementary. Given the importance of such studies, the miniscule size of the effects, and the extreme difficulty of the experiments, it is essential to probe the underlying principles of physics in the full realm of quantum systems using independent yet complementary experimental techniques. *In this area of precision tests, nuclei offer superb opportunities because of the variety of nuclear systems potentially available and because of the amplification effects on violations of fundamental symmetries that specifically chosen nuclides can offer. And in many cases, only RIA can provide sufficient quantities of the key isotopes.*

As an important example, the availability of specific heavy nuclei from RIA will greatly enhance studies of parity violation. In studying such small effects, it is useful to exploit the fact that the parity-violating part of the electron-nucleus interaction scales at least as fast as Z^3. Moreover, alkali atoms are often ideal because their simple atomic structure allows reliable calculations of the atomic levels. Finally, there are subtle theoretical corrections that are required but which are not precisely known. However, they generally depend on Z rather than N, and hence, if long series of isotopes (same Z) are compared, these theoretical uncertainties can be largely cancelled out. Previously, an important measurement was that in the Cs alkali atom. The next heavier alkali is Fr, where the effect is 18 times larger. Francium, like all of the actinide systems, has no stable isotopes. However, a facility like RIA can provide not only large amounts of Fr for use in advanced laser and ion traps that confine these isotopes for experiments, but can also do so over a sequence of isotopes which is essential for truly sensitive tests.

To give another example, violations of the symmetry of basic fundamental laws under reversal of the arrow of time seem to be too small by a factor of about a million to explain why the universe is composed mostly of matter, rather than matter and antimatter together. This riddle has led experimentalists to compose elaborate experiments to search for the missing symmetry breaking. If the Standard Model as presently configured is true, these searches will be in vain and the unexplained circumstance of a matter-dominated universe will remain. However, the discovery of an electric dipole moment, a polar displacement of electric charge, in a nucleus, atom or molecular system could provide us with the missing piece of the puzzle. Nuclear structure effects can greatly enhance such studies. Odd-A nuclei, especially isotopes of Rn and Ra, with octupole shapes (these are reflection asymmetric pear-shaped nuclei that occur only rarely and only in special regions of the nuclear chart) have level spectra with close-lying parity doublets of nearly degenerate levels of opposite parity and the same angular momentum. Such many-body correlations can enormously enhance searches for EDMs. The relevant nuclei should be readily accessible with RIA.

To summarize, the origins of RIA's advantages for tests of fundamental physics are highly varied. In some cases, it is access to higher Z elements of special atomic systems, and the availability of long sequences of isotopes with the same atomic number, that allows one to reduce theoretical uncertainties in interpreting the experimental results. In other cases it is specific nuclear structure effects that enhance the sensitivity of experiments.

VI. The Specifications of RIA

The scientific goals outlined in the previous sections will require that a wide range of ions, intensities, and energies be available from RIA.

Beam Intensities and Species

The intensities required from RIA for various experiments are determined by a number of aspects. Basic information on a nucleus, such as its stability to particle emission, can be determined with only a few atoms. Half-lives and masses can be measured with 100s to 1000s of atoms. With a few ions/s it is possible to obtain crucial information on nuclear wave functions, sizes, shapes, and excitation spectra. For more quantitative information, intensities greater than 10^4/s of fast fragmentation beams or reaccelerated beams with precisely controlled energies are needed, ~10^9/s for high-resolution precision measurements comparable to what is currently available with stable low-energy (≈ 5-10 MeV/nucleon) beams. The following list is far from a complete overview; in order to illustrate the intensity requirements some examples of experiments are:

- The determination of *single-particle states and effective interactions* near closed shell nuclei. Closed shell nuclei are benchmarks in nuclear physics and RIA will more than double the number of cases for study. RIA should provide access to regions where new magic numbers appear, such as near ^{60}Ca. Precision information and data comparable to that available with stable, magic nuclei would be of great value. A case where this is possible is ^{132}Sn and the nuclei differing by one or two nucleons from it. Precision measurements with low-energy beams (E/A ≈ 7 – 12 MeV) will require secondary beam intensities of >10^9/s and good beam qualities. Alternatively, for magic nuclei where beams of this intensity are not available, e.g. ^{60}Ca, ^{48,78}Ni and ^{100}Sn, important information on their level structure, resonance properties, single particle levels, and wave functions can be determined with higher energy beams of a few ions/s.

- What are the limits of the combinations of neutrons and protons that can make up a nucleus?
    - Currently we only know the answer to this question for elements up to Z=8. A goal of RIA should be the determination of the *neutron drip line* to approximately Z=25 and, depending on the actual location of the drip line, perhaps even up to Z=40. Intensities as low as 1/day or even a few/week are sufficient for an existence proof. For heavier nuclei, RIA should establish nuclear existence along isotopic chains 10 to 20 neutrons beyond the heaviest nucleus identified to date. This information, combined with mass measurements, will provide the stringent constraints required for accurate predictions/extrapolations of the location of the neutron drip line. The minimum requirement for a mass measurement is about 100 ions/day for 1:10^7 mass resolution.

- RIA should complement the present program of production of *superheavy elements* with stable beams in at least two ways. First, it will help delineate the "island" of super-heavy nuclei through the formation of many new, neutron-rich superheavy nuclei. For example, the fusion of intense beams (>10^9/s) of neutron-rich Kr isotopes from RIA at energies close to the Coulomb barrier (~5.5 MeV/A) with ^{208}Pb targets will form isotopes of element 118, predicted to be longer-lived than the less neutron-rich isotopes, which are accessible with stable beams. RIA should also make a significant contribution to our firm identification of the new superheavy elements created in fusion reactions with stable beams. These elements are identified by their alpha decay chains, which have end points in a region not accessible with stable beams. With neutron-rich beams from RIA it will be possible to create and study many of the nuclei which are part of these decay chains, thus putting the identification of superheavy elements on solid experimental footing. The production of longer-lived neutron rich superheavy elements will also aid in chemical studies of these nuclei.

- At present, the greatest area of uncertainty in the understanding of nuclei is for very neutron rich systems. This is also the area we know least about, and where there is the greatest potential for new phenomena because of the asymmetry in the Fermi surface. In these nuclei there may be a diffuse region near the surface consisting of almost pure neutron matter, something that is not the case in any well-known nuclei. There are theoretical speculations about the nature of the spin-orbit force, modification to the pairing interaction and other phenomena. To explore these, one needs to get as far out as possible in neutron excess.
  - RIA should provide access to nuclei near the neutron drip line and nuclei with large neutron skins over as large a mass range as possible.
  - Reaccelerated and fast beams are both required. Reaccelerated beams of light drip line nuclei, e.g. ^{11}Li, with intensities of 10^4/s will allow detailed probing of the wave functions and correlations of weakly-bound valence neutrons. For other drip line nuclei, fast beams of intensities of 0.1 ions/s provide access to information on sizes and configurations.
  - Production of as few as 100 atoms total will provide information on the decay modes and binding energies of drip line nuclei.
  - To study the evolution of shell structure towards systems with a large neutron skin, access to nuclei over an isotopic chain of 10 to 20 neutrons beyond the heaviest nucleus available today is necessary. Closer to stability, reaccelerated beams with intensities of >10^4 ions/s are needed for detailed measurements using Coulomb excitation and neutron transfer reactions. Farther from stability, where the skins are larger, less precise experiments using fast beams with intensities of a few ions/s are sufficient.

- What role do nuclei play in the cosmos? For measurements of *astrophysical interest*, it is necessary to produce the nuclei along the nucleosynthesis paths, particularly in the hottest environments, where the shortest-lived nuclei play important roles.
  - The *r-process*, thought to occur in supernova explosions and perhaps elsewhere, has a major role in the synthesis of heavy elements. Recent data from the Hubble

and Keck telescopes clearly show the fingerprint of the r-process, but interpretation of these astronomical data is not possible with our current knowledge of the properties of nuclei along the synthesis path. The key inputs needed are atomic masses, half-lives, and decay modes. Some information on structure that will help assess neutron capture reaction rates or the dipole response of these nuclei is also desirable. Most of these measurements can only be done with RIA. Of particular interest is the determination of masses and lifetimes along the isotones with N=82, and N=126 where there are closed shells. There is no information whatever along the relevant part of the N=126 line, and for N=82 it is limited. Some of these studies will require only 1 to 1000 atoms per day, others will require re-accelerated beams of 10^4 ions/s or more at stellar energies.

  - Novae and x-ray bursts are the most common explosive astrophysical events and, thus, have been studied extensively with both ground and space-based telescopes. These events occur in binary systems where one of the objects is a white dwarf or a neutron star. Due to their strong gravitational interactions with their companion star and the deep gravitational potential at their surface, these compact objects accumulate onto their surfaces hydrogen and helium that is ignited once sufficient material has piled up (the rp-process). Again there is a wealth of new observational data, including observations from X-ray and gamma-ray observatories of nuclides produced in these environments. The beginning of the rp-process and modeling of these environments requires knowledge of reaction rates for proton and helium capture on nuclei from oxygen to tin. Direct measurements of these rates are very difficult and require intensities of up 10^{12} ions/s. Such intensities should be available with RIA at the appropriate astrophysical energies. For many rp-process nuclei, especially those near ^{100}Sn, the intensities may not be sufficient to make direct measurements, and indirect techniques must be employed. Other relevant nuclear properties such as masses and resonance energies can be measured with beams of much lower intensities.

- Finally fundamental interaction studies will greatly benefit from the highest intensities that will enable measurements with a precision that is limited by systematic (rather than statistical) errors.
  - The best probe of CP or T violation for flavor conserving interactions is the measurement of the permanent electric dipole moment of an atom or the neutron. Indeed, supersymmetric theories predict values for the EDM that are just below the present limits. Rn (Z=86) is one of the best new candidates for discovery of EDMs and measurements should have a precision comparable to or better than the existing most precise EDM limits: ^{129}Xe (Z=54) and ^{199}Hg (Z=80). The higher Z provides greater sensitivity to CP violation, and for isotopes having low-lying octupole vibrational excitations or possessing permanent octupole deformations (e.g., ^{223}Rn), additional enhancement by a factor of 100 or more greatly improves the sensitivity.
  - Parity violation measurements in Fr (Z=87) will provide a more sensitive probe for deviations from the Standard Model than Cs, the best studied case thus far, as electron-nucleus interactions scale approximately as Z^3 . In addition, Fr isotopes can be studied over a very wide range of neutron number. This provides a test of

the predicted isotopic dependence of the spin-independent interaction. Precise measurements of electromagnetic interactions in atoms are now possible with modern atom trapping methods, and initial measurements with Fr atoms have provided tests of the atomic theory of Fr at the level of 1% with production rates of the order of 10^6 atoms per second. With improvements in trapping methods and higher intensities at RIA (more than 10^8 atoms per second for most isotopes between ^{205}Fr and ^{228}Fr, and up to 10^{11} atoms per second for the most intense), standard model tests at the level of 0.1% will be possible.

Beam Energies

For some classes of measurements stopped beams are best, others require precisely controlled beams of secondary short-lived nuclei with energies up to a few times the Coulomb barrier, yet others require high energies up to 400 MeV/nucleon.

- *Stopped beams for fundamental interaction studies and precise mass measurements*. The primary requirement, besides intensity of the beams of exotic ions, is isotopic and isobaric purity. In addition, for most applications good beam quality (low emittance, small energy spread) is also important to facilitate capture in traps or implantation in a tightly defined geometry.

- *Low-energy beams for measurements of astrophysical reaction rates* in the regime that are prevalent in hot stars. The necessary energies range from a few hundred keV to a few MeV per nucleon. The beams must have precisely controlled energy, excellent isobaric purity, and good emittance.

- *Intermediate and high energies for nuclear structure*, where a variety of energies are desirable.
    - Precision beams are needed at energies in the vicinity of the Coulomb barrier (e.g. 5-12 MeV/u) with good energy resolution and good timing properties, suitable for time of flight measurements--generally longitudinal emittances of << 100 keV-ns. Transverse emittances also need to be small for good definition of scattering angles and accurate compensation for kinematic shifts, on the order of 1 mm-mrad.
    - Higher energies permit clean isotopic identification and tracking of the fragments. At these energies, the luminosity can be greatly enhanced by using thick targets. These energies are also needed to allow the use of certain reaction mechanisms such as charge exchange and nucleon knock out.

Avoidance of Chemical and Half-life Limitations

The standard ISOL techniques with light production beams, protons, secondary neutrons, or light ions, can produce the most intense yields of secondary nuclei. Yet these must be extracted from the production target, and while this is easy for some of the elements (e.g. noble gases, alkalis, etc.) it is almost impossible for refractory elements or ones that are chemically very reactive. Essentially this drives the need for intense beams of heavy ions, using the helium gas stopper technique to catch any fragmentation product in an ionized state and ready for reacceleration. The multiplicity of production techniques with RIA will allow the optimization of yields, even in the completely unknown regime, where the predictions for yields are uncertain.

- For instance, for key nuclei in the r-process path it is particularly important to have the capability of carrying out measurements on waiting-point nuclei over a wide range of species, including neutron-rich isotopes of Fe, Co, Ni, Zr, Pd and Cd. The lack of chemical sensitivity of the fragmentation products is important in enabling these studies.

- Key nuclei for nuclear structure may not be accessible without the fragmentation capability (e.g. B, S, Ni, Zr,). For example;

  - Doubly magic nuclei such as ^{44}S (16 protons and 28 neutrons) or ^{68}Ni (with 28 and 40) - In both cases the detailed high-resolution exploration of the level structure will supply important information on the shell structure in weakly bound systems, and neither sulfur nor nickel diffuse readily out of a production target, so that the helium gas stopper technique and in-flight experiments are essential.
  - Nuclei with isospin 0, along the N=Z line - These are of considerable interest and the chemical sensitivity enters in a number of them, for instance, ^{78}Y, ^{80}Zr, ^{82}Nb, or ^{84}Mo. None of these can be reached with normal ISOL techniques. Measurements of transfer reactions will explore single-particle structure and pairing excitations.
  - The study of halo nuclei with high-resolution techniques - RIA may produce drip line nuclei up to A=100, but their half-lives will be very short. Interesting candidate halo nuclei of elements like B (^{19}B may have 6 weakly bound neutrons) and S will be extremely difficult, if not impossible, to study efficiently without taking full advantage of fast extraction from a gas cell or the power of the in-flight techniques.

Conclusions

The discovery potential of physics with exotic nuclei is enormous. To exploit this potential RIA must provide a broad range of isotopes. Unlike any existing radioactive beam facility or any other such facility under construction or in the development stage, RIA should be optimized to produce every exotic species in the best possible way and deliver it to scientists in the desired energy regime. If built with these greatly expanded capabilities, RIA will transform our understanding of nuclei, provide a firm foundation for quantitative descriptions of the processes that fuel the stars and create the elements, and provide large quantities of specific isotopes for precision tests of fundamental laws of physics. Large quantities of specific isotopes will also be used to address important societal needs. In short, RIA must be built as a world-class facility for nuclear science at the onset of the 21st century.