The Science of the Rare Isotope Accelerator (RIA)

A Brochure from the RIA Users Community

Contents

1. Overview

The fields of nuclear structure and astrophysics provide the link between our understanding of the fundamental constituents of nature and the understanding of the matter of which we, the Earth, and stars are made. Expertise in these areas is also central to applied fields such as energy, security, and medicine.

The Rare Isotope Accelerator (RIA) will be a key tool for nuclear science that promises to change the way we view and describe the nucleus. RIA will produce key new rare isotopes of atomic nuclei that are essential for our understanding of the universe.

As documented in numerous White papers and Long Range Plans worldwide, and reflected in major construction projects in Europe and Japan, it is the overall consensus of the international nuclear structure and nuclear astrophysics communities that the future of the study of atomic nuclei centers on and requires advanced facilities for access to exotic nuclei.

United States leadership in nuclear science is vital to the nation's well-being as well. RIA will have profound benefits to society; it will play an important role in the 21st Century's advances in modern technology, medicine, the environment, and national security.

This brochure provides a brief description of RIA, with a particular focus on the scientific justification, design, international context, applications, education, and workforce. It emerged from the "Meeting of the RIA Users Organization" held September 10-11, 2005, in Detroit, Michigan.

This document identifies questions that typify the science that will be addressed by RIA. The questions, listed below, are clearly not all-inclusive, but rather indicative of our view of the future of low-energy nuclear science research. They provide a guide to much of the scientific discussion that follows.

- **Physics of Nuclei**
  - How do protons and neutrons make stable nuclei and rare isotopes?
  - What is the origin of simple patterns in complex nuclei?
  - What is the equation of state of matter made of nucleons?
  - What are the heaviest nuclei that can exist?
- **Nuclear Astrophysics**
  - How are the elements from iron to uranium created?
  - How do stars explode?
  - What is the nature of neutron star matter?
- **Fundamental Interactions**
  - Why did the Big Bang produce more matter than antimatter?
  - What are the weak interactions among hadrons, and how are they affected by the nucleus?
- **How can our knowledge of nuclei benefit the nation and humankind?**
  - What is the reliability of the country's nuclear weapon stockpile in an era without testing?
  - What are the next medically viable radioisotopes required for enhanced and targeted treatment and functional diagnosis?
  - What are the critical electronic and magnetic properties of advanced materials for developing the next generation of superconductors, magnetic storage devices, and semiconductors?
  - Can we design an economically competitive, energy-efficient, proliferation-resistant, reduced-waste nuclear reactor to meet national energy demands for the 21st century and beyond?

The answers to these questions are crucial for our understanding of the universe, and are a link to our ability to explain natural phenomena that range over distance scales spanning 42 orders of magnitude – from the proton (10^{-15} m) to the whole of the universe (10^{27} m). The connections between the physics of nuclei and several areas of modern science are illustrated in Fig. 1.1. Just as nuclei themselves play essential roles in the cosmos, the conceptual techniques of nuclear science have close links with those of quantum many-body physics on the nanoscale and, hence, play a role in understanding the quantum world. Moreover, nuclei are the interface between quantum chromodynamics (QCD) and the fundamental forces and particles in nature on the one hand and the atomic and macroscopic world on the other.

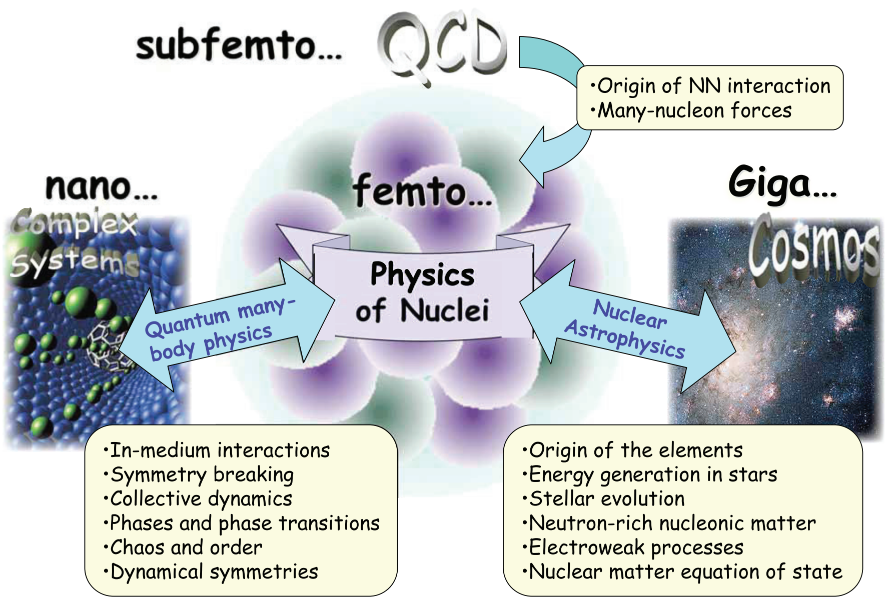


Figure 1.1: The physics of atomic nuclei is not only a fascinating quest, but also addresses some of the great challenges that are common throughout modern science. How does complexity emerge from simple constituents? How can complex systems display astonishing simplicities? How do nuclei shape the physical universe?

The pursuit of the grand scientific challenges that drive RIA will enhance the training of the next generation of nuclear scientists who will seek to exploit nuclei for the benefit of humankind and the security of our nation.

This document is not meant to repeat the more detailed discussions already described in a number of previous white papers from the RIA community. Indeed, many publications describe RIA physics and technical developments. Their level of detail differs; there are detailed scientific reports describing RIA physics and technology, and there are also high-level documents broadly outlining RIA and its goals. All these documents may be found on the website of the RIA Users Organization, http://www.orau.org/ria. The most important publications by the RIA community are:

- A Broader Context of RIA: http://www.orau.org/ria/pdf/intell.pdf
- RIA Theory Road Map: http://www.orau.org/ria/RIATG/Blue_Book_FINAL.pdf
- RIA Physics White Paper: http://www.orau.org/ria/pdf/ria-whitepaper-2000.pdf
- RIA Facility Pre-conceptual design: http://www.orau.org/ria/oldria/p-1-0-4.pdf

Other crucial documents, discussing RIA and RIA science, are:

- 2002 NSAC Long-Range Plan:
http://www.sc.doe.gov/np/nsac/docs/LRP_5547_FINAL.pdf
- Department of Energy 20-Year Science Facility Plan:
http://www.sc.doe.gov/Sub/Facilities_for_future/facilities_future.htm
- NSAC Report on Comparison of the Rare Isotope Accelerator (RIA) and the Gesellschaft für Schwerionenforschung (GSI) Future Facility
http://www.sc.doe.gov/np/nsac/docs/RIA-GSI-nsac-022604.pdf
- A Vision for Nuclear Theory NSAC Report:
http://www.sc.doe.gov/np/nsac/docs/NSAC_Theory_Report_Final.pdf
- NSAC Education subcommittee report:
http://www.sc.doe.gov/np/nsac/docs/NSAC_CR_education_report_final.pdf
- Interagency Task Force: A 21st Century Frontier for Discovery: The Physics of the Universe:
http://www.ostp.gov/html/physicsoftheuniverse2.pdf

Finally, the most recent NSAC review of nuclear science in the United States, "Guidance for Implementation of the 2002 Long Range Plan" (http://www.sc.doe.gov/np/nsac/docs/nsac-report-final1_Tribble.pdf), again reaffirmed the priority given to this project by the nuclear science community. The report states: "***RIA remains the highest priority of our field for major new construction****. The subcommittee reaffirms the compelling scientific case for the study of rare isotopes ... the long-term vision of our community is to pursue this compelling science with a major investment. The questions related to the nature of nuclear matter, the creation of new isotopes and elements, and the understanding of the origin of the elements, demand a facility with the capabilities of RIA*."

In all, the physics case for rare isotope nuclear science has been reviewed and supported by NSAC, and the agencies at least seven times in the last decade.

This brochure is organized as follows. Sections 2-4 describe the science of RIA. The NNSA relevance and other applications at RIA are discussed in Sec. 5 (reference material to this section can be found in appendix B). Section 6 deals with education, training, and workforce needs. The RIA facility (and related R&D program) and the international context of RIA are outlined in Sec. 7 and 8, respectively. Examples of concrete experiments with RIA are given in appendix A together with discussion of some of the unique features of RIA beams. Finally, appendix C contains the list of acronyms and abbreviations used in this brochure, and appendix D provides a glossary.

The document is based on drafts provided by the coordinators of seven working groups (Studies of Nuclei, Nuclear Astrophysics, Fundamental Interaction Studies, RIA Facility, NNSA and Applications, International Context, and Education and Manpower). A number of people contributed to this document, in particular: Larry Ahle, Jim Beene, Georg Bollen, Daeg Brenner, Alex Brown, Tim Chupp, Jolie Cizewski, David Dean, Jonathan Engel, Don Geesaman, Konrad Gelbke, Harvey Gould, Uwe Greife, John Hardy, Ed Hartouni, Meredith Howard, Kirby Kemper, Michael Kreisler, Andreas Kronenberg, I.-Y. Lee, Kim Lister, Paul Mantica, Peggy McMahan, Gerald Morris, Jerry Nolen, Erich Ormand, Mike Ramsey-Musolf, Guy Savard, Hendrik Schatz, John Schiffer, Michael Smith, Lee Sobotka, Gene Sprouse, Mark Stoyer, Sam Tabor, Michael Thoennessen, Frank Timmes, Bob Tribble, Michael Wiescher, Sherry Yennello, and Glenn Young. Special thanks are due to Marguerite Helversen (grammar and style editor), David S. Jacque (science writer), and Alex Parsons (cover design, graphic artist) for their contributions. Rick Casten, Robert Janssens, Witek Nazarewicz, and Brad Sherrill provided overall coordination. We are grateful to all those who helped in the preparation of this document.

2. Physics of Nuclei with RIA

The study of nuclei is a core component of modern science, connecting QCD phenomena, many-body systems, and the cosmos. In the last few years, perhaps more than ever, there has been an especially productive interplay between theory and experiment in forging a deeper understanding of the nuclear quantum many-body problem. Yet, there are significant missing components in our current understanding that must be addressed if we are to develop a comprehensive predictive theory of the nucleus and nucleonic matter that will answer a number of fundamental scientific questions. These questions can only be studied with access to new realms of nuclei – nuclei with proton and neutron numbers far different than those of the familiar nuclei found in nature.

The most recent experimental and theoretical advances in rare isotope research make it clear that RIA will open new avenues to explore these frontiers of knowledge, with the aim of understanding the richness of nuclear phenomena and clarifying the properties of bulk nuclear matter. With RIA data, and the interpretations that theory will provide, we will seek to explain the limits to nuclear existence and to observe the radically new phenomena that are expected to be present in highly unstable neutron-rich nuclei; we will be able to shed light on the equation of state for bulk nuclear matter; and we will probe the existence of new super-heavy systems at the limits of mass and charge.

This process involves two complementary approaches – a microscopic one that starts with constituent nucleons and seeks to build up the nuclear many-body system. The other approach looks at these systems and their systematic properties, and – by introducing effective degrees of freedom – seeks to describe them in terms of models based on symmetries, collective modes of excitation resulting from symmetry breaking, and phase transitions. New experimental information, in conjunction with data from nuclei near the valley of stability, will lead to the development of a new comprehensive and universal picture of nuclei spanning from the lightest systems all the way to bulk nuclear matter. Our current nuclear models will likely appear as particular manifestations of a much broader and richer framework.

How do protons and neutrons make stable nuclei and rare isotopes?

The domain of stable nuclei – the valley of stability – comprises a narrow band of proton and neutron numbers spanning slightly less than 300 isotopes; yet, this domain covers only a small fraction of nuclei bound by the strong force. It is surrounded by thousands of radioactive nuclei with lifetimes that vary from microseconds to the age of the universe. With RIA, we will have experimental access to much of this new territory and, as we will see, this data is absolutely crucial for a comprehensive understanding of the objects that comprise 99% of all the visible matter in the universe. The aim is not to study all newly available species, but to use this expanded gene pool of exotic species to select those that isolate or amplify specific physical properties.

Constructing a unified theoretical framework reliably describing all nuclear systems from the deuteron to bulk nuclear matter is the central goal in the study of nuclei and is one of the reasons to build RIA. In the past few years, substantial progress toward this goal has been made through our understanding of inter-nucleon interactions and the development of *ab-initio* theories for light nuclei. Here already, access to neutron-rich nuclei has been critical in order to understand the dependence of the effective interactions on the neutron-proton asymmetry. The challenge, made possible by these developments, is to build conceptual bridges that will allow us to describe the properties of nuclei of all masses, especially those exotic drip line nuclei whose properties are expected to be different from nuclei encountered thus far and are critical to our understanding of the evolution of the universe.

This effort will require new experimental data, especially from very neutron-rich nuclei produced at RIA, which will be the quantum-scale objects closest to bulk neutron matter that we can produce in the laboratory. These new data will provide the critical foundation for a comprehensive theory of atomic nuclei. Such a theory is necessary to provide accurate descriptions of the properties of nuclear systems that will never be synthesized terrestrially, but have existed in the cosmos.

A majority of these nuclei have never been studied experimentally and yet they hold the key to a clearer understanding of the nucleus and of element synthesis. Beyond the region of bound systems, unbound nuclei can exist, but they decay with lifetimes commensurate with the time it takes a nucleon to traverse the nucleus. The location of these borders of instability, the drip lines, depends only on the total binding energy of the nucleus.

For proton-rich systems, the Coulomb interaction limits the number of protons that can be bound, and the drip line is pushed toward, and eventually crosses over, symmetric systems with equal numbers of protons and neutrons. Because of its closer proximity to the valley of stability, the proton drip line has essentially been reached experimentally up to bismuth.

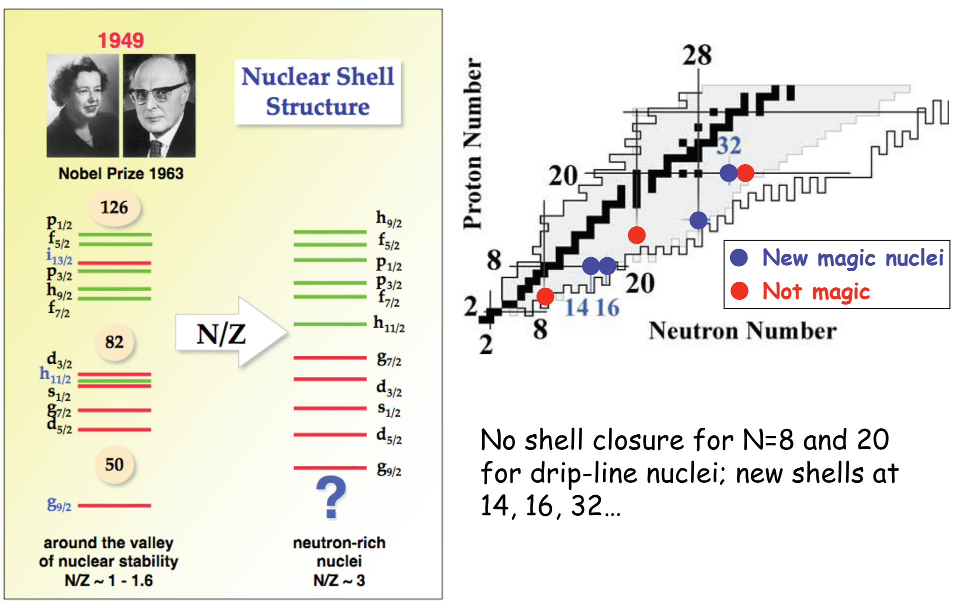


Figure 2.1: Shell structure, once conceived as a robust characteristic of all nuclei, is now being recognized as a more fluid concept. Left: familiar shell structure characteristic of nuclei close to the valley of stability and a possible shell structure that may be characteristic of drip-line nuclei. Right: part of the (*N,Z*) chart for light nuclei, recently extended by the emerging technology of radioactive beams. Increasing experimental evidence indicates that some magic numbers have disappeared in neutron-rich systems, some predicted ones have not appeared, and other new ones have been found. The study of nuclei having high neutron or proton imbalances will provide the missing links in our present understanding.

For neutron-rich nuclei, however, the situation is vastly different because the lack of electrostatic repulsion allows a nucleus to bind a large number of excess neutrons. It is with these very neutron-rich nuclei that RIA offers the greatest discovery potential. At this point in time, beyond the lightest nuclei, we have only a vague idea about where these neutron-rich bound systems can no longer exist. Evidence from light neutron-rich drip-line nuclei indicates that the knowledge we have from nuclei near stability and from proton-rich nuclei cannot be reliably extrapolated to neutron-rich species. Evidence for extended nuclear halos already exists in light weakly-bound nuclei, but the predicted large neutron skins, as well as their structural consequences, remain a nearly untouched area. Fascinating experimental discoveries in the last decade indicate that our understanding of the nucleus is fragmentary. For example, as illustrated in Fig. 2.1, nucleonic shell structure, once conceived as a

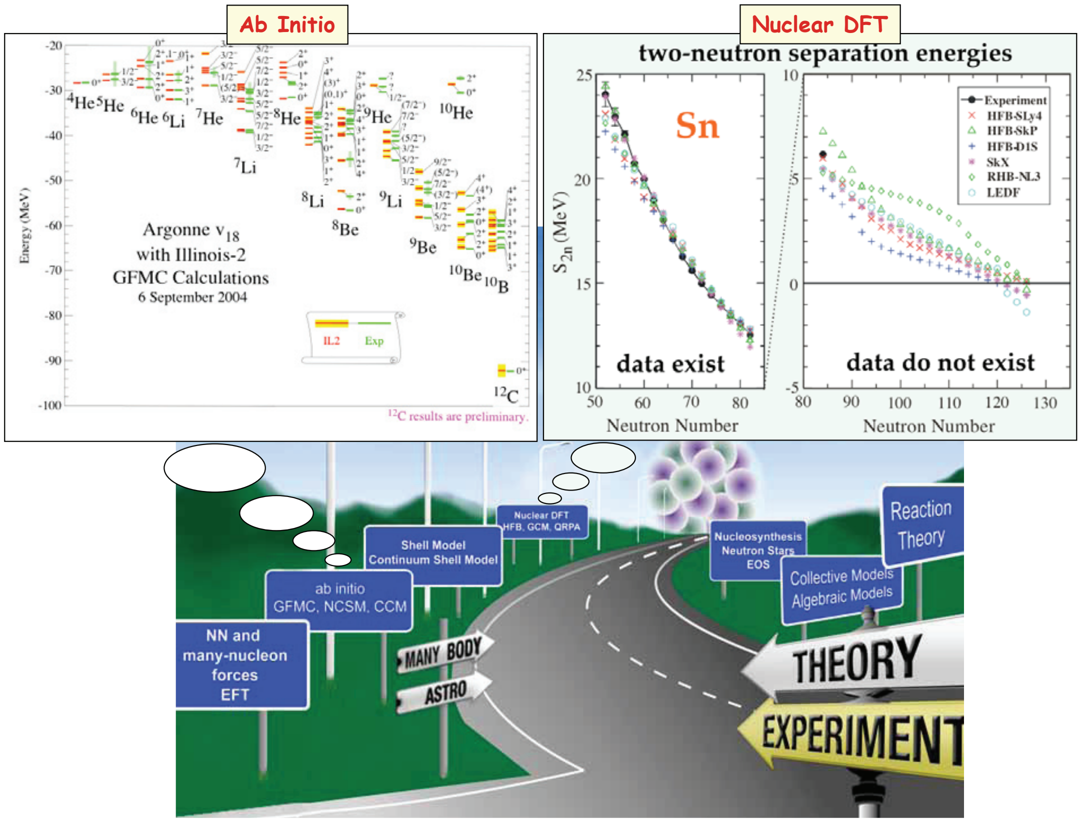


Figure 2.2: The goal of the field is to develop a unified, predictive theory of the nucleus. A roadmap has been developed (lower middle portion, see the *RIA Theory Blue Book* for details). We have a clear theoretical path that bridges light nuclei – which can be calculated precisely in terms of protons and neutrons interacting via inter-nucleon forces – with medium-mass nuclei and with complex heavy and super-heavy species. The left inset shows the quantum Monte Carlo *ab initio* description of the lightest nuclei in terms of realistic inter-nucleon interactions. The main theoretical uncertainty is the form of the three-nucleon force. The need for new data is clearly apparent in the right inset, where several density-functional theories are applied to an isotopic chain to predict the properties of unknown isotopes of tin with large neutron-to-proton imbalance. The models are essentially equal in their ability to reproduce the known data, but begin to diverge dramatically when attempting to extrapolate into *terra incognita*.

robust characteristic of all nuclei that provided the defining simplification for many-body descriptions, is being recognized now as a more local concept. It is already known that the magic numbers in light neutron-rich nuclei are not the immutable benchmarks they were once thought to be. RIA, with its ability to strike deep into the territory of neutron-rich nuclei, will be our key tool to probe how shell structure (shell gaps and single-particle strength) change with neutron excess. The existence of loosely bound nuclei near the drip lines crucially depends on many-body correlations that are impacted by the presence of the low-lying continuum of unbound nuclear states that can decay by particle emission. An understanding of neutron-rich nuclei is also crucial for the understanding of neutron stars, which are multi-layered structures that are 18 orders of magnitude larger than nuclei, but share many features in common with the most exotic neutron-rich species.

What are the theoretical tools that can be used to develop a thorough comprehension of nuclei? The search for a unified theory of nuclei begins with a description of the interactions between protons and neutrons. The low-energy regime of QCD produces the forces that bind nuclei. The connection of QCD to nuclei is an active and productive part of current nuclear physics research. Unfortunately, for the foreseeable future, full-fledged QCD calculations will be unable to give the properties of even the simplest nucleus – the deuteron. Effective field theories, which retain the symmetries of QCD, but allow for the formulation of a complete low-energy theory for how nucleons interact, represent a path forward to obtain a deeper understanding of inter-nucleon interactions.

These effective theories, and their more phenomenological cousins, have been developed and utilized in light nuclei to an impressive degree of accuracy in recent years (see Fig. 2.2). One striking feature of nucleonic interactions, only recently realized, is that three-body forces significantly contribute to nuclear properties, including binding and the structure of excited states. The presence of three-body forces both enriches and complicates our understanding of nuclei. However, the dependence of these forces on the neutron-proton asymmetry is very poorly known, as is their impact on such key questions as the location of the neutron drip line.

For heavy, complex nuclei, which — because of the sheer number of protons and neutrons involved — cannot be treated *ab initio*, a critical challenge is to develop new theories that are practical in use and identify the interactions between nucleons and the important degrees of freedom of the many-body system. This strategy is similar to what is being used in other fields of science, in particular in condensed matter physics, atomic and molecular physics, and quantum chemistry. Of particular importance is the development of the energy-density functional, which may lead to a comprehensive description of the properties of finite nuclei, as well as of extended asymmetric nucleonic matter. Here, the main building blocks are the effective fields represented by proton and neutron densities and their motions. The main question, which will be answered by RIA, is the form of the fields that result from differences between neutron and proton distributions. Those fields are poorly known, but they are essential for the structure of neutron-rich nuclei. (See Fig. 2.2).

Figure 2.2 also shows a theoretical strategy suggesting a guide to future research in RIA physics. A crucial challenge in the study of nuclei will be the systematic development of, and bridging between, approaches that correctly include inter-nucleon interactions for nuclei ranging from the lightest elements, which are the subject of current *ab initio* methods, all the way to the super-heavy elements, which can be described by the density functional theory. Of course, how well this strategy serves us, and what modifications to it may be needed, will be determined by the new data made possible by RIA.

What is the origin of simple patterns in complex nuclei?

The number of interactions between particles (in our case, nucleons in a nucleus) increases as a combinatorial of the number of constituents. A remarkable feature is that despite all this complexity, heavier nuclei exhibit novel collective properties that are not apparent in few-body systems. This is a feature also common to atoms, molecules, and condensed matter. In many cases, such regularities can be described in terms of many-body symmetries, which dramatically simplify the interpretation of certain states by introducing simple degrees of freedom. The scientific goals here are three-fold and reciprocal: (i) to understand how complex nuclear system can be constructed from simple ingredients (nucleonic constituents, inter-nucleon forces, quantum mechanics, and conservation laws); (ii) to discover the many-body symmetries that nuclei exhibit, and to use those symmetries as paradigms for the study of other nuclei; and (iii) to explain the microscopic origins of those symmetries in terms of elementary ingredients.

One recent example of emergent collectivity focuses on the rapid changes in structure that occur in mass regions where nuclei flip from spherical to ellipsoidal deformation. It is a remarkable and fascinating consequence of shell structure in the nuclear many-body system that these dramatic shape changes occur with the addition of just a couple of neutrons in nuclei with hundreds of nucleons. This phenomenon (See Fig. 2.3) can be understood in terms of a transition between coexisting spherical and deformed phases. When these phases have equal energies, a phase transition occurs (e.g., in ^{152}Sm). Such nuclei have been successfully described in terms of new analytic critical-point models, which have a number of characteristic spectroscopic signatures.

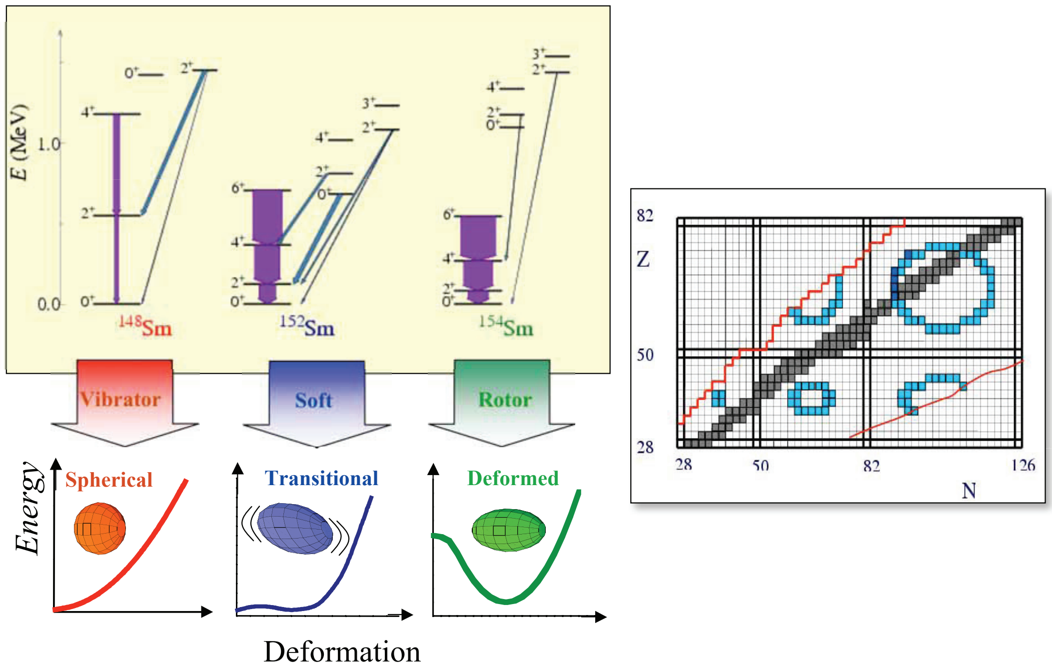


Figure 2.3: Illustration of the dramatic evolution of structure across the Sm isotopes, characterized by a transition between spherical and deformed shapes that has recently been understood in a critical-point description exhibiting characteristic signatures such as the presence of a low lying 0^+ state, nearly degenerate with the lowest 6^+ state. Below the experimental level schemes are sketches of how the nuclear energy evolves with shape deformation. The right side shows the expected locus of this class of critical-point nuclei (indicated by blue contours) in a section of the nuclear chart.

It is important to stress that access only to nuclei near stability and those at the very limits cannot alone lead to a truly comprehensive theory of nuclei since nuclei with a moderate proton-neutron asymmetry present their own realm of new physics. Therefore, in addition to exotic beam research at the limits of binding, equally important is access to intermediate nuclei that will allow the study of the evolution of structure across long isotopic chains. The study of phase transitions exemplifies this requirement. To fully understand these new phenomena, it will be essential to search for examples in nuclei far from stability. The right side of Fig. 2.3 provides the expected locus of possible examples of shape transitions over a large swath of the nuclear chart. Most of these regions lie off the valley of stability. RIA will enable new nuclei in these regions to be explored and will provide orders of magnitude enhanced yields of nuclei currently marginally accessible. With such data, we can hope to attain a deeper microscopic understanding of how these phase transitions in finite systems occur and where large neutron-to-proton asymmetries generate different types of quantum phase transitions in nuclei.

While the interactions between protons and neutrons are rather complex, certain characteristics arise from these interactions that are often enhanced in larger nuclear systems. For example, pairing, shape deformations, collective vibrations and rotations, shape coexistence, spontaneous fission, and shell structure, all represent properties that fully emerge in the context of heavy nuclei. These many-body systems display collective properties that are not obviously inherent in the inter-nucleon interaction itself. Novel collective phenomena are expected to develop in the presence of large neutron excess: neutron-skin excitations, appearance of few-nucleon clusters in the skin, or exotic deformations involving different proton and neutron geometries. Data on very neutron-rich nuclei provided by RIA will directly probe these issues.

What is the equation of state of matter made of nucleons?

An equation of state describes the relationship between a small set of thermodynamic variables (like temp, pressure and volume), which characterize the most important macroscopic properties of the matter. The main factors that enter the nuclear equation of state are the nuclear density and the neutron-proton asymmetry. The asymmetry-dependent part, which makes the dominant contribution to the energy density in neutron stars (see Sec. 3), has been determined near normal nuclear density from measured nuclear masses. Extrapolations to the regions of low and high density, however, are theoretical conjectures that are thus far largely unconstrained by experimental data. As a result, our ability to predict such observables as fission barriers of nuclei far removed from stability and the mass-radius-inertia relations for neutron stars is poor. RIA will amplify the asymmetry term in nuclear matter considerably and will provide an unrivalled ability to study nuclear thermodynamics in the asymmetry degree of freedom, accessing new regions of nuclides relevant for understanding reaction rates involving nuclei far removed from beta stability.

What are the heaviest nuclei that can exist?

One of the most intriguing questions in nuclear science is: what is the heaviest nucleus that can exist? The domain of known elements has steadily grown, certainly now to element 113 and perhaps to as heavy a proton number as Z=118 (see Fig. 2.4). Can RIA synthesize long-lived super-heavy nuclei and can their chemistry be determined? Due to their large Coulomb energy, one would naively expect these super-heavy nuclei to be unstable and spontaneously fission. However, quantum mechanics enters here in a dramatic way: nucleons orbit in specific quantal states, leading to shell effects that can overcome disruptive Coulomb effects and bind these nuclei. Just as in the case of the location of the neutron drip line, different theoretical predictions for the region of super-heavy nuclei are in disagreement. Data from RIA are required to constrain and improve theoretical models.

The new elements that have been found thus far are all short-lived, with alpha-decay lifetimes in the microsecond and millisecond regimes. Theoretical predictions indicate that these short lifetimes are due to their neutron deficiency, and that more neutron-rich isotopes of the same elements might have very long lifetimes.

Neutron-rich beams from RIA, mainly in combination with neutron-rich radioactive targets, will open up new avenues of exploration for super-heavy nuclei that will permit not only their discovery, but also the exploration of their unusual chemical properties – properties that arise from the relativistic motion of valence electrons subjected to the extraordinarily strong nuclear electric field.

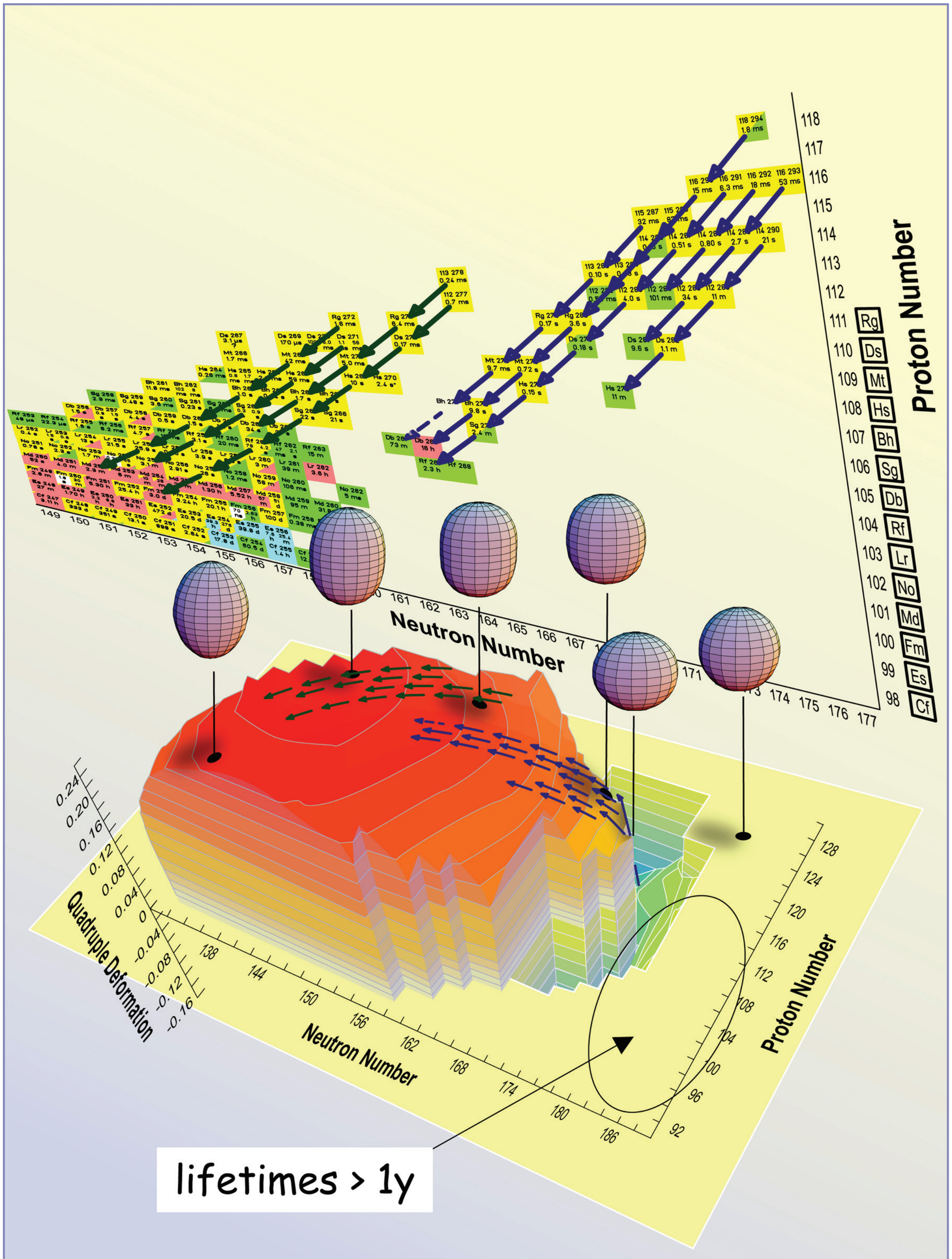


Figure 2.4: Deformations and shapes for the heaviest nuclei calculated in nuclear density functional theory. The Z=110-113 alpha-decay chains found at GSI and RIKEN (green arrows) go through prolate shapes (red-orange) while the Z=114-118 chains reported at JINR (blue arrows) start in a region of oblate shapes (blue-green). S. Hofmann (GSI) supplied the nuclear chart in the super-heavy region.

3. Nuclear Astrophysics with RIA

We are at a special junction in our journey towards understanding the universe and the physical laws that govern it. More than ever before, astronomical discoveries are driving the frontiers of nuclear physics, and more than ever before our knowledge of nuclei is driving progress in understanding the universe. Both disciplines – nuclear physics and astronomy – have seen stunning progress within their own realms of study in the past decades. This has brought these two fields together in new ways so as to tackle the enormous challenges that lay ahead. Some of the most fundamental questions being asked about the universe at its two extremes – the very large and the very small – are inextricably intertwined. The physics of unstable nuclei plays a critical role in many cosmic phenomena, but has been largely out of the reach of terrestrial experiments. Scientists have now been brought together by a shared vision of building RIA to finally study these unstable nuclei and to address, together with astronomical observations, important open questions that capture everyone's imagination:

- How are the elements from iron to uranium created?
- How do stars explode?
- What is the nature of neutron star matter?

Recent astronomical missions such as the Hubble Space Telescope, Chandra X-ray Observatory, Spitzer Space Telescope, and the Sloan Digital Sky Survey have provided incredibly detailed information on element synthesis, stellar explosions, and neutron stars over a wide range of wavelengths. Unfortunately, theoretical interpretations of these observations lack a firm empirical foundation because of the paucity of information on the physics of unstable nuclei. RIA will provide access to the vast majority of unstable nuclei important in astrophysical processes, and will launch a new era where nuclear science and astronomy synergistically push each other ahead. RIA and future astronomy missions such as the Joint Dark Energy Mission and the Advanced Compton Telescope will complement each other and provide a potent combination of tools to discover answers to important questions that confront the field.

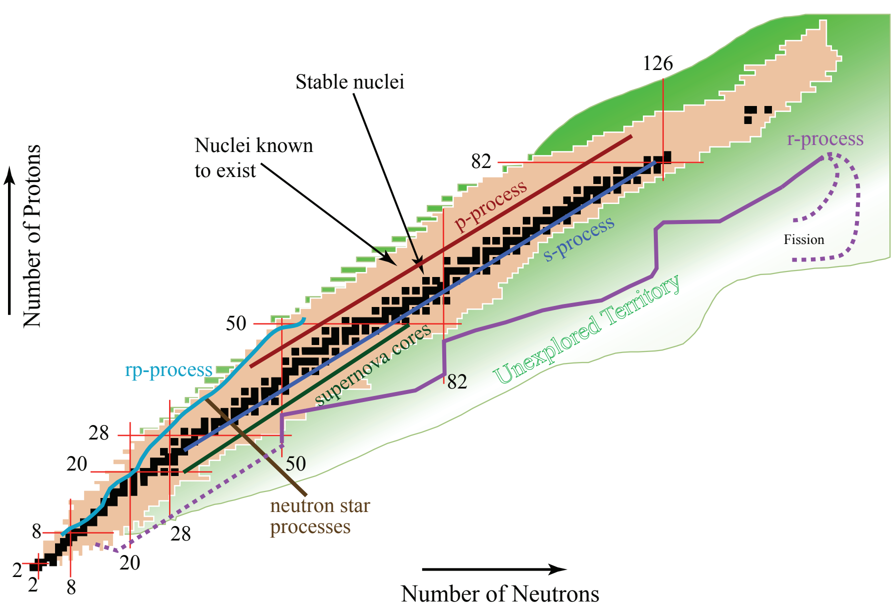


Figure 3.1: Lines on the chart of nuclides delineate schematically some of the important nuclear reaction sequences occurring in the universe. RIA can create most of the unstable nuclei participating in these processes. Note that the dashed line at the right end of the r-process path is not meant to indicate the actual path of the process, but to indicate that material is being recycled through fission of the heaviest elements.

How are the elements from iron to uranium created?

The elements from iron to uranium found in nature are thought to be mainly synthesized by neutron capture processes – about one half by slow neutron captures (the s-process) and the other half by rapid neutron captures (the r-process). Today, the r-process represents both a theoretical and an experimental challenge: theoretical since it requires an extremely high density of free neutrons that current astrophysical models do not reproduce; and experimental, because its reaction sequence of neutron capture, β-decay, and fission includes exotic nuclei far beyond the reach of current accelerator facilities. One of the most important open questions in nuclear astrophysics is the actual site of the r-process. Possible candidates include supernovae or merging neutron stars. Recently, the surface abundances of a few extremely metal-poor stars in the halo of our galaxy have provided the first hints of the products of individual r-process events early in the galaxy's evolution. In the coming decade, we expect that large-scale astronomical surveys such as SEGUE, followed by extensive campaigns of high-resolution spectroscopy with 8-10 m class telescopes, will provide data on hundreds of these extremely rare stars.

To disentangle and understand the various s- and r-processes reflected in these observations, accurate nucleosynthesis predictions are needed for each individual process. This can be achieved only with a greatly improved understanding of the underlying nuclear physics. RIA will provide access to the vast majority of the neutron-rich nuclei involved in the r-process for measurements of decay lifetimes, masses, and other properties — all essential information for reliable theoretical modeling of r-process nucleosynthesis. In particular, RIA is needed to access r-process nuclei near the shell closure at neutron number 126. As the last major bottleneck in the r-process, this region is an important normalization point for model predictions of the synthesis of heavy r-process elements such as uranium and thorium. Nuclear physics experiments at RIA, together with astrophysical simulations, are necessary to constrain temperature, density, timescales, and neutrino fluxes at the r-process site from observations of elemental abundances. They will, therefore, be an essential step in the search for the cosmic origins of the heavy elements. Furthermore, using isotope harvesting, RIA will enable neutron-capture cross-section measurements of long-lived unstable nuclei in the s-process. These are needed to accurately determine the contribution of the s-process to the observed abundances of heavy elements.

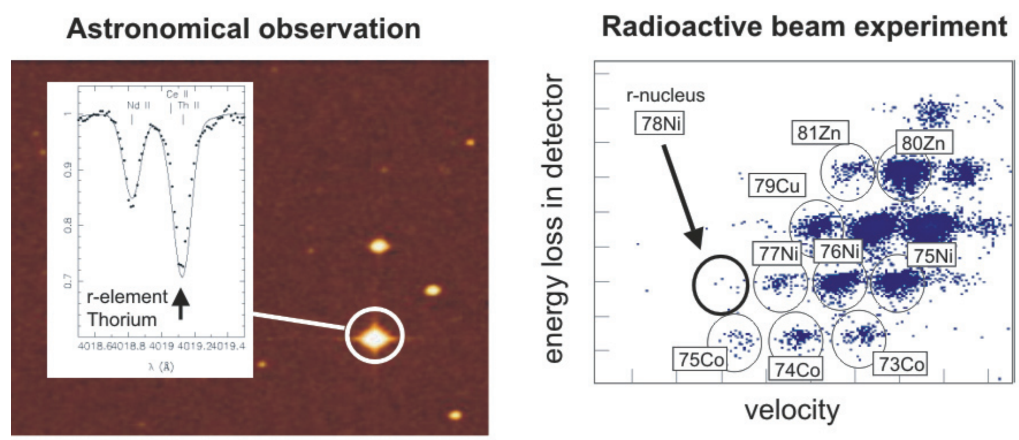


Figure 3.2: High resolution spectroscopic observation of one of the eleven detectable absorption lines of the r-process element thorium in the metal poor halo giant CS 31082-001 and the identification of the r-process nucleus ^{78}Ni in a radioactive beam experiment. The measured ^{78}Ni half-life was shorter than anticipated, which accelerates the r-process. As a consequence, modifications in r-process model conditions are needed to avoid overproduction of heavy elements such as thorium. Comparison of r-process model predictions based on experimental nuclear physics with observed element abundances constrains r-process model conditions and, in the case of thorium and uranium, the age of the universe.

With such joint progress in astronomy and nuclear physics, we can expect a new understanding of the chemical enrichment history of our galaxy and our solar system to emerge. At the same time, the greatly improved understanding of the s- and r-processes from RIA measurements will enable elemental or isotopic abundance observations to be used as probes of physics at the environments where those processes occur, including the expected extreme conditions at the r-process site. For example, an understanding of the s- and r-processes together with observations of the decay of radioactive r-process elements such as uranium and thorium will provide an independent measure of the age of the universe through radioactive dating.

How do stars explode?

Massive-star supernovae occur because stars of ten or more solar masses become unstable at the end of their lives. Such stars produce energy by successively combining elements up to iron, but at death this delicate balance of gravity and thermonuclear fusion is broken because there is no more nuclear fuel available in the core. Electron captures trigger a collapse of the inner core to beyond nuclear densities. The core violently rebounds and generates a shock wave boosted by neutrino heating that completely disrupts the outer layers of the star. Just how the shock can attain sufficient power to drive an explosion is an open question. Experiments at RIA are needed to provide a solid nuclear physics foundation for supernova models. For example, charge exchange reactions with radioactive nuclei will provide information on relevant electron capture and electron neutrino production rates; these rates have been shown to affect important properties of the collapsing core. RIA will also measure critical reaction rates that determine the nucleosynthesis of radioactive nuclei such as the galactic gamma-ray emitters ^{44}Ti and ^{60}Fe, observable in supernova remnants, in meteorites, or in deep ocean floor sediments.

White dwarf stars in close binary systems that accrete too much mass from a companion star also explode as supernovae. Carbon ignites in the central region and launches a thermonuclear flame that burns through the white dwarf and completely disrupts it. These white dwarf supernovae, called Type Ia supernovae, are observed to have characteristic light curves that allow an empirical calibration of their intrinsic luminosities and have provided evidence that the expansion of the universe is accelerating. Discovering why these supernovae form a homogeneous class is a high-priority objective of supernova research. Firm and reliable conclusions based on the use of these objects as distance markers will require that we understand and study possible variations in luminosity and nucleosynthesis. Electron capture rates on unstable nuclei, which will be measured at RIA, strongly influence the resulting nucleosynthesis and may affect the explosion energetics.

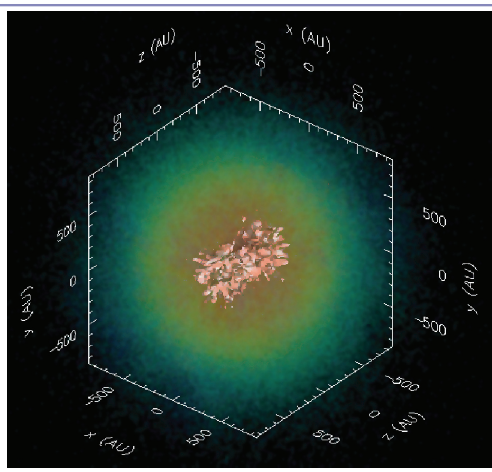


Figure 3.3: 3D simulation of the nucleosynthesis in a core collapse supernova. The red-white contour is the ^{56}Co number density and the volume rendered colors in the background represent total mass density. The heavy element distribution can retain the asymmetry from the explosion mechanism.

Given reliable nuclear physics from RIA, nucleosynthesis abundance determinations in supernova ejecta and the solar system will serve as a powerful diagnostic of the explosion mechanisms, and, in the case of core-collapse supernovae, determine the boundary separating ejected matter from matter falling back onto the remnant neutron star or black hole.

The study of explosive nuclear burning on the surfaces of accreting neutron stars and white dwarfs, observed as X-ray bursts and novae, respectively, is entering a renaissance. The X-ray satellites Chandra, XMM, RXTE, and BeppoSAX have discovered new and unexpected phenomena: oscillations during X-ray bursts, extremely long and energetic superbursts, the mixing of white dwarf matter into the ejecta of novae, and the inhomogeneity of the ejected material. These observations can offer insights into the explosion physics and the structure and evolution of the compact object, providing information about the equation of state of dense matter. RIA will allow detailed measurements of the reactions on unstable neutron deficient nuclei in the CNO-cycle breakout and on the critical waiting points in the rapid proton capture process (rp-process) powering novae and X-ray bursts, as well as on the neutron-rich nuclei that govern the thermal and structural properties of the underlying neutron star crust.

Understanding the physics of unstable nuclei that drives the observed phenomena is critical for interpreting the observations and for determining the fate of matter accreted onto compact objects. For example, measurements at RIA of the reaction rates that power an X-ray burst will allow accurate comparisons of observed light curves with model predictions. They will also motivate searches for spectral lines from rp-process ashes with X-ray telescopes and provide crucial input for determining the composition of the accreted neutron star crust.

Quantitative analysis of the observed composition of nova ejecta, including the observation of gamma radiation from the radioactive decay of the synthesized material, when combined with a thorough understanding of the underlying nuclear physics from RIA, will enable us to determine the trigger of the explosion, and the role that novae play in synthesizing the light elements. Understanding the nova phenomenon will also probe the evolution of accreting white dwarfs in general, an important component in understanding the nature of white dwarf supernovae (Type Ia) that are relevant for cosmology.

What is the nature of neutron star matter?

The nuclear physics driven phenomena on accreting neutron stars also serve as probes for neutron star properties. New observations of superbursts and the cooling of the neutron star crust during periods when the mass transfer is interrupted, could constrain the existence and nature of exotic phases of matter in the neutron star core. These studies are currently limited by the lack of understanding of the physics of very neutron-deficient and very neutron-rich nuclei. In addition, as discussed in section 2, heavy ion collision experiments at RIA will probe the equation of state of the extremely asymmetric nuclear matter present in neutron stars.

RIA — an essential tool for nuclear astrophysics

In order to address the scientific questions outlined above, nuclear astrophysicists must measure a wide range of nuclear reactions involving both extremely neutron rich and extremely neutron-deficient nuclei. In some cases it is sufficient to measure a lifetime or a mass of a range of nuclei along a projected path of nucleosynthesis. In other cases, precise cross sections of specific nuclear reactions are needed, for example to predict the amount of radioactive ^{44}Ti produced in a supernova whose decays serve as a target for gamma-ray astronomy. Nuclear astrophysicists, using the first-generation radioactive ion beam facilities, have developed the experimental techniques for these measurements. Numerous technical limitations, however, imposed by driver accelerators, ion-source chemistry, and other issues have greatly limited the nuclear information that could be obtained for astrophysics studies.

RIA will provide the wide variety of radioactive ion beams necessary to complete the mission. Specifically, RIA, owing to the unique gas catcher ion source (see Sec. 7), will be the only next generation reaccelerated beam facility that can provide beams of the full range of isotopes needed in nuclear astrophysics, including the short-lived refractory elements. These low-energy beams will be used to measure reaction rates to describe in detail nucleosynthesis in novae and X-ray bursts. They also will constrain the neutron capture rates in r-process nucleosynthesis. RIA's fast beams will be up to two orders of magnitude more intense than those at competing facilities in Europe and Japan and give us the only access to the majority of nuclei along the projected r-process path. These beams will also be essential for measuring charge exchange reactions as probes for weak interaction strength needed for supernova simulations, and for delineating the equation-of-state of dense matter in heavy ion collisions of nuclei with extreme neutron-to-proton ratios. As a welcome byproduct, RIA will also produce significant amounts of longer-lived radioactive nuclei. Harvesting these isotopes will permit, in combination with the planned cutting-edge NNSA neutron facility at RIA (see Sec. 5) or with neutron beams at facilities such as LANSCE or the SNS, neutron capture measurements relevant to both s-process pathways and stockpile stewardship.

In summary, for the first time in history, RIA will make the majority of the nuclei participating in astrophysical processes accessible to experiments. New data from RIA, in conjunction with modern astronomical observations, will address fundamental questions concerning the origin of the elements, the nature of stellar explosions, and the properties of neutron stars. They might lead to fresh discoveries concerning the existence of exotic forms of matter in neutron stars or new astrophysical nuclear processes, and will drive new approaches to probe the merger history of near-field cosmological structures such as the Milky Way using their nucleosynthetic signatures.

4. Fundamental Interactions Studies at RIA

The study of fundamental interactions by nuclear and particle physicists aims to clarify the nature of the most elementary pieces of matter and to determine how they fit together. Most of what has been learned already is embodied in the Standard Model of particle physics, a framework that has been astonishingly successful — three decades of experimental tests that have supported its predictions with ever-increasing precision. The Standard Model, however, is not entirely satisfying because it contains many parameters that must be fit directly to data and, furthermore, does not address certain very recent discoveries and cosmological facts. The nature of neutrinos and (of particular relevance for RIA) the dominance of matter over anti-matter are beyond its reach. Nuclear science contributes to the search for a fundamental understanding of nature, since often nuclei provide an excellent laboratory in which to look beyond the Standard Model for subtle indications of hidden interactions and symmetries.

The weak force was first discovered in nuclear experiments, and our current understanding of it is based in large part on what those experiments and the ones that followed them have revealed. Nuclear experiments have resulted in the discovery of parity violation, the first direct detection of neutrinos, the establishment of the vector/axial-vector structure of the weak current, the demonstration of neutrino mixing, and the establishment of stringent limits on neutrino masses. Experiments in nuclei have the powerful advantage that, with a large enough sample of different isotopes to choose from, a specific isotope can often be selected with unique properties that isolate or amplify important physical effects. For example, parity violation was first revealed by the correlation of nuclear spin and electron momentum in the decay of ^{60}Co, revealing a preferred "handedness." A ^{60}Co source was chosen for its special advantages; it could be aligned at very low temperatures and be calibrated by the angular correlation between the gamma rays in its decay. Another example is the measurement of neutrino helicity – the relationship between its spin and its momentum – that was revealed through the polarization of decay gamma rays in radioactive ^{152}Eu^{m}.

The tradition of using isotopes with unique properties to explore fundamental physics will continue at RIA. The machine's most important role will be to provide sufficient quantities of rare isotopes, available nowhere else, that will provide, as in the past, a means to probe the Standard Model and search for new physics beyond it. It is often necessary to have rare isotopes with a particular structure or decay characteristic that highlight a certain symmetry. A wide range of isotopes allows systematic atomic and nuclear uncertainties to be minimized. The remainder of this section will highlight two examples in order to illustrate the role of RIA.

The simultaneous violation of both parity and charge conjugation (CP violation), and its possible role in the matter-antimatter asymmetry of the universe, can be studied once experiments become sensitive enough to measure a permanent atomic electric dipole moment (EDM). RIA will enable that increased sensitivity by producing isotopes in which nuclear-structure effects enhance atomic EDMs. It will also make isotopes with large anapole moments, making it possible to probe the weak interaction in nuclei via atomic parity violation. Last but not least, RIA will provide the necessary stimulus to lead to the needed improvements in nuclear theory.

Why is there more matter than anti-matter?

The interactions between the quarks of the Standard Model change slightly under the simultaneous reversal of electric charge (C) and parity (P). This effect, called CP violation, is thought to have played a crucial role in producing the excess of matter over antimatter early in the history of the universe. The Standard Model does not violate the CP symmetry strongly enough to account for this excess. As a result, the details of baryogenesis – the physical process of generation of nucleons in the early universe – are completely unknown. To understand baryogenesis, we must first discover and elucidate

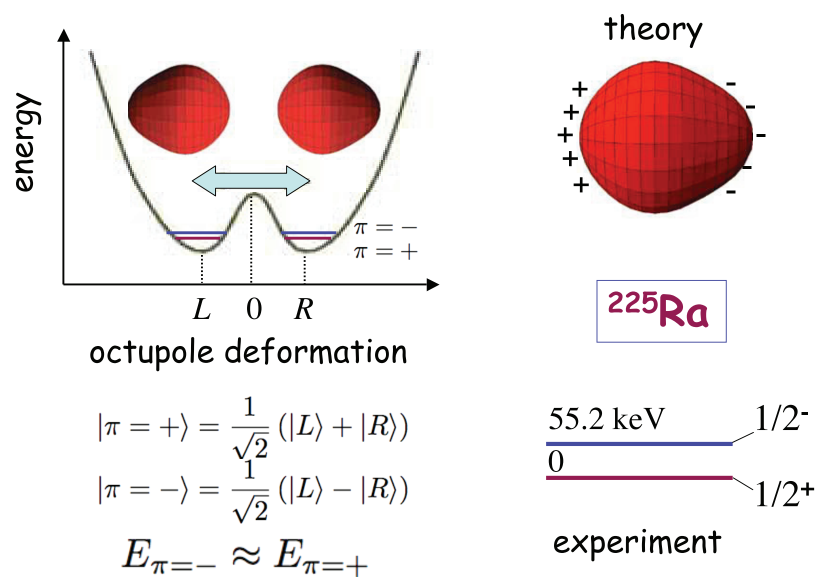


Figure 4.1: Violations of the symmetry of basic fundamental laws under reversal of the arrow of time seem to be too small by a factor of about a million to explain why the universe is composed mostly of matter, rather than matter and antimatter together. The discovery of an electric dipole moment, a 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. Left: Nuclear octupole deformation produces a pear-shaped distribution of nucleons. Parity eigenstates, E_π, are nearly-degenerate opposite combinations of the two mirror images (L and R); they are separated by a small energy related to tunneling through the potential energy barrier. Right: Pear-shaped nuclei occur only rarely and only in special regions of the nuclear chart. One of them is ^{225}Ra. Its calculated shape is shown at upper right. Due to a pear-like shape, an excess charge is induced that gives rise to an intrinsic nuclear dipole moment. Experimentally, ^{225}Ra has parity doublets of nearly degenerate levels of opposite parity and the same angular momentum. The small energy splitting amplifies the weak-interaction Schiff moment. A non-zero Schiff moment leads to the atomic electric dipole moment of a diamagnetic atom of ^{225}Ra in the laboratory reference frame.

the additional CP violation, if it indeed exists. Observation of nonzero atomic EDMs would signal CP violation from beyond the Standard Model and provide information about its source.

A permanent EDM results from a spatial separation of electric charge along the angular-momentum axis of a particle or system of particles. If an EDM exists, the system must have been electrically polarized by forces that violate time-reversal symmetry (essentially equivalent to CP symmetry), thus correlating spin, which changes direction under time reversal, with charge displacement, which does not. The best place to look for such effects is in specific rare isotopes, such as ^{223}Rn and ^{225}Ra, which have mirror-asymmetric shapes. A pear-like shape results in closely spaced nuclear energy levels of opposite parity (see Fig. 4.1), leading in turn to strong CP-violating polarization of the atom's electrons. The radioactive pear-shaped isotopes are hundreds of times more sensitive to CP violation than stable isotopes such as ^{199}Hg, which are currently used in the best atomic experiments. Measurements based on laser optical pumping of ^{223}Rn and on neutral-atom trapping with ^{225}Ra, therefore, have the potential to be better than today's experiments. Measurements in francium atoms will also be important, though for a different reason; they rely on relativistic and magnetic atomic effects to enhance the EDM. For all such measurements, RIA will provide hundreds to thousands of times more nuclei than are available now and will thus allow orders-of-magnitude greater precision. It will also provide a wide range of francium isotopes, allowing us to check the influence of nuclear structure on atomic properties. RIA will usher in a new era of precision EDM measurements that could help explain the cosmological baryon asymmetry.

What are the weak interactions among hadrons, and how are they affected by the nucleus?

The weak interactions among quarks produce parity-violating components in the effective interactions among nucleons and mesons. Theory tells us which terms are important in the nuclear interactions at low momentum, but their coupling strengths seem to be quite different from the predictions of quark-based models. Determining them experimentally will teach us about the interplay between the strong and weak interactions, providing a good test of the Standard Model.

Two venues appear particularly promising for probing the hadronic weak interaction: the first is the nucleon and few-body nuclei interacting with free neutrons, and the second is atoms of heavy rare isotopes. Parity-violating interactions of free neutrons will be studied in experiments planned, e.g., for the new Fundamental Neutron Physics Beam at the Spallation Neutron Source (SNS) at Oak Ridge. RIA will add to these studies by producing atoms of heavy rare isotopes. The weak interactions of nucleons bound in the nucleus give rise to an electric dipole coupling that depends on the spin of the nucleus. In rare isotopes of francium, a significant nuclear "anapole moment" – the leading order parity-violating electromagnetic moment – contributes to atomic parity violation.

The anapole moment probes distance scales much smaller than the size of the nucleon because it arises due to exchange of massive particles, called gauge bosons, that mediate weak interactions. Measurements of the weak interaction between nucleons are uniquely sensitive to the exchange of the Z-boson between quarks. At the same time, these measurements provide a complementary probe of the interplay between weak and strong interactions in hadronic systems, and they may provide new insights into long standing puzzles surrounding strangeness-changing hadronic weak decays. In francium isotopes, the observable anapole moment effect is enhanced by the size of the nucleus and relativistic effects. RIA will produce hundreds of times more francium atoms than current facilities and provide measurements complementary to those planned with neutrons or few-body nuclei with comparable or even greater precision.

Developments in Nuclear Structure Theory

The measurements discussed in this section, as well as attempts to determine the neutrino mass through double beta-decay and the probability of down-quark to up-quark transformation, V_{ud} , through *super-allowed* beta decay, rely on accurate calculations of nuclear matrix elements in complex nuclei. These calculations in turn rely on models of the effective inter-nucleon interactions. As discussed in Sec. 2, measurements of nuclear states with large neutron-proton asymmetry at RIA will isolate and amplify the spin- and isospin-dependent terms in the interaction that are important for fundamental-symmetry calculations. To relate, for example, an atomic EDM to an underlying source of CP violation, one needs to understand the response of the nucleus to that source, the CP-violating effect discussed above, with a good precision. In another example, the accuracy of V_{ud} is currently not limited by experiment, but by the uncertainty in theoretical corrections. Additional measurements of super-allowed beta decay for heavier nuclei with equal numbers of protons and neutrons, ranging from ^{56}Ni to ^{100}Sn, will provide a mechanism for testing and constraining theoretical models for the corrections, which in turn will improve the overall accuracy of the tests of the Standard Model.

5. NNSA and Other Applications at RIA

In addition to producing beams of rare isotopes, RIA will also produce large quantities of near-stability isotopes and large fluxes of neutrons and muons. The full suite of particles available offers the opportunity for advances in other scientific fields and applied technologies, including national security, medical technology, material science, and nuclear energy. Often, work in these areas can proceed "parasitically" to the RIA primary nuclear science operations, thereby optimizing the overall scientific output. Research in several of these areas is already being actively pursued at current radioactive ion beam facilities such as ISOLDE and ISAC. In fact, some of these applications were discussed at a recent workshop on the future of radioactive ion beams at CERN (http://indico.cern.ch/conferenceTimeTable.py?confId=a052). The list below is illustrative of the potential impact of RIA, but is by no means all-inclusive. For more detailed information about any of these areas, please see the references listed in appendix B.

What is the reliability of the country's nuclear weapon stockpile in an era without testing?

The major goal of the National Nuclear Security Administration (NNSA) Stockpile Stewardship Program is an accurate and complete modeling of the behavior and performance of devices in the nation's aging nuclear weapons stockpile. Improving the accuracy of that understanding is central to the continuing process of certifying both the safety and reliability of the stockpile, without a resumption of nuclear testing. The program assesses its progress in part by comparing the predictions of computational models with the data collected and archived during underground nuclear tests. These models are extremely complex, involving processes and input as varied as hydrodynamics, plasma physics, materials science, nuclear physics, and fluid flow phenomena.

To measure the enormous intensities of radiation (particularly neutrons) produced in the extreme conditions of an explosion, special radiochemical "probes" were developed. Known quantities of various isotopes (the "probes") were placed in or near the unexploded device. After the explosion, samples of the bomb debris were obtained and subjected to radiochemical analyses to determine the resultant isotopic abundances. These values are then compared to the predicted values from simulations in order to assess the accuracy of the models. Critical inputs to these comparisons are the cross sections for the creation, destruction, and transmutation of the isotopic probes (and the resulting products) by neutrons and X-rays. Since the vast majority of the isotopes involved have lifetimes of days or less, it has never been possible to collect enough of a given isotope to allow measurements of those cross sections. Current models have been forced to use only theoretical estimates, which introduce significant uncertainty. In fact, it has been recognized that the uncertainty in the interpretation of the radiochemical probe data is often the largest contributor to the overall uncertainty of the calculation.

RIA will dramatically increase the number of isotopes relevant to Stockpile Stewardship for which measurements can be performed. RIA will be able to produce large quantities of, and beams of, the specific isotopes of interest, making it possible to collect them in unprecedented quantities and purities. Even for those isotopes for which the lifetime is too short to allow direct measurements at RIA, RIA will still enable indirect studies of these unstable nuclei using surrogate reactions. This will increase our general knowledge of the physics of nuclei, thereby permitting more accurate theoretical models of processes beyond even the enormous reach of RIA. To fully realize the impact of RIA on Stockpile Stewardship, a co-located neutron source would be needed, and NNSA is actively working with the RIA community in planning for such an addition. This neutron source as well as the experimental techniques and methods to measure neutron cross sections on short-lived isotopes are also of interest to the astrophysical community and those studying nucleosynthesis. It is not anticipated that any experiments at RIA will be classified or would involve restrictions on participation in the measurements, and all cross section data will be published in the open literature.

In addition to Stockpile Stewardship, RIA will make important contributions to the Nuclear Forensics/Attribution Program of Homeland Security. Should a terrorist nuclear bomb be exploded on U.S. soil, policy makers will insist on specific information about the source and design of that bomb. Indeed, were such a terrible incident to occur, models will be required to work backward from radiochemical analyses of the bomb debris to obtain those answers. Such models are currently under development. Data from RIA are essential to improve the physics input into this type of calculations. Also, RIA will have impact on the development of diagnostics for High Energy Density Physics facilities. Just as in stockpile stewardship, radiochemical probes will be part of the diagnostic suite at facilities such as NIF, OMEGA, and Z-Machine. The accuracy of such probes will be enhanced by data from RIA. RIA would also fill the role of a much needed training ground for the next generation of nuclear physicists and radiochemists required by NNSA to fulfill its national security missions.

What are the next medically viable radioisotopes required for enhanced and targeted treatment and functional diagnosis?

RIA could be used to produce a portfolio of isotopes in amounts useful in a variety of research applications in high specific activities, with sample sizes up to 10^{20} atoms. RIA's unique high-energy primary beam will ensure production of a broad spectrum of candidate isotopes for use as research materials in radio-immunotherapy and functional imaging for medical diagnosis. For therapy applications, it is known that alpha particle decay energies are ideally suited for localized destruction at the few cell level (see Fig. 5.1).

Combinatorial chemistry and high-throughput biological screening is needed for new, attractive isotopes that have half-lives shorter than a few days. RIA would be the source of such potential alpha emitters with appropriate half-lives, alpha particle energies, and chemistry, such as ^{211}At.

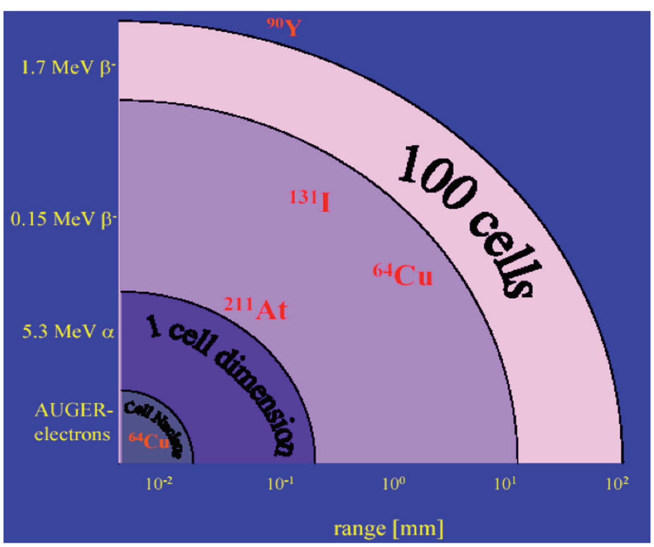


Figure 5.1: Range of alpha and beta particles compared to cellular dimensions.

The functional imaging information obtained from nuclear medicine applications has vastly improved medical diagnostics and helped reduce the number of more costly invasive procedures. The development of new isotopes for application in functional imaging will improve access to a wider range of elements to better target biological functionality as well as improve radiotherapy treatments. As an example, the development of positron emission tomography sources such as ^{86}Y, ^{89}Zr, and ^{124}I would allow monitoring of the distribution of ^{90}Y used in radio-immunotherapy. The successful implementation of a medical isotope research program at RIA will require steady supplies of potential isotopes; high reliability, advanced scheduling, and frequent availability will all be keys in RIA operations.

What are the critical electronic and magnetic properties of advanced materials for developing the next generation of superconductors, magnetic storage devices, and semiconductors?

The relatively low energy radioactive ion beams that RIA can also provide will enable the study of advanced materials for superconductors, magnetic storage devices, and semiconductors using well known nuclear techniques, such as beta-detected nuclear magnetic resonance (β-NMR), nuclear spin relaxation studies, and beta-detected nuclear quadrupole resonance (β-NQR). While β-NMR studies of materials are currently being carried out at existing radioactive ion beam facilities, the variety and intensity of ion beams available at RIA would greatly expand the number of possible measurements. The short and variable range of ion implantation depths, from several to hundreds of nanometers, combined with the high intrinsic sensitivity typical of these nuclear techniques, make it possible to carry out depth-resolved investigations of near-surface phenomena in both ultra-thin and bulk materials, where conventional NMR and other techniques lack sufficient sensitivity. It will be possible, for example, to directly measure temperature and magnetic field dependencies of the magnetic penetration depth in superconductors, a key parameter in elucidating the underlying physics and material properties conducive to superconductivity. Some theories predict the emergence of a time-reversal symmetry-breaking order parameter just within the surfaces of superconductors giving rise to weak magnetic fields, which may be detectable with low energy β-NMR. Also, magnetism in thin-film magnetic multi-layers and near-buried interfaces can be characterized via the β-NMR line-shape, reflecting the local field distribution, and nuclear spin relaxation, which is sensitive to spin dynamics. Magnetic multi-layers are commonly used in data storage devices and it is widely anticipated that nanoscale magnetic devices will be important in advancing computing technologies. Additionally, β-NMR and β-NQR in zero applied field yield information about the electronic environments of impurities in semiconductors. These nuclear techniques using low energy radioactive ion beams provide an excellent means of studying the initial states of very dilute impurities found in semiconductors.

RIA will also be an intense source of muons. Like implanted radioactive ions, muons are used to address a wide variety of current problems in materials sciences, including the physics of superconductors and the interplay of magnetism and superconductivity, magnetic materials, semiconductors, and chemical reaction kinetics. Muon spin rotation, relaxation and resonance (collectively termed μSR) is an established experimental technique in condensed matter physics and chemistry, although its application is presently limited by the scarcity of beam time at the few suitable accelerators worldwide. While no study has yet been done to fully determine the additions and modifications to the RIA baseline necessary to enable a μSR facility, it is clear RIA could provide the international μSR community with a U.S.-based, world-class μSR user facility with unique capabilities to study bulk and thin-film materials in addition to microscopic samples.

Can we design an economically competitive, energy efficient, proliferation resistant, reduced-waste nuclear reactor to meet national energy demands for the 21st century and beyond?

Nuclear energy will be an increasingly vital portion of this nation's future energy portfolio in the 21st century and beyond as the demand for carbon-emission-free energy sources grows. With more emphasis on designing safer and highly efficient nuclear reactors, there will be increasing demands for improved nuclear data for minor actinides (neptunium, americium, and curium) and fission products. The overall burn rate of plutonium and longer-lived fission products is dependent on shorter-lived nuclides as intermediary products which are subsequently burned. Improving the quality of nuclear data for these short-lived isotopes will improve the modeling of Generation-IV nuclear reactors or Accelerator Transmutation of Waste systems.

The RIA facility will have a powerful set of capabilities for addressing several aspects of the fuel cycle problem. This includes the ability to produce and separate quickly isotopically pure samples of short-lived isotopes for the measurement of specific production and destruction rates. These measurements could be accomplished at the co-located neutron-generator facility proposed for Stockpile Stewardship. Also, the spallation neutrons generated in the RIA target area can be tailored to simulate various fast reactor energy spectra, enabling measurements of integrated burn rates for simulated reactor fuel composites. These composites could be quickly analyzed for trace quantities of trace mutation products by having the post-accelerator operate in the Accelerator Mass Spectroscopy mode for ultra-sensitive trace analysis. Thus, RIA not only enables specific nuclear data measurement, but quick turn-around integral measurements.

6. Ensuring the Future: Expertise in Nuclear Science, Nuclei, and Nuclear Technology

The expertise of nuclear scientists is critical to our nation's economic welfare and security. Understanding isotope science, radiation detection, nuclear medicine, and nuclear reactions is essential to the mission of U.S. national laboratories and is critical for many industries that apply nuclear technology. Nuclear scientists also provide significant foundational expertise in related fields such as accelerator physics and nuclear engineering.

The prospects for RIA come at a time when the demand for expertise in nuclear and radiation science is increasing while the supply is decreasing. The production of nuclear science PhDs has declined over the past decade from nearly 120 per year in the 1990s to approximately 80 per year now. This decline is occurring while facing increased demands for nuclear expertise from homeland security and energy, and much of the existing nuclear workforce is aging and approaching retirement. Indeed, NRC News (No. S-01-022) reported that an estimated 76 percent of the nuclear workforce will be at retirement age during the period from 2000 to 2010.

Concern about the decline in the number of individuals trained in nuclear science was highlighted in "The Education and Training of Isotope Experts," a report from the AAAS presented to Congress in 1999. This report stated:

"Too few isotope experts are being prepared for functions of government, medicine, industry, technology and science. Without early rescue, these functions face nationally harmful turning points, including certainty of slowed progress in medicine and some technologies, near-certainty of shocks in national security, and probable losses in quality of health care."

Since then, the situation has become even more critical. An NSAC subcommittee on education recently estimated that the national need is between 100 and 120 nuclear science PhDs per year to meet the demand. The current rate of production is approximately 70 percent of this amount. Hence, there is a critical need to maintain, if not expand, the number of talented experts in nuclear science and, in particular, in rare isotope science. This can only be done by having forefront research opportunities, such as RIA, that will attract the most talented students into the field.

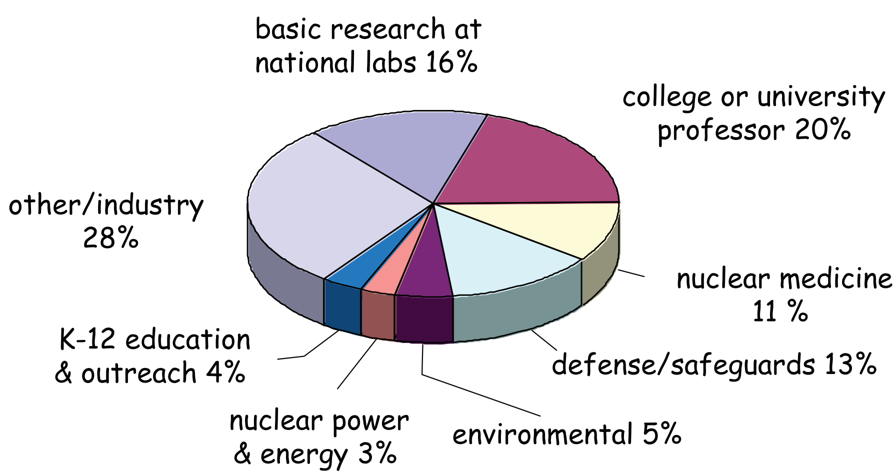
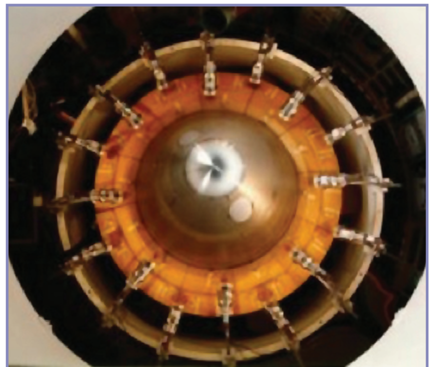


Figure 6.1: Trends in the employment of low-energy nuclear physics and nuclear chemistry PhDs compiled from a survey of students up to 20 years past their PhD. The results from the recent NSAC survey of graduates over the past 5 years are nearly identical.

Advanced education and training in nuclear science have a long tradition of preparing early career scientists for the challenges in basic research, higher education, and meeting national needs for national and homeland security, nuclear medicine, and developing instrumentation and techniques for a wide range of industries. This tradition is highlighted in Fig. 6.1, which shows that historically at least 60 percent of nuclear science PhDs have careers outside of education and basic research in our universities or national laboratories. An example of how this training can contribute to meet national security needs is highlighted in the sidebar.

The national need for individuals educated in the science of the nucleus manifests itself in many areas. Nuclear medicine–both diagnostic and therapeutic–has increased the duration and quality of life of many individuals. One of the forefront areas in the treatment sector is hadron therapy, which has proven to be very effective for both skin melanomas and ocular tumors. This development would not have been possible without trained nuclear scientists who understand the increased energy deposition in a local area. The further example of new radioisotope therapies given in section 5 of this report is another indication of the importance of expertise in nuclear science to medicine.

Homeland security is another area where individuals trained in the science of the nucleus are vital to the nation's interest. These scientists are working to design methods of detecting nuclear materials that might enter our country, developing portable radiation monitors, as well as training first responders in the use of radiation detection equipment. A related aspect of our national security is Stockpile Stewardship and the need to understand fundamental nuclear reactions, often on rare isotopes, that impact nuclear device performance.



In the 1980s when the U.S. and Russia were discussing reduction of nuclear weapons, the question arose, "How do we test a Russian missile that is to be dismantled to see if it contains a real nuclear warhead or some mock warhead of non-fissile material?" Jerry Cole, a PhD scientist who received his training in nuclear science won the Edgerton Award given by EG&G for helping to design a system (now unclassified) to experimentally determine if a missile contained a real nuclear warhead. He drew on his knowledge of nuclear physics, including fission, radiations emitted by radioactive nuclei, and fast coincidence γ-ray detection techniques, to design a system to answer this question. He tested his device by lowering his equipment into silos to demonstrate whether a nuclear warhead could be detected. The picture above shows the arms control system as deployed on a Peacekeeper (MX) missile. Scientists with expertise in low-energy nuclear phenomena have special skills in such developmental applications of nuclear science.

The physics of the nucleus impacts many aspects of our lives. In this era when high technology drives the economy and when decisions of national interest demand an understanding of nuclear technology, its risks and opportunities, it is more important than ever that the public be informed about science in general and nuclear issues in particular. Scientists trained in the study of the nucleus not only contribute to the education of the next generation of nuclear scientists, but also to the education of teachers and the general public. The latter is a particularly important component of scientific literacy. As more lives are saved by nuclear medicine, more people are affected and need to know about the biological effects of ionizing radiation. It is only with a basic understanding that they can make an informed risk-benefit analysis. The need for understanding the biological effects of radiation goes beyond optional exposure such as nuclear medicine to issues fraught with misinformation and fear such as radon-based radiation. Beyond biological effects there are issues of the effect of ionizing radiation on materials and the impacts of cosmic ray damage to communications or defense satellites. And one cannot expect the public to make informed decisions (or be accepting of decisions made by public officials) about such issues as nuclear waste without a basic knowledge of the science of the nucleus. In order to improve this very critical aspect of science literacy, we need nuclear scientists in the universities teaching the K-12 teachers of tomorrow, the undergraduates, the graduate students, and reaching out to the general public.

Currently, we have a world-class program in low energy nuclear science. The DOE and NSF support national user facilities at Argonne and Oak Ridge National Laboratories and Michigan State University, as well as local laboratories at universities across the United States. Collectively, these facilities attract and train the U.S. workforce in the science of the nucleus. The thrust of this research is moving rapidly to the use of rare isotopes to reach nuclei far from stability and, therefore, the frontiers of discovery will move from today's facilities to those with enhanced rare isotope capabilities.

As discussed in Sec. 8, laboratories in Europe and Japan are moving rapidly to develop better rare isotope accelerators. Without RIA, the United States will likely lose its position of leadership in this crucial area of research. This will also affect all the ancillary aspects of it in areas of nuclear technology, medicine, national security, and education. Although the reason for building RIA is its outstanding discovery potential, as outlined in previous sections, the added value of these specially trained individuals should not be underestimated. With RIA we will continue to attract many of the best and the brightest young minds due to this exciting science.

Joann Prisciandaro illustrates how training in rare isotope nuclear science uniquely prepares students for service to the nation.

Joann plays an important role in cancer treatment at the University of Michigan hospital, where she is on the faculty of Radiation Oncology Physics. She received a PhD in nuclear chemistry, studying nuclei far from stability with radioactive beams at the National Superconducting Cyclotron Laboratory under the direction of Paul Mantica. She says, "As a student in a nuclear physics laboratory, I was given the opportunity to work with experts and independently on various experiments. This required setting up and testing electronic equipment, interpreting the response of radiation detectors, understanding the interactions of radiation, writing subroutines, and analyzing data. The experience and knowledge I gained as a nuclear scientist has prepared me well for radiation oncology physics."

7. RIA Facility and R&D Program

The RIA facility concept brings together a unique combination of recent technological developments that will enable world-leading science with beams of rare isotopes. The concepts have evolved and been strengthened through a vigorous national R&D program that has been ongoing for about 10 years at several national laboratories and universities in the Unites States. A schematic layout of the proposed facility is shown in Fig. 7.1.

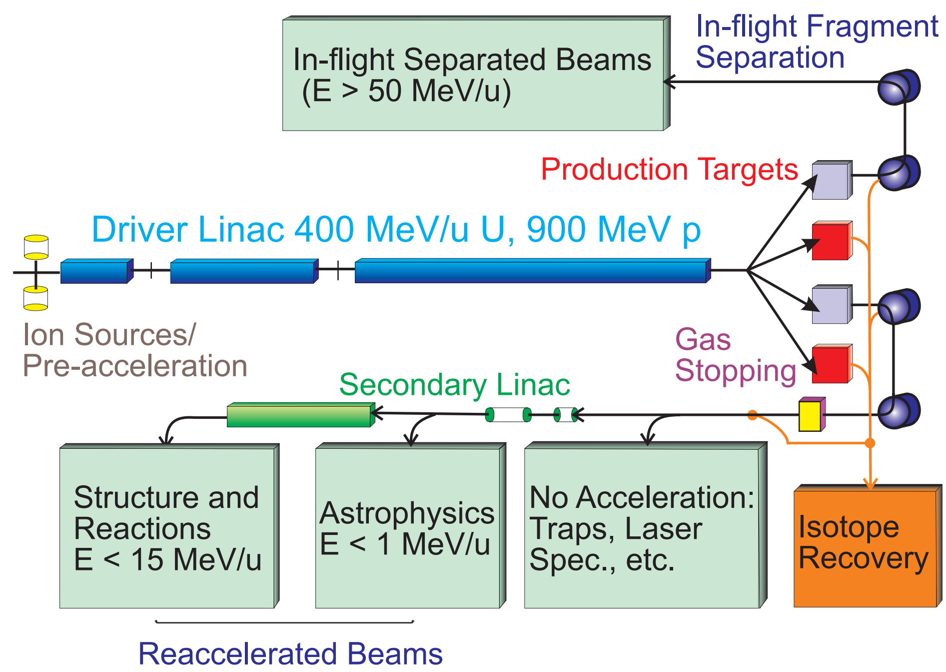


Figure 7.1: General layout of the RIA facility.

The rare isotopes are produced via beams from a high-power superconducting driver linac. The driver can deliver beams of up to 400 kW of any element from protons (900 MeV) to uranium (400 MeV/u) by using a state-of-the-art ion source, and a variety of recently developed superconducting resonators. Detailed simulations have shown that high-power heavy ion beams such as uranium can be achieved through a unique feature, the simultaneous acceleration of several different charge states of a given beam.

The availability of both light and heavy ion beams from the driver gives RIA the capability of using the best features of all production mechanisms so that the highest yields of all exotic beams can be made available to the users. This feature makes RIA unique worldwide (see Sec. 8). The production methods fall into two general categories. One method uses fragmentation or fission of the incoming heavy beams to produce the desired species, which are subsequently selected in a fragment separator and can then be used directly for certain classes of experiments.

A second method requires re-acceleration of the ions produced either by projectile fragmentation or fission as just discussed, by spallation of nuclei in a thick target or by generating neutrons in a cooled tungsten target, which subsequently induce fission in a surrounding barrel of uranium-carbide material. The short-lived isotopes are either separated in a fragment mass separator, slowed down in a degrader foil of appropriate thickness, brought to rest and extracted as 1^+ ions from a He gas cell (fast gas catcher in Fig. 7.1) or diffuse into an ion source for ionization (ISOL method). Ions from the gas catcher or from the ion source are subsequently mass separated and re-accelerated. The importance of being able to use all the available production mechanisms is illustrated in Fig. 7.2 where the optimal reaction mechanism is given for each isotope in the case of re-accelerated beams. The expected yields of mass-separated 1^+ ions for re-acceleration and those of mass separated fast beams are given in Figs. 7.3 and 7.4.

No existing or proposed facility worldwide has all these essential capabilities. One of the most important innovations in the RIA concept is the gas catcher, which has been demonstrated under the RIA R&D program. The gas catcher will significantly broaden the reach of RIA for high quality re-accelerated beams of rare isotopes not available by the ISOL technique.

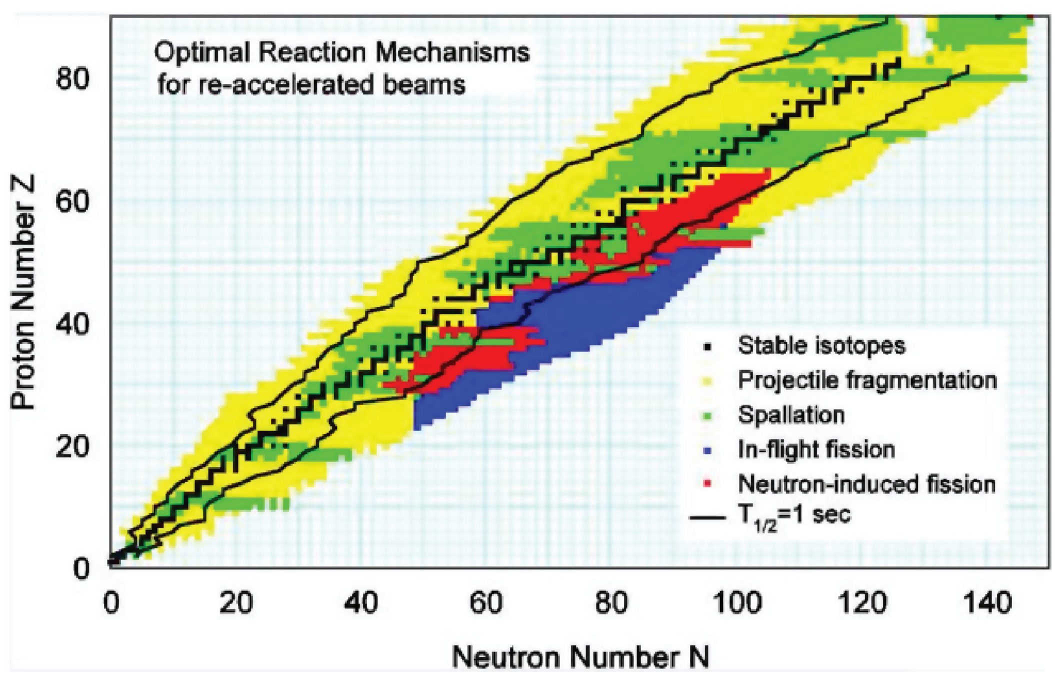


Figure 7.2: Color map of the optimal production method for re-accelerated secondary beams produced at a 400 kW, 400 MeV/nucleon facility. The plot extends to a production of 10^{-4} s^{-1}.

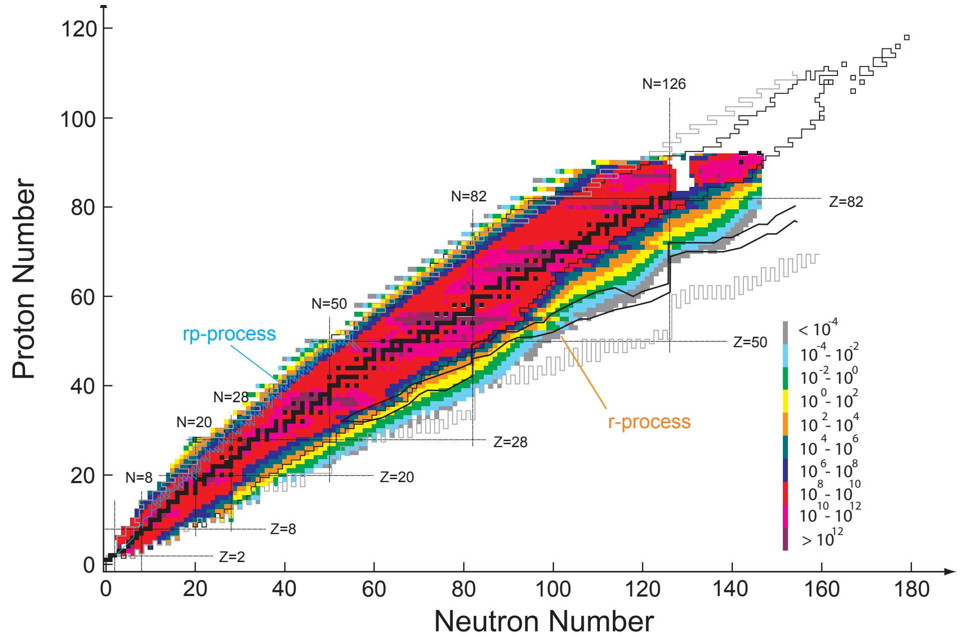


Figure 7.3: Contour map of re-accelerated beam intensities for all isotopes calculated based on a 400 MeV/nucleon 400 kW primary beam. The plot includes beams produced by ISOL and those extracted from a gas-stopping cell; the optimum yield is chosen for each case. For reference the r- and rp-process paths are shown, as well as the projected location of the proton and neutron drip lines. The rates are given in particles per second.

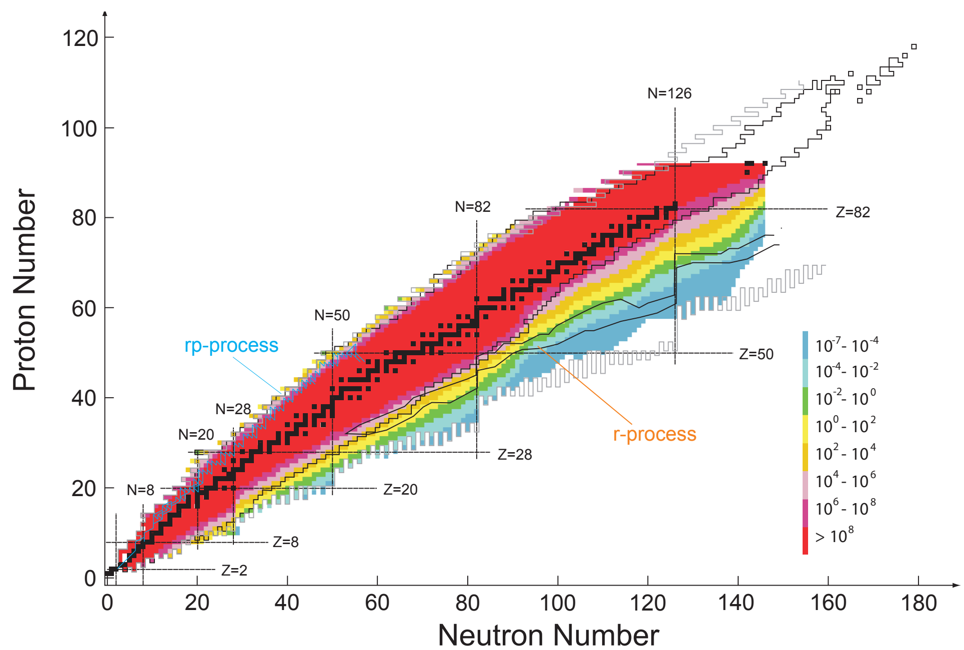


Figure 7.4: Contour map of isotopes calculated for fast beams produced with a 400 MeV/nucleon 400 kW primary beam. The plot includes beams produced by either fragmentation or in-flight fission; the optimum yield is chosen for each case. For reference the r- and rp-process paths are shown, as well as the projected location of the proton and neutron drip lines. The rates are given in particles per second.

8. International Context for RIA

Science with beams of rare isotopes is demonstrably a vibrant and broadly international enterprise. The importance and uniqueness of such beams as a tool for exploring a variety of topics in science and technology has been recognized, not only by the U.S. nuclear science community in its endorsement of RIA, but also by scientists around the world. More than a dozen rare isotope facilities are now operational or under construction worldwide. The fact that so many countries in Europe, Asia, and North America are making such strong investments in these facilities can only be seen as a ringing endorsement of the science. It has also led to broad international collaboration on research and development work relevant to the realization of next-generation facilities.

Two intermediate-scale rare isotope facilities, and several smaller-scale projects are nearing completion outside the United States. These include an upgrade of the ISAC facility at TRIUMF in Canada and major new capability at RIKEN in Japan. Both are scheduled for completion within the next two years. Upon completion, ISAC-II will be the leading ISOL facility in the world, while RIBF at RIKEN will become the leading fast-fragmentation facility with an upgrade that provides a factor of 100 increase in intensity over existing capabilities. Another intermediate-scale facility has been approved for funding at GANIL in France. This facility, known as SPIRAL-II, will be optimized for production of re-accelerated beams of fission fragments using the ISOL method, and should produce beam intensities somewhat larger than ISAC-II when completed around 2011. The largest-scale rare isotope facility on the international landscape, with at least conditional funding, is the Facility for Antiproton and Ion Research at the Gesellschaft für Schwerionenforschung (GSI/FAIR) in Germany. The scale and cost of FAIR is similar to that of RIA, however it encompasses a broad range of scientific disciplines, including relativistic heavy ions, plasma physics, atomic physics, and research with antiprotons. As impressive as it certainly is, the rare isotope capability of FAIR is more limited and specialized than that projected for RIA. The superiority of RIA in one critical performance metric is illustrated in Fig. 8.1, which displays the maximum rare isotope beam intensities expected at RIA divided by the corresponding beam intensities at GSI/FAIR for the entire set of nuclear species that will be available. Note that RIA intensities exceed those of FAIR by factors of at least 10 to 100 for all unstable species. This ratio gets much larger as one approaches the particularly interesting systems near the limits of stability for neutron-rich nuclei. Moreover, RIA will provide high-quality reaccelerated beams, but FAIR will not. Such beams provide a capability of critical importance to a significant part of the research program in nuclear astrophysics and nuclear structure planned for RIA.

The intense international effort directed at the development of rare isotope beam facilities emphasizes the strong worldwide interest in the science that such facilities can enable, and has led to international collaborations to develop and test novel concepts, techniques, technologies, and devices that will improve the scientific reach and cost-effectiveness of future facilities worldwide, including RIA. However, as plans for large scale, next-generation facilities are considered, issues of overlap and redundancy of capabilities inevitably arise, and related questions are raised. Can the needs of the U.S. community be met by modest investment in non-U.S. projects? What would be the implications of such a course? Such issues have, in fact, recently been considered in some depth by a subcommittee of the U.S. Nuclear Science Advisory Committee. This subcommittee was charged with comparing RIA with its closest and most ambitious international competitor, the FAIR project at GSI. Several of the conclusions reached and issues raised by this subcommittee are of direct relevance here. The principal conclusion can be embodied in the following quotation from the executive summary of the report of this subcommittee:

> *While both facilities will produce rare isotopes by fast beam fragmentation and there is collaboration between the U.S. and European communities on R&D issues, we find that this overlap in capabilities is less than it would appear. It is clear that the RIA rare-isotope research capability*

is more extensive than GSI. The question of whether an upgrade of GSI would duplicate the rare isotope capability at RIA is answered firmly in the negative. (From the "Report of the NSAC Subcommittee on Comparison of the RIA and GSI Future Facility")

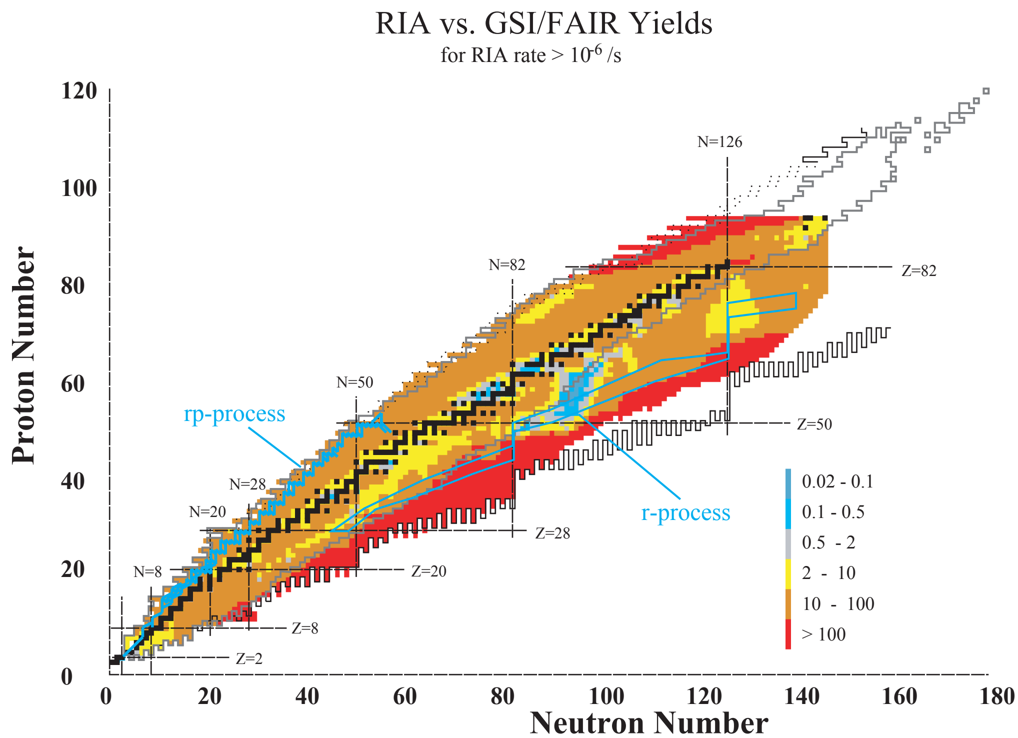


Figure 8.1: Rare Isotope Yields at RIA compared to GSI/FAIR. The maximum projected rare isotope beam intensities at RIA divided by the corresponding beam intensities at GSI/FAIR are plotted as a function of neutron and proton number.

The current membership of the RIA Users Group exceeds 800. An extrapolation well beyond 1000 by the time RIA comes on line is probably conservative. Estimates of the user base radioactive ion beam science in Europe are also about 1000. These large user communities provide the background for another of the conclusions of the subcommittee:

The user communities for RIA and GSI, including those devoted to rare isotopes, are both large and distinct; neither facility could accommodate the full user base. Both facilities would impact several areas of local national importance, particularly training personnel needed in a number of important societal areas dependent upon nuclear physics.

The general issue of manpower and education (which is considered more extensively in Sec. 6 of this document) is discussed in the body of the report with an explicit consideration of some of the results that might flow from depending primarily on non U.S. facilities such as FAIR as the base for U.S. research in science with rare isotope beams:

... low energy nuclear physics – by which we mean nuclear physics in the keV and MeV range – is a critical component of stockpile stewardship, nuclear medicine, nuclear reactor design and safety, hazardous waste disposal, and homeland security. Without RIA on the horizon (10 to 15 years from today), an entire generation of young U.S. nuclear physicists may be lost as the center of gravity of this field shifts even more toward Europe. This could have future ramifications for the U.S. that extend well beyond the immediate scientific opportunities of RIA itself.

The case has been made that RIA will provide important tools and capabilities for carrying out research relevant to the NNSA Stockpile Stewardship Program (see the discussion in Sec. 5). What impact would a decision to base this NNSA program at a facility outside the United States such as FAIR have? There are strong practical considerations, which weigh strongly against such a decision. It is obvious that NNSA scientists could not expect to have input on overall facility design and on the provision of specialized infrastructure needed for their research at a facility outside the United States. Potential difficulties could arise in the interaction with a program advisory committee since the justification for the research would not rest primarily on the forefront scientific issues to which such a committee customarily gives primary weight. Unforeseen political developments in the facility's host country could result in denial of access to NNSA scientists. Even in the absence of political impediments, substantial bureaucratic headaches related to working outside the United States could arise for NNSA scientists originating from agencies of both the U.S. and host-country governments. The potential positive impact of RIA on future production of young U.S. nuclear physicists was mentioned in the previous paragraph. The loss of the impetus RIA would have to production of potential manpower for staffing NNSA laboratories would probably be the most important negative impact of the loss of RIA on the NNSA research programs.

Science with rare isotope beams is being pursued vigorously around the world. This strong, active, and vibrant program will generate collaborative efforts that will advance the development of the techniques and technology for producing radioactive ion beams at RIA, and will influence, enhance, and strengthen the science program to be carried out. This broad international effort will generate clear benefits for all involved. It would be a mistake, however, to imagine that U.S. investment in a foreign-based rare isotope facility such as FAIR could provide an adequate substitute for the remarkable capabilities, exciting science, and far-reaching direct and indirect impacts that RIA will provide for the United States.

APPENDIX A: Examples of Experiments with RIA

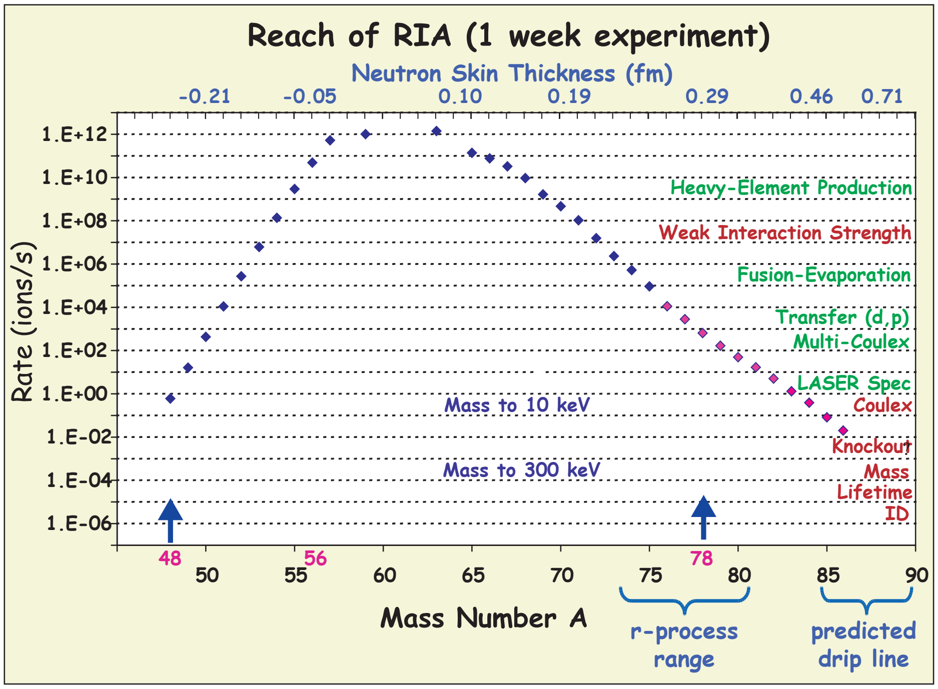


Figure A.1: The nickel yields at RIA. See text for details. Blue diamonds indicate nuclides with highest yields produced by projectile fragmentation and magenta diamonds those isotopes best produced by in-flight fission.

The breadth of science made possible with RIA can be illustrated in the case of one chain of isotopes, the nickel isotopes. Figure A.1 shows the Ni yields at RIA versus the nickel atomic mass number. In order to address the science, a number of techniques will be employed. The figure gives an indication of what classes of experiments will be possible at various beam intensities. Those listed in green require reacceleration, while those in red are best done directly in-flight or after stopping in-flight ions. To judge the scientific reach, a few landmarks are included. Shown in the figure is the possible range of r-process nuclei, a range where the neutron drip line might be discovered, and the traditional magic numbers (purple labels). The top of the figures gives a prediction of the neutron skin thickness for these isotopes. The blue thick arrows indicate the limit of current facilities (at mass numbers 48 and 78), i.e. the isotopes for which a production sufficient for identification (10^{-5}) is now achieved.

The best current mass models predict that the neutron drip line might appear at mass 85, but it may also appear at 90, depending on the bunching of single-particle levels when the binding becomes low. This may be a result of a kind of pairing at the drip lines and is something that RIA will study. RIA, for example, would likely allow determination of the drip line for nickel. Study of the single particle (and hole) states near ^{78}Ni is critical for nuclear shell structure. RIA has sufficient intensity to allow these studies. The rate is sufficient to allow a longer, dedicated, several-week experiment to measure single-particle states in ^{79}Ni via reaccelerated beams and use of the (d,p) reaction in inverse kinematics. Detailed studies of the structure of heavy Ni isotopes with a skin thickness of 0.5 fm will be possible by reaction cross section measurements, detailed decay spectroscopy, and knockout reactions. Near-barrier and sub-barrier transfer reactions (and fusion studies) will be possible for nuclei with three times the skin thickness of normal nuclei. With a Penning trap it will be possible to determine the mass of ^{48}Ni with an accuracy of better than 50 keV/c^2 within about a week and on the neutron-rich side it will be possible measure out to ^{81}Ni. Time-of-flight measurements at RIA may reach as far out as ^{84}Ni.

In the following, we provide more details on some of the other types of experiments that can be envisioned, and the reader is referred to Fig. A.1 for intensity limits and a more complete list of the techniques.

Ground-state magnetic-moment measurements for structure determinations have been performed at implantation rates below 10 Hz taking advantage of the large polarizations observed for fragments collected off the normal beam axis following intermediate-energy heavy-ion reactions. Thus these can be carried out from ^{49}Ni to ^{82}Ni.

Identification of new isotopes is limited by the amount of available beam time and is possible with rates of particles/day or per week. The precision of the lifetime measurements is then limited by the available number of ions, but RIA will provide data over the entire range shown in the figure. Masses can be measured with Penning trap mass spectrometry for isotopes with half-lives down to 10 ms or slightly less. A mass accuracy of about 10 keV/c^2 can be easily achieved with sufficient yield. For shorter-lived isotopes, time-of-flight measurements can provide an accuracy of several hundred keV/c^2.

Measurements of the properties of nuclear excitations and associated transitions can be carried out with a broad range of beam energies and experimental techniques. The mapping of collective strength requires multi-step Coulomb excitation with thin and thick targets and reaccelerated beams with intensities of 1,000-10,000 Hz. Observables include transition energies that can be converted into level energies and transition matrix elements. Excited state energies (but not transition matrix elements) can be deduced from in-beam fragmentation experiments, with beam intensities of the order of 1 Hz. Intermediate-energy Coulomb excitation populates low-lying excited states which couple to the ground state through E1, E2, E3 or M1 or M2 transitions. Thick secondary targets of the order of 0.1-1 g/cm^2 can be used. The interaction times between projectile and target are so short that multistep excitation is highly suppressed. With an efficient photon detector, experiments are feasible with secondary beam rates of about 0.1-0.5 Hz to achieve meaningful data in a three-day experiment.

Probing the wave function of states in exotic nuclei can also be done far from stability using direct reactions with fast beams. This is a powerful tool that allows the determination of orbital angular momentum quantum numbers and spectroscopic factors for reactions leading to individual excited states. Single-nucleon removal reactions are feasible in three-day experiments with secondary beam rates above 0.01 Hz. In experiments where individual bound excited states are to be tagged with an efficient photon, experiments are feasible with rates of about 0.1Hz.

Figure A.1 also addresses the possibility that beams of exotic nickel isotopes may be used for other purposes such as the production of new elements using fusion-evaporation reactions. Here as well, RIA provides an attractive set of beams.

In the following, examples of compelling experiments at RIA are briefly discussed, illustrating different areas of science.

Example 1: Shell structure, once conceived as a robust characteristic of all nuclei, is being recognized now as a more fluid concept. It is already known, for example, that the magic numbers in the light neutron-rich nuclei are not the immutable benchmarks they were once thought to be. RIA, with its ability to reach extreme isospins, will be key in probing how shell structure, shell gaps, and magicity change near the drip lines. These questions are also important for explaining nucleosynthesis processes such as the r-process, which is directly affected by shell structure. Precision measurements near the short-lived doubly-magic nuclei ^{48}Ni, ^{60}Ca, ^{78}Ni, and ^{132}Sn, will enable us to accurately determine effective interactions for much of the nuclear chart. This will be a key and critical experimental/theoretical program of any future rare isotope research program. *The shell structure of nuclei is determined by gaps in the spacings of single-particle states and by the angular momentum character of these states. Those are best determined by one-nucleon transfer reactions. Such transfer reactions can be carried out with precision beams of the appropriate energies (10–20 MeV/u). The intensities expected at RIA for beams such as ^{100}Sn, ^{48}Ni, ^{78}Ni, and ^{132}Sn are on the order of 50, 0.8, 80, and 3x10^{10} ions/s, respectively.*

These are typically two to three orders of magnitude above what is currently available. In addition, nucleon knock-out reactions with fast beams represent another tool to study single-particle structure. Such experiments are currently performed with rates of 0.1 ions/s. At RIA, gamma-ray detection with 30% efficiency and particle detection with 100% efficiency is envisioned. Hence, the properties of wave functions can be studied with as few as 0.01 ions/s. As a result, relevant information will be easily obtained for nuclei around ^{78}Ni and other nuclei quite far from stability.

Example 2: One of the most important goals of research in nuclear structure and chemistry is to reach the region of super-heavy elements around Z=112 and N=184. Nuclei from this region are predicted to live longer than a year before decaying by alpha emission and their atoms have unusual chemical properties due to the relativistic motion of their valence electrons. However, no target-projectile combination of stable isotopes will directly lead to the center of the island in a fusion-evaporation reaction. The long-term perspective is the use of intense neutron-rich radioactive beams, such as ^{132}Sn, mainly in combination with neutron-rich radioactive targets, to produce the most neutron-rich nuclei of heavy actinides, transactinides, and, ultimately, super-heavy elements. *Intense beams from RIA will complement studies of the heaviest nuclei with stable beams in at least two ways. First, in favorable cases, i.e., instances where the intensity of the rare isotope is large (^{90,92}Kr, ^{90,92}Sr >10^{11}/s), so-called cold fusion reactions become feasible. These measurements will require reaccelerated beams of high intensity with a precise energy that will only be available at RIA. There is also interest in chemistry and atomic physics, where the longer half-lives facilitate manipulation of the atoms produced. For example, the production of new, heavy isotopes of Fm using so-called hot fusion reactions with beams of $^{16\text{-}22}$C on ^{244}Pu targets would range from thousands of atoms/d down to 1 atom/d.*

Example 3: It is believed that in heavier neutron-rich nuclei, *neutron skins* will develop that will dramatically impact their structure, reactions, and decays — when compared to their stable counterparts where a homologous mixture of neutrons and protons is present. New symmetries and collective modes may well develop in such nuclei with partially decoupled neutron and proton fluids. For example, one expects the presence of low-energy *isovector* vibrational modes of the skin-neutrons. Such pygmy resonances considerably impact neutron capture cross sections, hence the r-process path and the r-process freeze-out. *The available intensities at RIA will allow these studies to cover a range of neutron skin (r_n-r_p) six times larger than what is available now, i.e., from –0.21 to 0.60 fm in the nickel isotopes (see Fig. A.1).*

Example 4: Any attractive interaction between fermions at low temperatures generally leads to fermion pairing and, therefore, superfluidity, 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 bulk nuclear matter in neutron stars (nucleonic pairing) and it is believed to exist in the quark-gluon plasma (color superconductivity). 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 (In condensed matter physics, finite-size effects, going beyond the BCS theory, have been found only very recently in ultrasmall aluminum grains.) In extremely neutron- and proton-rich (N=Z) nuclei different superfluid phases may appear, characterized by nucleonic Cooper pairs carrying different isospin, spin, and total angular momentum. The role of pairing may be enhanced in loosely bound nuclei, even to the possible extent of impacting the nature or viability of the mean field ansatz. *The expected intensities at RIA for key N=Z nuclei, ^{56}Ni, ^{64}Ge and ^{72}Kr, that can be used for these studies are 10^{11}, 10^9 and 10^8/s, respectively, while rates for heavier N=Z nuclei between ^{80}Zr and ^{100}Sn will vary from 10^6 to 40 ions/sec. Two-nucleon transfer studies to measure pairing properties are best carried out with the reaccelerated beams that RIA will provide, since they require beam energies in the vicinity of 10-20 MeV/u, depending on the Q-values of the specific reactions. Two-neutron transfer experiments can be carried out at RIA within one week with beams of the order of roughly 10^4/s. Thus, experiments with ^{56}Ni, ^{64}Ge, ^{72}Kr, and the heavier N=Z nuclei up through ^{92}Pd will be possible — the (^{3}He,n) reactions may require somewhat higher intensities and would probably be limited up through ^{88}Ru.*

Example 5: Symmetries of the many-body system have played a key role in understanding nuclear structure. While only a few nuclei display these in nearly unperturbed form, dynamical symmetries provide benchmarks that allow simple interpretation of similar nuclei. An important research program, entailing experiments at fixed Z and increasing neutron number, involves the transition between quantum symmetry phases in nuclei. Phase transitional behavior in finite fermion nuclear systems has recently been successfully described with new critical-point descriptions. RIA, with its access to extended chains of new nuclei, often spanning several major shells, will allow these phases and structural trajectories to be mapped as never before. A key question is whether new spherical-to-deformed phase transitional regions, in neutron rich nuclei such as ^{112}Zr, ^{96}Kr, and ^{156}Ba or the proton rich nuclide ^{134}Sm, can be described by these same symmetries or will new ones, reflecting the proton-neutron asymmetric nature of these nuclei, be needed? *These nuclei, and others nearby in the expected transition regions, will be available at RIA with intensities ranging from 10- 10,000/s, which are suitable for mass, decay, Coulomb excitation, and other experiments.*

Example 6: The nuclear equation of state (EOS) describes the possibility of compressing nuclear matter. It plays a central role in nuclear structure and heavy ion collisions and 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 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 isospin dependence of the EOS, crucial for the supernova problem. *Measurements with RIA beams at incident energies E_{beam}/u=50-400 MeV could probe a range of densities ρ/ρ_0=0.5-2.0 times normal saturation densities. To probe the asymmetry term, two systems such as ^{102}Sn+^{112}Sn and ^{138}Sn+^{124}Sn that have similar charges, but extremely different isospin asymmetries, will be compared. Other measurements with systems of different total mass and mass asymmetry would be needed to constrain the isospin dependence of the effective masses and in-medium cross sections and to constrain Coulomb and finite size effects. It is estimated that the total program at RIA could require roughly 2,000 hours of beam time, while at the best competing facilities these experiments will take 10 to 20 times longer due to lower beam intensities.*

Example 7: The primary control points along the r-process path are the nuclei that are thought to possess closed neutron shells (N=50, 82, and 126 are the prime examples). As at these points, beta-decay rates dominate neutron-capture rates, and the r-process slows down and produces the prominent abundance peaks seen in observations. Access to these r-process nuclei, their masses, and half lives, is essential to an understanding of the astrophysical conditions in which the r-process operates as these nuclei determine the timescale of the entire process and the abundance pattern around the abundance peaks. The N=126 nuclei in the r-process are particularly important as they represent the last control point towards the synthesis of lead and the actinides. *RIA will enable measurements of the half-lives of the N=126 r-process nuclei - ^{192}Dy, ^{193}Ho, ^{194}Er, ^{195}Tm, and ^{196}Yb, which are, according to current r-process models, the most important bottlenecks. Most of the important branchings for beta delayed neutron emission as well as mass measurements are also within reach. With these measurements astrophysical models will have a solid nuclear physics underpinning to investigate the synthesis of r-process nuclei in the A~195 peak region and beyond to explain the production of the heaviest nuclei found in nature.*

Example 8: Certain reactions are more critical than others in our understanding of astrophysical events. The reaction ^{15}O(α,γ) results in a breakout of material from the CNO cycle and starts a rapid-proton (rp) process that leads to nucleosynthesis possibly as far as tin. The reaction rate determines the temperature at which break-out occurs, triggering the NeNa cycle in novae or the rp-process in X-ray bursts. Within the current range of uncertainty in this reaction we cannot exclude break-out for high temperature nova explosions and cannot address the question about the on-site production of the observed Ne abundances. X-ray bursts model predictions also depend critically on this particular rate. Recent simulations suggest significant differences in the burst amplitude and sequence depending on the present uncertainties in the rate. *An experimental verification of the predicted low energy resonance parameters in the $^{15}O(\alpha,\gamma)$ reaction is desperately needed. Only RIA will provide re-accelerated beams of sufficient yield (>10^{11} ions/s) to measure the associated resonance strength within the required accuracy*

Example 9: Recent observations of ^{60}Fe activity in the galaxy by gamma-ray observatories underline the production of ^{60}Fe by neutron-induced nucleosynthesis in supernovae. The recently discovered ^{60}Fe enrichment in deep-sea manganese-rich sediments even suggests a nearby supernova explosion about 2-3 million years ago. Reliable understanding of the nucleosynthesis pattern leading to the production of ^{60}Fe requires the knowledge of the $^{59}Fe(n,\gamma)^{60}Fe$ rate. This would eventually enable us to use galactic ^{60}Fe for supernova diagnostics. *A measurement of the $^{59}Fe(n,\gamma)$ reaction is desperately needed. This can be done with isotope harvesting methods taking advantage of the high beam intensity provided by RIA. This experiment would make use of the envisioned low-energy neutron generator for neutron capture measurements.*

Example 10: The ISOL method for rare isotope beam production can provide research quantities of isotopes for medical applications. The method offers both universality in available isotopes and unprecedented purity. The key is the production of useful isotopes in carrier-free form. One recent example of the use of ISOL beams for research on radio-immunotherapy is the development of ^{149}Tb-Rituximab. The radioisotope ^{149}Tb is an alpha emitter with half-life 4.12 h. It has been produced at CERN/ISOLDE by irradiating a Ta target with high-energy protons, and using resonance laser ionization to enhance extraction efficiency. The carrier-free ^{149}Tb was then employed in alpha therapy in vivo for single cancer cell kill [Beyer et al. Eur. J. Nucl. Med. Mol. Imaging 31, 547 (2004)]. *Other potential alpha emitters with attractive half-lives, alpha particle energies, and chemistry are awaiting further exploration at RIA.*

Example 11: The mission of the Stockpile Stewardship Program is to determine the reliability and safety of the aging nuclear weapons stockpile without recourse to a resumption of nuclear testing. Although that mission uses a variety of techniques to accomplish its goals, the experimental basis representing the "ground truth" for all of the techniques is the suite of data collected during the era of underground nuclear testing. This associated physics description may be incomplete (and perhaps inaccurate) because most of the intermediate processes occurring during this extremely rapid transformation have never been measured and the theoretical models that were used in the past to describe these reactions were limited. These processes involve very short-lived isotopes, which will be the domain of experimental programs at RIA. A combination of improved experiment and theory will permit the calibration of the probes to an impressive new level of accuracy, which in turn would improve the data as well as the confidence in the accuracy of that data.

Example 12: Violation of charge-parity symmetry (CP) and, equivalently, time-reversal symmetry (T), is among the most fundamental issues in physics. The last decade has witnessed a large number of experimental efforts directed towards searches for new types of CP-violation or T-violation effects in low-energy phenomena. Thus far, the search for an atomic electric-dipole moment (EDM) has achieved the greatest sensitivity. As already shown in Fig. 4.1, the isotope ^{225}Ra is an especially good case to search for an EDM because of a very large enhancement of CP violating effects due to octupole nuclear deformation. This leads to a sensitivity to T-odd, P-odd effects expected to be 2-3 orders of magnitude larger than in ^{199}Hg, the isotope where the most stringent limits on CP violating phenomena have been set thus far. The relatively long lifetime (14.9 days), and the nuclear spin of 1/2, which eliminates systematic effects due to electric quadrupole couplings, make this radium isotope a good candidate to use laser cooling and atom trapping techniques. *RIA will produce ^{225}Ra at a rate of 3×10^{10} s^{-1}, i.e., at a rate 2-3 orders of magnitude larger than what is available today. This will enable measurements of an EDM with much greater sensitivity. When combined with the effects of octupole enhancements, sensitivity to CP violating phenomena will be increased by a factor of 400 -700.*

APPENDIX B: Reference Material to Section 5

National Security

- Report from the 2000 RIA applications workshop
http://www.lanl.gov/orgs/t/workshop/Proceedings/Workshop_summary.pdf
- L. Ahle et al., Proceedings of International Conference on Nuclear Data for Science and Technology, Santa Fe, NM September 2004, AIP Conference Proceedings 769, p796.
- ACS Symposium on Radiochemistry at RIA, New Orleans, LA, March 2003
http://www.cem.msu.edu/~mantica/radio-ria/

Medical Isotopes

- Report from the 2000 RIA Applications Workshop
http://www.lanl.gov/orgs/t/workshop/Proceedings/Workshop_summary.pdf
- Report from Expert Panel: Forecast Future Demand for Medical Isotopes
http://www.nuclear.gov/nerac/isotopedemand.pdf
- *Isotopes for Medicine and the Life Sciences*, National Academies Press (1995)
http://www.nap.edu/books/0309051908/html/
- ACS Symposium on Radiochemistry at RIA, New Orleans, LA, March 2003
http://www.cem.msu.edu/~mantica/radio-ria/

Materials Science

- *Application Of Low Energy Spin Polarized Radioactive Ion Beams in Condensed Matter Research*, R.F.Kiefl *et al*., Nucl. Phys. News vol.**15**, No.1, (2005).
- µ*SR Studies of the Vortex State in Type-Ii Superconductors,* J.E.Sonier, J.H. Brewer, R.F.Kiefl, Rev. Mod. Phys. vol.**72**, No.3 (2000).
- µ*SR on Muonium in Semiconductors and its Relation to Hydrogen*, K.H. Chow, B. Hitti, R.F. Kiefl, Semiconductors and Semimetals vol. 51A (Academic Press, New York, 1998), p. 137.
- *Studies of Semiconductors,* T. Wichert and M. Deicher, Nucl. Phys A **693**, 327 (2001).
- *Exploring Solid State Physics Properties with Radioactive Isotopes,* D. Forkel-Wirth, Rep. Prog. Phys. **62**, 527 (1999).
- Report from the 2000 RIA Applications Workshop
http://www.lanl.gov/orgs/t/workshop/Proceedings/Workshop_summary.pdf

Nuclear Energy

- Report from the 2000 RIA Applications Workshop
http://www.lanl.gov/orgs/t/workshop/Proceedings/Workshop_summary.pdf
- Workshop on Nuclear Data for the Transmutation of Nuclear Waste, GSI-Darmstadt, September 1-5, 2003 http://www-wnt.gsi.de/tramu/proceedings/salvatores.pdf
- P. Finck et al., Proceedings of International Conference on Nuclear Data for Science and Technology, Santa Fe, NM September 2004, AIP Conference Proceedings **769,** p. 3.

APPENDIX C: List of Acronyms and Abbreviations

AAAS	American Association for the Advancement of Science
BeppoSAX	X-Ray Astronomy Satellite
CERN	European Organization for Nuclear Research (Switzerland)
CNO cycle	Astrophysical carbon-nitrogen-oxygen cycle
EDM	Electric dipole moment
FAIR	Facility for Antiproton and Ion Research at GSI
GANIL	Grand Accelerateur National d'Ions Lourds (France)
GSI	Gesellschaft für Schwerionenforschung (Germany)
ISAC	Isotope Separation and Acceleration facility at TRIUMF (Canada)
ISOL	Isotope Separation On-Line
ISOLDE	On-Line Isotope Mass Separator at CERN
JINR	Joint Institute for Nuclear Research in Dubna (Russia)
LANSCE	Los Alamos Neutron Science Center
MuSR	Muon Spin Resonance Spectroscopy
NIF	National Ignition Facility at Lawrence Livermore National Laboratory
NMR	Nuclear Magnetic Resonance
NQR	Nuclear Quadrupole Resonance
NNSA	National Nuclear Security Administration
NSAC	Nuclear Science Advisory Committee
OMEGA	Laser system at the Laboratory for Laser Energetics of the University of Rochester
QCD	Quantum Chromodynamics
RIA	Rare Isotope Accelerator
RIBF	RIKEN RI Beam Factory Project
RIKEN	Institute of Physical and Chemical Research (Japan)
RXTE	Rossi X-ray Timing Explorer Satellite
SEGUE	Sloan Extension for Galactic Understanding and Exploration, a part of the Sloan Digital Sky Survey
SNS	Spallation Neutron Source at Oak Ridge National Laboratory
TRIUMF	TRI-University Meson Facility, Canada's National Laboratory for Particle and Nuclear Physics
XMM	X-ray Multi-Mirror space observatory mission
Z Machine	Fusion device at Sandia National Laboratories

APPENDIX D: Glossary

Ab-initio: from first principles. A calculation is said to be "ab initio" if it relies on basic and established laws of nature without additional assumptions or special models. *Ab initio* theories of nuclear structure are formulated in terms of realistic inter-nucleon interactions. The corresponding many-body calculations are usually exact or nearly exact.

Accelerator Mass Spectroscopy (AMS): an ultra-sensitive method of trace analysis that is based on ionization and acceleration to energies of several MeV. These energies are higher than standard mass spectrometry techniques and allow for high sensitivities and smaller sample sizes.

Accelerator transmutation of waste systems: a method of "burning" radioactive waste, converting long-lived radioactive products into shorter-lived isotopes, via neutron reactions. These neutrons are generated by a high-power proton accelerator and a spallation neutron target.

Anapole moment: a vector quantity that characterizes the distribution of the current density. A permanent anapole moment is a fingerprint of parity violation. It is present in systems which have both electric dipole and magnetic dipole moments.

Baryogenesis: the physical processes that generated an asymmetry between baryons (protons and neutrons) and anti-baryons in the very early universe.

Beta decay: a process of radioactive decay by which some unstable atomic nuclei spontaneously dissipate excess energy and undergo a change of one unit of positive charge without any change in mass number. Beta decay involves weakly-interacting particles such as electrons and neutrinos.

Beta-Detected Nuclear Magnetic Resonance (Beta-NMR): a technique based on precession of nuclear magnetic moments in magnetic fields. Beta-NMR obtains a signal via the anisotropy of radioactive decay in which the direction of the outgoing energetic electron (beta particle) is correlated with the nuclear spin orientation at the instant of decay.

Beta-Detected Nuclear Quadrupole Resonance (Beta-NQR): a technique similar to beta-NMR where the principal interaction of the implanted radioactive probe atom with nearby atoms and ions is via its nuclear electric quadrupole moment rather than magnetic dipole moment. NQR is thus sensitive to the electric field gradient at the site of the probe atom.

Charge conjugation: (or C-symmetry) a transformation equivalent to changing particles into anti-particles. Like parity (P), and time reversal (T), it is a discrete transformation.

Charge exchange reaction: a nuclear reaction that exchanges a neutron for a proton or vice versa.

CNO cycle: the carbon-nitrogen-oxygen cycle, proposed in 1938 by Hans Bethe, is one of two fusion reactions by which stars convert hydrogen to helium, the other being the proton-proton chain. While the proton-proton chain is more important in stars the size of the sun or less, theoretical models show that the CNO cycle is the dominant source of energy in heavier stars.

Core collapse supernova: the explosion of a massive star (greater than about 10 times the mass of the sun) that produces an extremely bright, short-lived object that emits vast amounts of energy. The iron core that accumulates in the center of such stars at the end of their life collapses and blows off the outer layers of the star. Core collapse supernovae are the source of most of the elements in the universe. The exact mechanism that leads to the explosive ejection of matter is not understood yet. Core collapse supernovae leave behind either a neutron star or a black hole.

CP symmetry: the combination of two symmetries: charge conjugation C and parity P. The strong interaction and electromagnetic interaction are invariant under the CP transformation operation, but this symmetry is slightly violated by weak interaction.

Density Functional Theory (DFT): one of the most popular approaches to quantum mechanical calculations of many-body systems. It is based on a theorem stating that the total energy of a system could be calculated if the spatial distribution (density) of all particles within that system were known. The nuclear energy density functional depends on isoscalar and isovector densities, which are, respectively, sums and differences of proton and neutron distributions.

Double beta decay: a beta decay process in which two neutrons in the nucleus are converted to protons, and two electrons and two (or zero) anti-neutrinos are emitted.

Down or up quark: a first-generation quark with a charge $q=-(1/3)e$ or $q=+(2/3)e$. According to the Standard Model, these two stable quarks are the fundamental constituents of the nucleons; the proton contains two up quarks and a down quark, while the neutron contains one up quark and two down quarks

Drip line: a locus in the N–Z chart of nuclei that separates the last particle-bound nucleus in an isotopic chain (either in neutron rich or proton rich nuclei) from particle-unbound nuclei.

Effective interaction: A derived or parameterized interaction in a many-body system that accounts for short-range and in-medium polarization effects.

Effective Field Theory (EFT): An approximate theory (usually a quantum field theory) that contains the appropriate degrees of freedom to describe physical phenomena occurring at a chosen length scale, but ignores the substructure and the degrees of freedom at shorter distances (or equivalently a higher energy scale).

Ejecta: in astrophysics the term can refer to material expelled in a stellar explosion such as a novae, an X-ray burst or a supernovae. The chemical composition of the ejecta serves as an important diagnostics of the event and its nucleosynthesis.

Electric dipole moment (EDM): a vector that describes the separation of positive and negative charge in a system. A permanent electric dipole moment is a fingerprint of parity and time reversal violation.

Electron capture: a capture of an electron by a nucleus, thus changing a proton into a neutron and a neutrino. By changing the number of protons, electron capture transforms the nuclide into a new element.

Equation of state (EOS): a mathematical relationship between the values of pressure, volume, and temperature of a given substance in thermodynamic equilibrium.

Fragmentation: the name of a nuclear reaction process in which high energy primary beams of heavy ions irradiate targets of light materials such as lithium or carbon to produce short lived nuclear fragments of the primary beams at approximately the primary beam velocity. Fragmentation is the reverse of the spallation reaction.

Fuel cycle: the full life-cycle process of nuclear reactor fuels from the mining process (of uranium or thorium), the isotopic enrichment, chemical and metallurgical processing, operation in the reactor, and processing or storage of waste products.

Functional imaging: the application of medical imaging methods to characterize the time-elapsed behavior of bodily systems.

Gas catcher ion source: high-energy rare isotopes can be decelerated by solid absorbers to low energy and finally slowed to rest in pure helium gas. Rare isotopes stopped in this way remain charged and can be extracted quickly from the helium gas by a combination of electric fields and gas flow. Such a "gas catcher ion source" provides high quality beams of rare isotopes of any element except helium.

Gauge boson: a bosonic particle which acts as a carrier of the fundamental force. In the Standard Model, there are three kinds of gauge bosons – photon, gluons, and W and Z bosons –corresponding to the electromagnetic, strong, and weak forces.

Hadron: a subatomic particle that experiences the strong nuclear force. Hadrons are not fundamental particles, but are composed of quarks and gluons.

Hadronic weak interaction: the weak interaction between quarks or hadrons.

Halo nucleus: a weakly bound nucleus exhibiting a threshold phenomenon in which, due to the low separation energy, the outermost nucleon (or cluster of nucleons) can tunnel into the space well outside the nuclear surface.

Isospin: a symmetry of the strong interaction used to describe groups of particles which have nearly the same properties. The neutron and proton form an isospin doublet, called a nucleon. The third component of the nuclear isospin is one-half of a difference between the number of neutrons and protons. The isospin symmetry in nuclei is slightly broken by the electromagnetic force.

Linac: short for "linear accelerator", which is a device used to accelerate ions or electrons from very low energy to high energies for various applications. This type of accelerator is "straight" and comprises a series of resonators or cavities that provide the energy for acceleration via high frequency electric fields.

Magic numbers: a number of nucleons such that they are arranged into complete shells within the atomic nucleus. The traditional magic numbers as of 2005 are: 2, 8, 20, 28, 50, 82, 126. Nuclei which have both neutron and proton numbers equal to one of the magic numbers are called doubly magic. The discovery of new magic numbers, or the inapplicability of the traditional ones in certain mass regions, is one of the key areas of experimental research with exotic nuclei.

Magnetic multi-layers: tailored materials made up of extremely thin layers of alternately magnetic and non-magnetic metal atoms which exhibit novel electrical and magnetic properties.

Metal-poor star: a term that is used to describe the chemical make up of an object. In astronomy, a "metal" refers to any element heavier than helium. Metal-poor objects are those which contain relatively small amounts of the elements heavier than helium compared to the sun. Since the galaxy gets more metal-rich as time goes on, metal-poor objects are believed to be old.

Muon Spin Relaxation, Rotation, and Resonance (μ-SR): a set of techniques, closely related to beta-NMR, employing beams of muons which are implanted into materials to probe magnetism, dynamic processes, and chemical reactions. Muons are short-lived, sub-atomic particles and can be thought of as heavy, radioactive electrons.

Near-field cosmological structure: Understanding the formation and evolution of galaxies is one of the great outstanding problems of astrophysics. Our galaxy is thought to be the product of past and ongoing mergers of smaller components. Along with the other galaxies of the Local Group, the Milky Way defines a near-field cosmological structure that contains information about how galaxies were born at high redshifts (far-field cosmology). Most of this information resides in the distinct abundance signatures, the nucleosynthesis histories, of the pieces that merged.

Neutrino mixing: neutrinos are always created or detected with a well defined flavor (electron, muon, tau). However, in a phenomenon known as neutrino mixing (or flavor oscillation), neutrinos are able to oscillate between the three flavors. Neutrinos are produced in the sun as electron neutrinos, but the mixture content changes as they travel to the earth. This leads to the observed flux of electron neutrinos from the sun, which is less than that produced by nuclear fusion in the sun's core.

Neutron skin: the excess of neutrons on the surface of a neutron-rich nucleus. The neutron skin thickness is given by a difference between the neutron radius of a heavy nucleus and the proton radius.

Neutron star: one of the few possible endpoints of stellar evolution. A neutron star is formed from the collapsed remnant of a massive star. A typical neutron star has a mass around 1.4 solar masses, with a corresponding radius between 10 and 20 km. Neutron stars have a thin crust made of ordinary matter. Their interior composition is mostly neutrons with admixtures of other particles. The composition at the highest density near the center is uncertain.

Novae: explosions on the surface of white dwarfs that accrete matter from a nearby companion star. The nova is observed as a dramatic brightening of the star that lasts on the order of months and is thought to reoccur on timescales ranging from decades to 100,000 years. Novae are triggered by explosive nuclear burning of hydrogen. The ashes of the burning are ejected into space where they can be observed and analyzed.

Nucleon: a collective name for the two baryons, a neutron and a proton.

Nucleosynthesis: the process of creating atomic nuclei by nuclear reactions. There are a number of processes that are believed to be responsible for nucleosynthesis in the universe, the forerunners being stellar fusion reactions, and the r-, s-, and p-processes.

Oblate nucleus: a nucleus with flattened (disk like) shape.

Optical pumping: a technique that transfers the angular momentum from a circularly-polarized laser beam to atoms and nuclei.

Pairing: is a collective phenomenon occurring in nuclei, similar to superconductivity in metals. It is caused by the attractive part of the effective interaction that couples nucleons into "Cooper" pairs. The most important pairing phases are associated with pairs of neutrons or protons coupled to zero spin or proton-neutron pairs with spin one.

Parity: a transformation that creates the mirror image of a physical system. Parity (or P-symmetry) is not a symmetry of the universe. Although it is conserved in electromagnetism, the strong interactions, and gravity, it is violated in the weak interactions. The presence of an electric dipole moment or an anapole moment signals parity violation.

Positron emission tomography (PET): a method of medical imaging where radioisotopes decaying by positron emission are injected into a patient and used to pinpoint unusual cell activity.

Prolate nucleus: a nucleus with elongated (American football-like) shape.

Quantum Chromodynamics (QCD): the theory of the strong interaction. QCD describes the interactions of quarks and gluons; it forms an important part of the Standard Model of particle physics.

Radio-immunotherapy: a treatment of cancerous tissues by designer chemical compounds that specifically target cancer cells and which also contain particle-emitting radioisotopes for cell destruction.

Re-accelerated beam: a mode of operation for a rare isotope facility based on creating the short-lived isotopes at rest via irradiation of targets with beams from a primary or "driver" accelerator, and then using a second or "post" accelerator to create beams of these rare isotopes at the energies required for nuclear science or other applications.

r-process: (r for rapid) a neutron-capture process that occurs under conditions of high neutron density. In the r-process, nuclei are bombarded with a large neutron flux to form highly unstable neutron-rich nuclei. The r-process is thought to produce about half of the naturally occurring elemental abundances beyond iron, but its site is still uncertain.

rp-process: (rp for rapid proton) a proton-capture process that occurs under conditions of high proton density and high temperature. In the rp-process, nuclei are bombarded with a large proton flux to form highly unstable proton-rich nuclei. The rp-process is the energy source of most X-ray bursts and may under certain conditions also occur in novae and supernovae.

Shell structure: in the nuclear shell model, the nucleons populate energy levels forming shells; once a shell is filled, there is a significant drop in the binding energy for the next nucleon added. The shells are created by an average potential resulting from the mutual interactions of all nucleons.

Schiff moment: a kind of radially-weighted dipole moment that characterizes a displacement of charge that varies with the distance from the center of the nucleus. A permanent Schiff moment is a fingerprint of parity and time-reversal violation.

Spallation: a nuclear reaction process in which high-energy light ion beams such as protons or deuterons irradiate thick targets of heavier materials to produce rare isotopes at rest.

Spin relaxation: a population of nuclei, initially with their angular momenta ("spins") highly oriented in one direction, is said to be spin-polarized. Differences in magnetic field experienced by each spin, whether from static inhomogeneity throughout a sample, or dynamical processes, will result in a reduction in the degree of polarization. The spin polarization is then said to undergo relaxation toward its equilibrium value, usually zero.

s-process: (s for slow) a neutron-capture process that occurs under conditions of lower neutron density and lower temperature than the r-process. Unlike the r-process, the s-process tends to produce stable isotopes that are less neutron-rich. The s-process is believed to occur in stars larger than Earth's sun, most notably red giant stars.

Standard Model: a quantum field theory that describes the strong, weak, and electromagnetic fundamental forces (but not gravity), as well as the known fundamental particles that make up all matter.

Strangeness: a quantum number needed to describe certain short-lived particles. Strangeness is conserved by the strong and the electromagnetic interaction, but not by the weak interaction.

Stockpile Stewardship Program: the NNSA program to insure the reliability of the nation's nuclear stockpile by using theoretical models and archived test data to predict the current performance of weapons in the stockpile. The program aims to improve our understanding of nuclear explosions by improving the quality of theoretical models and the physical data used in the simulations.

Superallowed beta decay: a beta decay connecting very similar initial and final states. Most of those of interest for probing the Standard Model occur between spin-zero states in mirror nuclei.

Superconducting driver accelerator: a high power primary accelerator or linac to be employed for the production of rare isotopes. In a superconducting linac, the acceleration of the particles is provided by electric fields in a series of superconducting resonators.

Superconducting resonator: high frequency electric fields that are used in superconducting linear accelerators to create high energy beams of ions or electrons are provided by superconducting resonators. Such resonators or cavities are typically constructed from niobium, a metal that is superconducting at liquid helium temperatures.

Surrogate reactions: a technique for obtaining physical data about a nuclear reaction by the use of another nuclear reaction. This technique exploits the fact that, at low energies, most nuclear reactions proceed through an excited compound nucleus that equilibrates before decaying. Thus, if the same compound nucleus is created via a second reaction, information can be obtained about the first reaction. This technique will be important at radioactive ion beam facilities to gain insight into neutron reactions on very short-lived species.

Three-body force: a force that does not exist in a system of two objects, but appears in a system of three objects. There is growing evidence that three-body forces exist among the nucleons inside atomic nuclei. Nuclear three-body forces arise due to the fact that the nucleon is a composite particle made of quarks and gluons.

Time reversal: (or T-symmetry) a transformation that corresponds to reversal of motion. The universe is not symmetric under time reversal because T-symmetry is violated by the weak interaction. However, the CPT symmetry that involves the inversions of charge, parity, and time simultaneously is believed to be a fundamental symmetry of physical laws.

Type Ia supernova: (also called thermonuclear supernova or white dwarf supernova) a thermonuclear explosion of a white dwarf star that produces an extremely bright, short-lived object that emits vast amounts of energy. Type Ia supernovae are distinguished from core-collapse supernovae by a lack of hydrogen and helium and the presence of a silicon absorption line in their spectra near peak brightness. Type Ia supernovae are thought to be the result of a white dwarf accreting matter from a nearby companion star, typically a red giant, until the white dwarf reaches a fundamental mass limit. Fusion of carbon in the dense core triggers a thermonuclear explosion that incinerates the white dwarf. Type Ia supernovae are used to measure the distance to faraway galaxies.

Weak current: a weak-interaction generalization of an electric current. The charged weak current is carried by the $W_{\pm}$-bosons while the neutral Z-boson carries the neutral weak current.

White dwarf: is produced when a low or medium mass star dies. These stars are not heavy enough to generate the core temperatures required to fuse light elements all the way to iron. After they have become a red giant during their helium- or carbon-burning phase, they will shed their outer layers to form a planetary nebula, leaving behind a dense inert core consisting mostly of either carbon and oxygen or neon and oxygen.

X-ray burst: a flash of X-rays caused by the explosion of accumulated hydrogen-rich matter on the surface of a neutron star. X-ray bursters are a class of binary stars, which have periodic outbursts luminous in X-rays. They contain a neutron star and an accreting companion. In most cases, hydrogen-rich material from the companion accretes onto the surface of the neutron star. After enough of this material accumulates, fusion reactions ignite and the accreted layer explodes. The resulting spike in X-ray luminosity is called an X-ray burst. These X-ray bursts typically re-occur on an hourly to daily basis.

Z-boson: the neutral gauge boson of the weak interaction.