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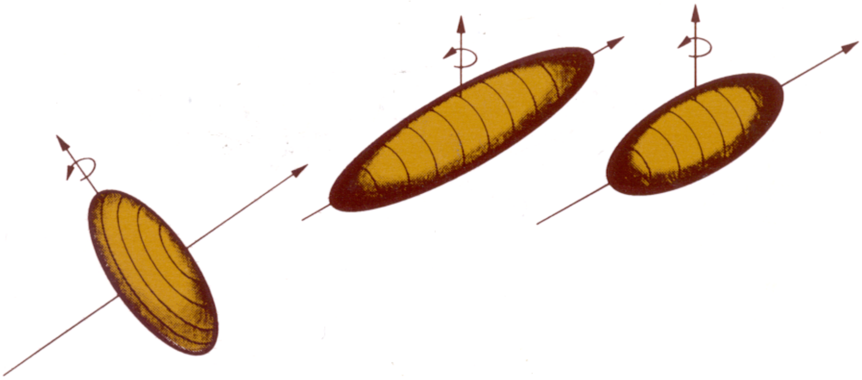

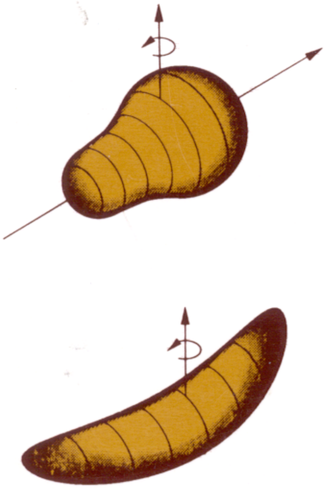

The IsoSpin Laboratory

Research Opportunities with Radioactive Nuclear Beams

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The IsoSpin Laboratory (ISL)

Research Opportunities with Radioactive Nuclear Beams

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PROLOGUE

Over the last several years, intense worldwide interest has developed in radioactive nuclear beams (RNBs) and the scientific opportunities they offer. This activity was reflected in the discussions reported in the 1989 Long Range Plan for Nuclear Science [LRP89]. Two recent major international conferences, at Berkeley [Mye90] and Los Alamos [McC90], have been devoted to the scientific and technical issues in RNB science and to the recognition that this field promises a bright future in significant areas of nuclear physics, astrophysics, and atomic and materials science. This recognition is already embodied in the existence of several facilities worldwide and proposals for a number of others. Some of these facilities are first-generation projects that will produce an impressive variety of RNBs and provide valuable access to many physics possibilities. Other facilities that will come on-line late in the decade will address the entire range of the science. In addition, extensive R&D work—planned and in progress—seeks to resolve key technical issues or assess the viability of different methods of production and acceleration of RNBs.

As an outcome of the Los Alamos National Laboratory (LANL) meeting, a North American Steering Committee was formed to determine the scientific case for RNBs, survey worldwide efforts in this field and, based on these assessments, make recommendations concerning the possibility of a dedicated North American facility for intense, high-quality beams of radioactive nuclei. A USERS group has also been formed and polled concerning their interests. This group of about 300 scientists, primarily from the nuclear physics community, represents only a portion of those who are interested in RNB science and its future. The USERS group comprises a broad array of research interests and expertise, which points toward the need for a broadly based facility that is highly flexible and capable of a large variety of experiments.

The Steering Committee's assessment of USER needs and its own sense of the scientific possibilities with RNBs is embodied in the present document. The following text summarizes some of the rich variety of scientific opportunities and leads to a strong recommendation for the construction of an accelerator complex [denoted the IsoSpin Laboratory (ISL)], which would be based on the ISOL production method and would produce accelerated RNBs with intensities up to 10^{11} part./s. The ISL would complement existing and planned RNB facilities both here and abroad [many of which use the Projectile Fragmentation (PF) method in research that focuses on studies with higher energy beams]. The ISL would provide the greatest variety and most intense source of accelerated RNBs—from the lightest nuclei to the actinides—at energies ranging up to the Coulomb barrier and beyond. These beams would be suitable for studies in nuclear structure, nuclear reactions, astrophysics, atomic physics, and materials science; they could be used in decay studies, for the accumulation of radioactive targets and, especially, to initiate secondary reactions. The ISL would place the North American scientific community in an excellent position to participate in and exploit a strong growth area in nuclear physics and allied subjects and to assert a leadership role in this field.

The text in the following pages consists of a summary and set of recommendations, an overview of RNB science, a review of the scientific possibilities offered by RNBs, and a discussion of facility options and production methods (primarily the ISOL and PF approaches). The facility discussion outlines a conceptual plan for the ISL, including a description of a BenchMark Facility (BMF) that achieves the scientific goals envisioned; this discussion also incorporates a summary of worldwide efforts in RNB science and R&D.

It should be emphasized that this document is a starting point, not a final statement. Without doubt, new scientific opportunities available through the use of RNBs will be recognized and on-going RNB research will reveal new capabilities, more realistic assessments of what is possible, and perhaps wholly new directions as well. Continued R&D will certainly lead to an evolution of the ISL concept as a greater understanding of the production and acceleration of RNBs is gained. The BMF discussion in this document is intended primarily to show that a technologically feasible approach does exist. The actual methodology and design of the ISL will depend to a great extent on the laboratory at which it is built and, in particular, the nature of its pre-existing accelerators and the local infrastructure.

We hope that the present efforts will help stimulate community interest and discussion leading to the advancement of an ISL proposal. Questions or comments on this document should be addressed to members of the Steering Committee.

SUMMARY AND RECOMMENDATIONS

SUMMARY

The burgeoning field of Radioactive Nuclear Beam (RNB) research is one of the most exciting developments in nuclear science in the last few years and offers the promise of revealing wholly new horizons for this and related topics. The advent of RNBs may rival or surpass, in its impact on nuclear physics, other great technological strides from past decades such as the proliferation of heavy-ion beams in the 1960s. The following pages discuss the rich and varied scientific case and present a conceptual plan for a dedicated North American Radioactive Nuclear Beam facility, which we call the IsoSpin Laboratory or ISL. The discussion of the scientific program, in Chapter II, focuses on nuclear structure, low-energy nuclear reactions, astrophysics, and atomic physics and material science. Chapter III includes an assessment of realistic facility goals and performance specifications, a survey of the worldwide RNB scene, and an outline of one possible realization of the ISL—denoted the BenchMark Facility (BMF). The BMF illustrates that within the framework of the ISOL (Isotope Separation On-Line) approach and current technology, it is possible to achieve the design criteria.

As noted in the Prologue, we view this document as a step toward the realization of the ISL, but not as a final statement of either the science or the facility. For example, the final design details of the ISL will not be those of the BMF but will include modifications that will be dependent on any pre-existing accelerators at the particular site where it is built and the infrastructure of the host laboratory.

We strongly encourage active discussion in the scientific community concerning what we feel is an uncommonly exciting opportunity. The Steering Committee that produced this document has limited resources and areas of competence. Wide-ranging community discussion will certainly disclose many other equally interesting and exotic scientific opportunities afforded by RNBs and will refine the facility concept as well. Because RNB science is a new field in which both scientific and technical ideas are rapidly developing, this process will enhance the scientific attractiveness of the ISL.

As will be evident in the chapters that follow, the scientific opportunities afforded by RNBs are both exciting and myriad. It is extremely difficult to describe them all in a reasonably sized document and impossible to summarize them in several pages. Picking and choosing a few highlights can give a misleading impression about the breadth of the novel physics made accessible by RNBs, and not everyone will concur in the choice of highlights. Nevertheless, in an effort to focus on a few central themes, we cite in this summary some of the innovative ideas that can be addressed by a dedicated RNB facility such as the ISL.

First, however, it is appropriate to outline our concept of the ISL, which is discussed in detail in Chapter III. This facility is envisioned as an extremely broad range and flexible multi-accelerator complex (portions of which may already exist) that will provide intense RNBs ranging in mass from the lightest elements to the actinides, at currents up to 10^{11} part./s at energies from a few keV to ~10 MeV/u. The conceptual plan foresees a primary (production) accelerator capable of providing up to 100-μA (or greater) beams of protons (or possibly other light ions), at an energy between 500 MeV and 1 GeV, that impinge on a ~1-mole/cm^2 target and produce a wide spectrum of radioactive species. (One option that should also be considered—at least as an alternative for specialized production of some elements—is a thin-target approach, which has both advantages and disadvantages when compared to the thick-target concept.) The radioactive nuclides produced in the target matrix will diffuse and desorb from it and then be ionized in an ion source, pre-accelerated, and formed into a beam that will be separated in a high-resolution isotope/isobar separator. These low-energy separated ions can be used directly in some experiments (especially in astrophysics and material science), or they can be accumulated to serve as radioactive targets. In most cases, however, they will be accelerated—probably in two stages: first to ~1.5 MeV/u (an interesting energy range for astrophysics experiments) and then up to 10 MeV/u. Although this concept appears feasible with current technology, several important components (especially those relating to target heating, radiation, and release processes in the target-ion source) have yet to be tested, especially at high primary-beam currents. These issues, as well as other important and much-needed R&D efforts and demonstration experiments, are also discussed in Chapter III. The beams obtained from this accelerator complex will provide a rich arsenal of probes that can be used to initiate further scattering or reaction processes and, thus, open up the full panoply of the science described in the following chapters. Figure 1 gives an indication of the RNBs that will be produced at the IsoSpin Laboratory (ISL) and dramatically shows the expansion of our vistas.

In generic terms, several qualitative features of RNB nuclear science make it so enticing.

- *Few-body quantal system.* The nucleus is a unique finite-body quantal system in which a few (mostly valence) nucleons dominate the structure and its evolution with N and Z. Because of this fact, our knowledge and understanding of this system depend on the examples that are accessible for study. Near stability, our view of this evolution is restricted. By using RNBs, we will be able to expand these horizons enormously through access to extended isochains of nuclei. This access allows the number of active nucleons—and (because of the Pauli principle) the orbits they occupy—to be radically altered and will permit us to study important residual interactions, such as the T=0 p-n interaction, in new orbits and combinations of orbits not accessible near stability. This versatility will lead to a new understanding of nuclear residual interactions and nucleonic correlations (and consequently, the nuclear shell model itself) of the evolution of structure in a finite body system as a function of the number and quantum states of its constituents.

- *Access to specific exotic orbits.* This access will reveal new nuclear shapes and new kinds of collectivity, including such possibilities as hyperdeformation, "banana" shapes, $\Delta l = 5$ modes, and extreme examples of quantal localization. Of particular interest will be the

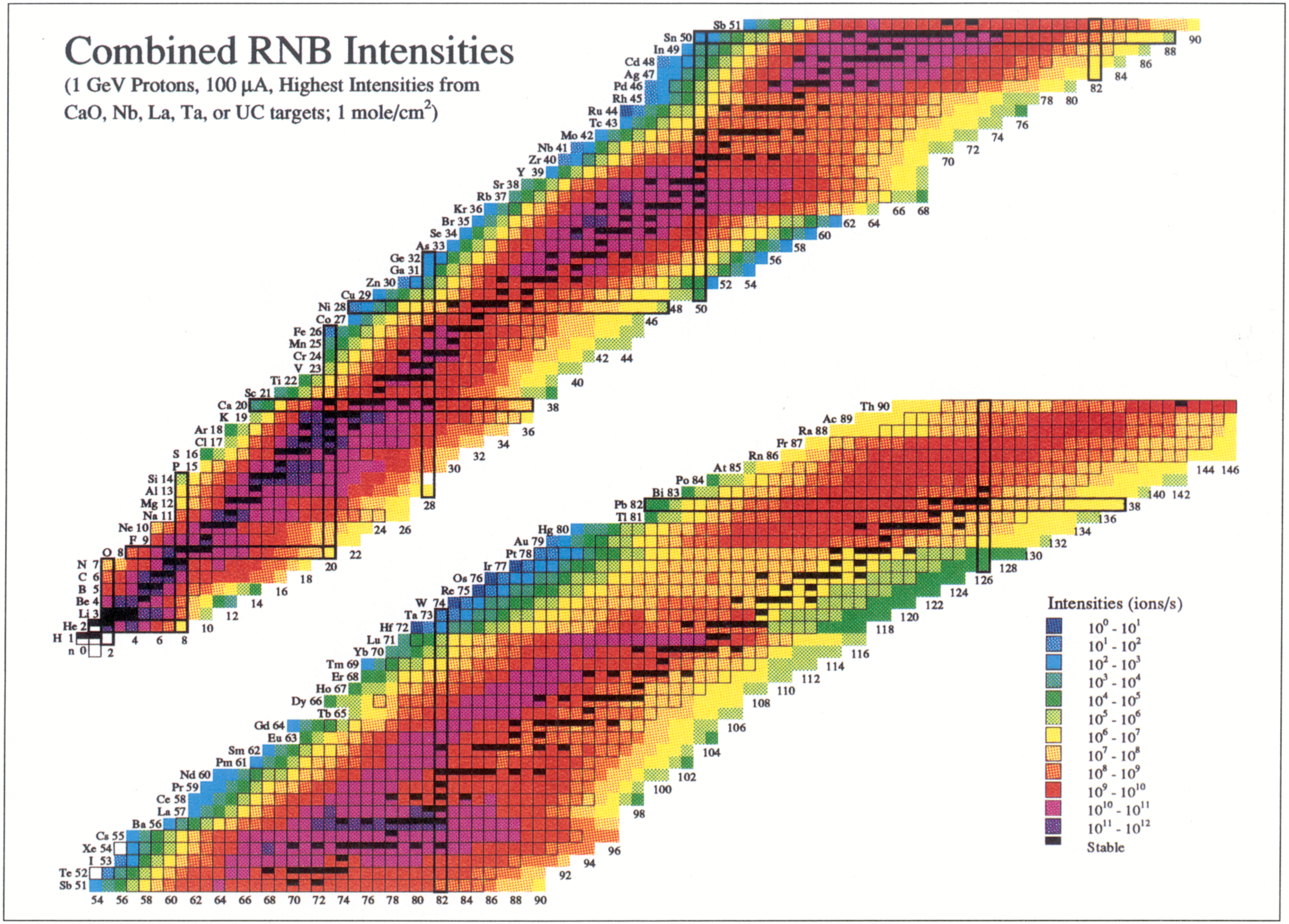

Fig. 1 An illustration of the radioactive beams that can be produced at the ISL. Indicated are all isotopes that should be produced by 1-GeV 100-μA proton beams impinging on 1-mole/cm^2 targets of CaO, Nb, La, Ta and UC, according to the calculations discussed in Chapter III. The intensities are identified by colors shown in the color legend at the lower right. Nuclei still further from stability can be produced by using these beams to initiate secondary reactions.

highest attainable j orbits (e.g., $\nu\ 1k_{17/2}$) because these are critical to many of the above correlations as well as to the possible existence of superheavy nuclei.

- *Exotic matter distributions at extreme N/Z ratios.* Especially on the neutron-rich side, RNBs will provide access to fascinating density distributions such as neutron halos with their abundance of intriguing features. If neutron matter is bound, or only slightly unbound, a wealth of exotic shapes and topologies (or their precursors) may occur near the drip lines.

- *Access to special nuclear regions.* It will only be with the advent of advanced RNB facilities that we will be able to study regions such as the nuclei near (probably doubly magic) ^{100}Sn, the enigmatic N = Z sequence from ^{80}Zr to ^{100}Sn, new phase-transitional regions, and possible regions of extra stability among superheavy nuclei.

- *Access to special states.* RNBs will provide unique opportunities to observe and study certain states that only occur in nuclei with extreme N/Z ratios and to populate other states by exploiting the high Q values that characterize reactions with RNBs far from stability. For example, in neutron-rich nuclei accessible with RNBs, higher spin states than usually studied may be stable against fission. Also, studies of the transition from order to chaos will be facilitated, and new possibilities to observe exotic decay modes (multinucleon or even cluster decay) can be expected.

- *Exploitation of new features in nuclear reactions..* In neutron-rich nuclei, the presence of neutron halos that extend to tens of fermis from the core will enhance new reaction processes occurring at much larger interaction distances than those currently attainable. Reactions with halo nuclei will lead to exotic phenomena such as neck formation in fusion reactions, neutron flow phenomena, multinucleon transfer, high Q values (stemming from the weakly bound nature of the outermost valence nucleons) that can lead to further cross section enhancements, and special reaction channels such as enhanced fission-fusion channels that become available with RNBs like those near ^{132}Sn. In proton-rich nuclei, reactions should be possible with species extending fully out to the proton drip line—from very light to rather heavy nuclei. Moreover, special reactions, such as charge-exchange reactions in heavy mirror nuclei, will become possible for the first time.

- *Astrophysics-nucleosynthesis.* In explosive stellar events, nuclear processes occur far from stability. Only with RNBs can these reaction processes be studied in the laboratory. Determination of key nuclear parameters (such as reaction rates, half-lives, masses, and β-decay Q values) for nuclei involved in the rp-, s-, p-, and r-processes will help fix the site, environment, and time scales for the explosive stellar events leading to nucleosynthesis. Although nucleosynthetic processes entail only a small fraction of the energy economy of explosive stellar phenomena, the study of these processes with RNBs will give tremendous leverage in constraining our understanding of their nature and the time evolution of these dramatic events.

- *Atomic physics and material science.* There are many applications for RNBs in these fields, some of which are summarized in the sections to follow. A large number of these applications exploit the highly variable nature of RNBs because one is able to choose, for a given element, different half-lives, decay energies, bombarding energies, and intensities. For example, in the area of doping phenomena, RNBs will allow selectivity of the half-life of the dopant and therefore will enable the study of time-delayed chemical transformations as well as allow the accumulation of comparable data with much lower "dose" rates. These low dose rates have obvious advantages, not only in medical applications, but also in material science because dopant ions can come to rest in undisturbed host environments. It will also be possible to study Mössbauer effects, hyperfine interactions, polarization phenomena, and chemical effects on atomic structure through time-delayed conversion electron studies.

The above highlights provide an overview of the exciting scientific opportunities available with RNBs; the full text in Chapters I and II offers a more detailed discussion, including many specific examples of the ideas summarized above.

RECOMMENDATIONS

I. In view of the exceptional scientific opportunities afforded by RNBs, the intense and rapidly developing worldwide interest in them, and the current technological situation, in which the realization of an RNB facility such as envisioned for the ISL is feasible, ***our principal recommendation is that the North American nuclear physics community should seriously pursue the construction of a dedicated, flexible, broad-range RNB facility that would provide intense beams of nearly all elements up to energies of ~10 MeV/u for a program of scientific studies in nuclear structure, low-energy nuclear reactions, astrophysics, and atomic and material science.*** Although the ISL would ultimately be built at a particular site, we hope for and encourage a multilaboratory collaborative approach to establish the facility and to investigate the R&D issues surrounding it. A conceptual plan for such a facility, and one possible realization of it, is provided in Chapter III. Some of the scientific opportunities available with the ISL were listed above and are discussed in detail in Chapters I and II. The ISL will complement existing and proposed RNB facilities and will allow this community to participate in what is clearly a major growth area of nuclear (and allied) science research. A large, enthusiastic and dedicated group of more than 300 North American scientists (and others who would use a North American facility) belong to the ISL USERS Group. This group is ready and eager to exploit the research opportunities of the ISL. Realization of the ISL will ensure that the North American scientific community plays a major role in the scientific and technological developments that will surely ensue in this field.

II. To further assess and develop our understanding of the potential of RNB science, to stimulate new ideas for RNB research, to provide a venue for initial RNB research, to foster the entry of young scientists into the field, and to gain experience with the specialized experimental techniques and detection devices that the field requires, ***our second recommendation is that we strongly support the pursuit of RNB research at existing facilities and encourage the construction and operation of first-generation ISOL RNB facilities.*** Through these efforts, we will be able to address some of the exciting physics questions in the RNB field, delineate new ones, and resolve many technical issues that will enhance the research potential of the ISL. This near-term issue is of high importance: the essentially new field of RNB science cannot be expected to suddenly appear in mature garb upon the advent of a completed ISL; an evolutionary scientific and educational process is critical.

III. To enhance the future capabilities of the ISL, ***we recommend another equally important component of this process: an active and on-going R&D effort*** in many technical areas related to the production, separation, and acceleration of RNBs that employ the ISOL post-acceleration method as well as RNBs in experiments. It is important that this R&D effort proceed immediately so that technological issues related to the planning and design of the ISL can be even better understood and possible improvements to the design concept can be incorporated in a timely fashion. Important aspects for this R&D effort center on the use of intense primary beams and thick targets, including the study of beam heating, target handling with high levels of radiation, and target/ion source stability in such radiation fields. The productivity of the ISL will be enhanced by the study of optimal target configurations (e.g., solid, porous, pellets, molten, sectioned, granular, etc.) and operating temperatures (which may be element-dependent), the diffusion-desorption processes in and from these targets, and new designs of highly efficient ion sources to prepare the radioactive species for subsequent acceleration. Yields of mass-separated beams with the gas jet/thin target approach also require careful study. An equally important R&D area concerns the structure of the first, low-β acceleration stages and the choice between room-temperature or superconducting strategies. Finally, advances in radioactive target techniques and the development of specialized experimental equipment that is characterized by high detection efficiency and large background rejection ratios are also key areas; indeed, this development is one of the motivations behind the research supported by our second recommendation.

We feel that the successful pursuit of the objectives embodied in these recommendations, which will culminate in the construction of the ISL and the initiation of its research program, constitutes one of the most exciting and potentially rewarding scientific opportunities in nuclear science for the next decade.

I. OVERVIEW OF RADIOACTIVE NUCLEAR BEAM SCIENCE

THE SCIENCE

The nucleus is a unique system: it is neither a set of noninteracting single bodies nor a true many-body environment. Rather, it is a few-body system whose single-particle structure, nucleonic correlations, and excitation modes depend not only on the specific orbits of its active constituents, but also on their number, which can vary rapidly across a series of nuclei. This system provides a quantal laboratory that is unavailable in other physical systems and leads to a richness of phenomena not observed in other fields. Arguably, the most pervasive and dramatic facet of nuclear structure—evolving from its single-particle basis and residual interactions—is the correlation among nucleons, the collective modes to which this correlation leads, and the evolution of that collectivity. The finite degeneracy of nucleonic orbits (a consequence of the Pauli principle for fermions) forges an irrepressible link and interplay between single-particle and collective degrees of freedom that are at the heart of many key issues in nuclear physics. This interplay endows the nuclear world with a rich phenomenology and has spawned a wealth of models—many macroscopic—to correlate these properties.

In parallel to these phenomenological models, microscopic nuclear theory has made great advances: many-body mean-field approaches now give a rationale for single-particle energies and the magic numbers applicable to nuclei along the valley of stability. The shell model, with residual interactions where tractable, provides a microscopic model for nuclear-ground state properties, simple excitations, correlations, and even collectivity. Yet these approaches are seldom tested outside the nuclear realms near stability in which they were incubated. Their applicability at the limits of stability has only been sporadically tested—and even then, mostly in the lightest nuclei.

The limitations in our understanding of the nucleus and its interactions reflect our narrow *empirical* purview of the nuclear landscape, which—in practice and with but a few exceptions—is restricted to stable nuclei and very specific classes of unstable species. Today, nuclei far from stability are primarily produced and studied with techniques such as heavy-ion fusion evaporation reactions (primarily for proton-rich species) and fission (primarily for neutron-rich species). Yet the constraints of these techniques in A, N, and Z are rapidly becoming apparent and limiting. Because the only avenue available to surmount this barrier of accessibility is exploitation of the unique advantages of *radioactive nuclear beams* (RNBs), there is intense worldwide interest in facilities that provide such beams. This interest is enhanced by the fact that nuclear properties manifest themselves in the cosmos and are used in a variety of applications in atomic and applied physics and medicine. All these fields will benefit from full exploitation of RNBs.

The reason our currently constricted horizon has such an impact on our science stems directly from the aforementioned few-body aspect of the nuclear environment and the nucleon orbit dependence of the interactions and correlations that dominate the evolution of structure and collectivity. Near stability, the number of active nucleons can only be changed by small amounts, and only a few orbits can be populated. If we had access, however, to a much wider span of nuclei, extending far from stability, many new opportunities would be presented, new phenomena would be disclosed, and many experimental techniques could be exploited anew and more potently. Beams of radioactive nuclei are precisely the tool that will lift the veil on these new vistas.

While low-energy RNBs can, of course, be studied as exotic nuclei in their own right, their real power is revealed when they are *accelerated* and used to initiate secondary reactions. In this way, one can study the reactions themselves, which reveal new processes, topologies and flow patterns, significant enhancements of various processes, and favorable energetics. They allow access to information on heretofore unavailable outer reaches of the nuclear potential. Alternatively, these reactions can be exploited either to make and study new nuclei still farther from stability or to produce excited states of the RNBs themselves.

These beams provide us with the ability to radically alter and sequence through both the *number* of active nucleons and the *orbits* they occupy, accessing long iso-chains and exotic configurations—thus offering a completely new vista on the evolution of nuclear structure. On the proton-rich side, fusion evaporation reactions of lighter proton-rich RNBs can lead to substantial production of heavier nuclei even farther to the left of the line of stability and provide entry to nuclear phenomena that extend fully from stability to the drip lines and even beyond. On the neutron-rich side, nuclei farther from stability can be produced by means of single- or multineutron transfer reactions through the use of light neutron-rich RNBs to bombard the heaviest stable isotopes of other elements. Access is thereby given to nuclei that range from exotic species with neutron halos to the heaviest, and possibly superheavy, elements. Moreover, it is natural and profitable, with radioactive beams, to invert the normal reaction process, impinging the RNB on a light target to exploit many of the appealing features of inverse kinematics (e.g., forward-focusing, high-efficiency, and large Doppler shifts). Also, the extremely weak binding of the last nucleon (e.g., a neutron) far from stability leads to high reaction Q values and, often, to substantial enhancements of cross sections because the last nucleons extend to large radii.

There are two overlapping but partly distinct aspects of nuclear structure that will be disclosed by using RNBs. The first aspect centers on new classes of nuclei and wholly new exotic phenomena that can only occur for extreme N/Z ratios or can only be studied in nuclei made available with RNBs. For example, using RNBs will provide an opportunity to produce and study the heaviest elements, perhaps locate the long-sought island of superheavy nuclei, gain access to high-spin states and complete spectroscopy in special nuclei near stability, exploit extraordinarily high Q_β values for studies of hot nuclei and the transition from order to chaos, observe multiparticle and even cluster decay modes, and reach special states otherwise inaccessible. However, perhaps the most obvious and intriguing of these new phenomena occurs in extremely neutron-rich nuclei, where the weak binding of the outermost neutrons leads to the concept of neutron halos, which are regions of nearly pure neutron matter. Studies of these halos will have ramifications for a whole gamut of topics, including the binding (and other) properties of neutron matter and the nuclear equation of state, nuclear medium effects, fascinating new nuclear reaction possibilities, and excitation modes of extremely weakly bound systems, including possible implications for r-process nucleosynthesis. Other topologies involving significant density fluctuations, such as Coulomb redistribution (proton bubbles), can also be imagined, in as much as they depend sensitively on the binding or near-binding properties of neutron matter.

The second aspect discernable by using RNBs focuses on new varieties of the single-particle and collective modes that have long been the domain of nuclear structure. New orbit combinations (for example, of protons and neutrons) are not just "more of the same" but will expose wholly new interactions that are interesting for the light they can shed on residual interactions and for the role they play in the evolution of collectivity; new forms of correlations, shapes, and collective modes; and new types of phase transitions at both low and high spin. RNBs will also provide new ways to exploit these phenomena in dynamic processes such as decay and transfer reactions.

New phenomena and ideas will often emerge only from sophisticated experiments involving the full arsenal of modern experimental techniques such as arrays of high-resolution γ-ray detectors or recoil mass separators. However, it is a fortunate aspect of nuclear physics that often the most readily available observables, namely the mass, excitation energy of the lowest states [e.g., the 2^+_1 and 4^+_1 states in an even-even nucleus], and a few key B(E2) values [e.g., B(E2:$0^+_{gs} \rightarrow 2^+_1$)] are excellent signposts of structure. Therefore, simple experiments that measure even these few observables for a plethora of currently inaccessible new nuclei far from stability can also provide an enticing opportunity that should lead us much further toward understanding the microscopic nuclear laboratory and enable us to resolve innumerable key issues (while doubtless raising others).

In nuclear reaction studies, RNBs provide a fascinating tool that opens vast new areas and can entail entirely new reaction processes. The most obvious aspect is simply that *each* RNB can be used to initiate any number of reactions, generally by exploiting the very favorable features of inverse kinematics in which the RNB and target play roles opposite their usual ones in traditional studies of stable nuclei. Where we are now almost always limited in nuclear reactions to stable or long-lived targets, this limitation suddenly vanishes with RNBs. Moreover, just as has been the case for angular momentum, the capability to stress the nucleus toward extremes in N and Z and observe its response will produce remarkable new phenomena in both nuclear structure and nuclear reactions.

However, besides this, RNBs also offer qualitatively new features. Many of these result from the very weak binding of the outermost nucleon far from stability. This binding translates into wave functions that are spatially very extended and allows reactions to take place at what have previously been impossibly large interaction distances. This feature is interesting in itself because it leads to intriguing phenomena such as the free flow of neutrons in sub-barrier fusion reactions (which promotes neck formation) and to greatly enhanced fusion or multinucleon transfer cross sections. However, this aspect is also important because of the role it will play in elucidating the outer structure of the nuclear optical potential (its diffuseness and skin thickness) and minimizing the obscurantist role of competing processes (e.g., Coulomb excitation). The same weak binding also provides reactions with large Q values, which can be useful in achieving selected matching conditions, enhancing cross sections, and facilitating access to a large variety of final states and exit channels. Finally, the use of RNBs with specific structure (e.g., the doubly magic ^{132}Sn nuclei) will enable studies of special new fusion-fission channels that may allow enhanced access to some of the heaviest elements. RNB bombardment of the heaviest stable targets can involve the transfer of nucleons into exotic, highly localized quantal states—interesting for both understanding the corresponding reaction mechanism and locating and studying such states.

In astrophysics, RNBs are part of the very fabric of the science because the stellar objects of interest are essentially RNB laboratories themselves. Most of the key astrophysics processes, especially nucleosynthesis, take place along paths through the nuclear chart that lie far from stability. In many cases, it is only with RNBs that these processes can be studied. Measurements of cross sections and reaction rates are central to determining both the nucleosynthetic path and the energy economy of stellar objects. Studies with accelerated RNBs will have a catalytic impact on astrophysics by helping to unravel stellar nucleosynthesis and the evolution of stellar energy production during explosive events. Measurements of β-decay half-lives far from stability—especially of a few critical nuclei—will help pin down the time scales for supernova processes as well as other explosive stellar or galactic phenomena. By establishing specific nuclear parameters, it will be possible to reduce the other uncertainties in various stellar models and processes. Finally, RNBs will aid the burgeoning field of γ-ray observational astronomy because the interpretation of such data, which is currently being collected, requires a knowledge of both the abundances of long-lived isotopes produced in nuclear reactions and the decay processes of short-lived isotopes in various stellar burning processes.

It is both fortunate and ironic that through RNB studies of a few reactions and decay rates involved in only a tiny fraction of stellar energy economies, we may be able to understand or constrain models for entire processes that entail vast astrophysical energy sources.

Atomic and applied physics will also be enriched by RNB studies. The ISL will make available to North American scientists a new tool whose worth has been abundantly proven in Europe where low-energy (~60-keV) RNBs are heavily used in atomic, applied, and condensed matter studies. There are so many applications in these fields—ranging from studies of radiation damage and relaxation phenomena to the development of diagnostic tools for quality control and advanced electronic devices—that it is impossible even to outline them. Suffice it to mention in these introductory paragraphs one broad area that is particularly rich and varied: the doping of host environments. The advantages of RNBs in these experiments are many. The short lifetimes of radioactive dopant nuclei far from stability allow the study of time-dependent phenomena such as the response of the host to the dopant intrusion. Because nuclear β decay involves a change in element (Z), the ability to choose RNB lifetimes over a broad range for a given dopant element allows the introduction, in effect, of time-delayed or -controlled chemical transformations. The high specific activity of RNBs permits the use of much lower dopant densities so that each intruding atom travels and comes to rest in a previously undisturbed environment. Variation of RNB energies can be used to selectively control the depth of implantation; for example, relative to the locations of various components of a semiconductor device. The decay of a radioactive dopant nucleus by conversion electrons can be used to study its atomic structure and the response of that structure to the atomic and chemical environment.

RNBs can be used in atomic physics to study crystal or lattice structure. By exploiting various well-known techniques such as those used to measure nuclear g factors or quadrupole moments, it is possible to study atomic hyperfine fields when the nuclear quantities are already known. Transient fields generated in the slowing down process may also be amenable to study. In this broad area of atomic, applied, and materials science, the opportunities are myriad.

PRODUCTION METHODS

There are two basic approaches for producing a broad spectrum of high-intensity RNBs: the Projectile Fragmentation (PF) and the Isotope Separator On-Line (ISOL) post-acceleration methods.

In the PF method, medium- to high-energy (typically 50- to 2000-MeV/u) heavy-ion beams are used in peripheral reactions to produce exotic fragments that are emitted with much of the momentum of the incoming projectile at forward angles in the laboratory system. A reasonably large fraction of the fragments can be captured by an electromagnetic device and separated according to mass and atomic number by using a combined magnetic and energy-loss technique.

For the ISOL method, a high-intensity, high-energy (500- to 1000-MeV) light-ion (usually proton) beam is used to produce a variety of reaction products that are thermalized in the target matrix. The products diffuse and desorb out of this matrix and are transported to an ion source where they are ionized. An isotope separator is used to separate ions according to mass, after which the reaction products of interest are either post-accelerated to the desired higher energy or used in low-energy studies.

Each method has its strong and weak points. The PF method has the advantage of being both general (i.e., no Z selectivity) and fast (because the reaction products recoil out of the target at near-primary-beam velocities). However, because of the lower primary beam intensities and thinner targets, this method suffers from lower secondary beam intensities and poorer beam quality [i.e., large emittances, a higher level of beam contaminants (other N, Z species), and a wider energy spread] than are provided by the ISOL approach. These problems can be exacerbated in the case of reaction products for which N and Z differ greatly from those of the projectile because the reaction leads not only to smaller cross sections but also to much broader momentum and angular distributions.

The ISOL method has the advantage of higher RNB intensities as a result of more intense primary beams (e.g., protons) and much thicker targets. Moreover, because the separated fragments are accelerated in the same way as in any modern stable heavy-ion machine (e.g., LINAC), the beam quality is vastly superior, and the RNB energy can be freely chosen up to the maximum design value. The main drawback to the ISOL method is that the diffusion/desorption and ionization processes are strongly element (chemical)-dependent and slower than in the PF method. In many cases, significant decay losses can occur in this "release" stage. Of course, this feature can also be an advantage because it can give Z selectivity and, consequently, can enhance beam purity. In practice, the strong Z-dependence of the ISOL method makes a straightforward comparison of the two approaches difficult, if not impossible; at the least, the comparison becomes element-dependent.

The comparison and choice between the two methods is strongly dependent on the physics one wishes to address. In large part, the two methods offer complementary approaches. In general, research using the PF approach is well suited to both the study of a variety of reaction mechanisms at rather high beam energies and the study of the radioactive nuclei themselves if they are stopped and collected as radioactive sources. Although the energy of these PF beams can be decreased either by using energy degraders or by employing cooler/deceleration (storage ring) methods for studies at lower beam energies, each of these approaches has its own problems. The energy degrader method suffers from large secondary-reaction processes, multiple scattering, and energy/range straggling that generally results in poor beam quality; the cooler/deceleration method is limited by secondary-beam emittance/acceptance, long cooling times, and space charge problems. Both methods can result in significant intensity losses. In the case of the degrader, the large momentum spread after degradation can cause much of the potential intensity to be rejected by subsequent electromagnetic devices; in the cooler method, decay losses and phase space density effects limit beams to ~10^6 to 10^7 part./s in currently existing PF facilities. Thus, in general, PF is not well suited to lower energy RNB studies.

In contrast, this energy region is where the ISOL method excels. In this method, the radioactive fragments emerge from the target at thermal energies and—as is the case with any ordinary primary beam in an accelerator facility—they are ionized, separated, and injected into the accelerator(s). The beam qualities (energy resolution and emittance) can be as high as feasible with technologically advanced accelerators. For low-energy reactions such as Coulomb excitation, nucleon transfer, and elastic scattering, which aim to elucidate nuclear structure *per se* or are used for astrophysics and atomic physics studies, the ISOL approach is ideal. Moreover, an ISOL facility is well adapted to the accumulation of radioactive targets. (A more detailed discussion of the PF and ISOL methods is provided in Chapter III.)

This overview has delineated some of the nuclear, astrophysics, and atomic physics opportunities that RNBs proffer and identified many of the powerful new opportunities to address a wide variety of scientific questions that are realizable with a dedicated RNB accelerator facility. In Chapter II, issues cursorily discussed in these introductory paragraphs will be addressed more thoroughly with specificity and an assessment of the realistic possibilities afforded by such a facility.