The Rare Isotope Accelerator Project

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Only 300 out of thousands of isotopes are stable and exist in nature. The others are unstable and decay within a wide range of lifetimes. The properties of most of these rare isotopes are unknown and can only be inferred, with considerable uncertainty, from theoretical calculations. The proposed Rare Isotope Accelerator (RIA) will make it possible to produce and study more than a thousand new rare isotopes in the laboratory. RIA will be driven by a highly flexible superconducting linear accelerator which will be capable of delivering intense beams of all elements from hydrogen to uranium. The RIA facility will be the most powerful rare isotope research facility in the world.

1 Introduction

In the U.S. the Nuclear Science Advisory Committee (NSAC) of the Department of Energy (DOE) and the National Science Foundation (NSF) has recommended the construction of a Rare Isotope Accelerator (RIA) in order to explore the scientific opportunities of the terra incognita of rare isotopes in the nuclear landscape [1]. RIA would be capable of delivering intense beams of all elements from hydrogen to uranium, with beam power in excess of 100 kW and beam energies up to 400 MeV per nucleon [2]. The recently developed RIA concept is bold and novel; no present accelerator can provide such intense and diverse beams. It combines both major techniques of rare isotope production: (1) projectile fragmentation or fission and in-flight separation, and (2) target spallation or fission, and isotope separation on-line (ISOL) followed by acceleration of the isotope of interest. These two techniques are complementary in the species and energies of the beams that can be produced and drive different aspects of the science. Past facility concepts were based on the implicit assumption that these two techniques require two separate facilities.

The traditional ISOL technique is based upon isotope production at rest in thick targets via fragmentation or fission of a target nucleus, followed by extraction, ionization, separation and acceleration of the desired isotopes to modest energies. It is the technique of choice for the production of precision beams of low energy ($E/A < 20$ MeV). In most cases, beam development involves both physical and chemical methods and requires a considerable amount of time and effort. For very short-lived isotopes, losses due to decay can be appreciable. Beams created by the ISOL technique are ideal for precision studies at or near the Coulomb barrier, such as transfer reactions, multi-step Coulomb excitation, and sub-barrier fusion or capture reactions.

Projectile fragmentation (or fission) combined with in-flight separation, is the most economical way of producing medium-energy ($E/A = 50$ MeV) beams of rare isotopes. This technique allows sub-microsecond isotope separation by purely physical methods, yielding short beam development times. Thus, projectile fragmentation/fission is the technique of choice for experiments requiring energetic beams, e.g., knockout reactions, charge-exchange reactions, spin-flip excitations, and studies of giant resonances.

At RIA rare isotopes at rest in the laboratory will be produced by conventional ISOL target fragmentation, spallation, or fission techniques and, in addition, by projectile fragmentation/fission and stopping in a gas cell. Upon extraction, these stopped isotopes can be used at rest for experiments, or they can be accelerated to energies from below to above the Coulomb barrier. The fast beams of rare isotopes, which are produced by projectile fragmentation/fission, can also be used directly after separation in a high-resolution fragment separator.

2 Scientific Reach of RIA

The physics of the RIA facility has most recently been summarized in the RIA Physics White Paper [3]. This summary was based on “Scientific Opportunities with an Advanced ISOL Facility” [4] and “Scientific Opportunities with Fast Fragmentation Beams from the Rare Isotope Accelerator” [5]. The three main research areas of RIA will be the nature of nucleonic matter, the origin of the elements and tests of the standard model. The nuclei that RIA will be able to make available for these studies cover an unprecedented range. The production rates and efficiencies are similar for re-accelerated and direct fast beams. However, fast beams can be used for certain studies with significantly smaller intensities. While 10^3 particles/s could be sufficient for selected experiments at an ISOL facilities [3], fast fragmentation beams will, in addition, allow selected experiments with nuclei produced with intensities of 1-10^3 particles/s and in some cases with $10^{-5} - 1$ particles/s. For medium-mass to heavy nuclei, direct fast beams will extend the scientific reach of RIA to a region about 8 neutrons further from the line of stability than is presently possible.

With fast beams from RIA the neutron drip line may be reached for elements up to manganese (Z = 25), and maybe again at zirconium (Z = 40). For comparison, the heaviest known drip-line nucleus is ^{24}O (Z = 8). Fast beams from the upgraded NSCL facility will make it possible to reach the drip line for all elements up to sulfur (Z = 16) [6].

Even with very low intensities useful information can be obtained using fast beams. At the level of 10^{-5} particles/s the stability of an isotope (and hence in some cases the location of a drip line) can be determined [7, 8] and its half-life measured [9, 10, 11] if the background is sufficiently low. At the level of 0.01 particles/s the total interaction cross section of the isotope can be determined, and information on its matter distribution can be inferred [12, 13, 14]. Also at this level, modest-resolution mass measurements can be made [15]. When the beam intensities reach 0.1 particles/s, nucleon knockout reaction measurements are possible [16]. Recently, knockout reactions have proved to be an effective tool to learn about the structure of neutron- or proton-rich nuclei [17]. At about the same intensity it is possible to perform Coulomb excitation experiments to measure the energies of low-lying states and B(E2) values to obtain information about nuclear deformation [18, 19, 20].

3 Properties of Nuclei far from Stability

Over the past few decades, nuclear models have been fine-tuned primarily to reproduce the properties of nuclei close to the valley of stability. RIA will allow the study of nuclei of vastly different composition. Experiments at RIA will provide an unprecedented wealth of new data in very remote regions of the nuclear landscape that will challenge the best of nuclear models. Theoretical predictions become increasingly uncertain for nuclei very far from stability. For very neutron-rich nuclei, the subtle interactions between weakly bound discrete states and slightly unbound continuum states will play an important, yet poorly understood role. At the very least, new numerical implementations of existing theoretical frameworks together with newly optimized sets of parameters will be needed. More likely, entirely new approaches to solving the many-body problem will be necessary. It is possible that different magic numbers are encountered far from stability and even that the basic premises of shell model and mean field descriptions become questionable.

The Limits of Nuclear Existence: A major long-term experimental challenge for research with exotic beams is the exploration of the extremely neutron-rich regions of the nuclear chart. These regions are, for the most part, terra incognita - and for the heavier elements they are likely to remain so for a long time. For example, the heaviest stable isotope of tin found in nature is ^{124}Sn, and the heaviest isotope identified in the laboratory is ^{134}Sn, with a half-life of one second. Theoretical estimates range widely, but suggest that the heaviest particle-stable isotope could be ^{176}Sn, 42 mass units further out, and beyond the range of any proposed accelerator. Since we cannot expect to study these nuclei directly, it is crucial to study nuclei that are as neutron rich as possible, so as to permit a more reliable extrapolation to the regions of astrophysical processes and to the neutron drip line where neutrons become unbound.

Extended Distributions of Neutron Matter: Experimentally, the properties of nuclei at or very close to the neutron drip line can only be explored for lighter elements. Several new phenomena have been observed in the most neutron-rich light elements. For example, the valence neutron(s) of the neutron-rich, weakly bound nuclei ^{11}Li and ^{11}Be have density distributions that extend far beyond the core. Such neutron halos present an exciting opportunity to study a variety of nuclear phenomena: diffuse neutron matter, new modes of excitation, and reaction mechanisms of weakly bound nuclei. The few nuclei studied so far give us a hint of what will happen as one closely approaches the drip lines. Since the decreasing neutron binding energies result in extended and diffuse neutron matter distributions, surface effects and coupling to the particle continuum will strongly influence the properties of these nuclei. Pairing correlations will become increasingly important because the continuum provides an increased reservoir of states for scattered particles. New collective modes due to different proton and neutron deformations might appear, and the shell structure may change dramatically due to the strong pairing force at the surface and due to the expected decrease of the spin-orbit force. At present, ^{19}C is the heaviest nucleus in which a one-neutron halo has been observed. Much heavier nuclei with extended multi-neutron distributions remain to be discovered and explored.

Properties of Neutron-Rich Bulk Nuclear Matter: During a central collision of two nuclei at energies of E/A $\sim$ 200-400 MeV, nuclear matter densities approaching twice the saturation density of nuclear matter can be momentarily attained. The resulting hot and compressed reaction zone subsequently cools and can expand to sub-nuclear density. Nuclear collision experiments offer the only terrestrial situation in which such densities can be achieved and experimentally investigated. Key issues are the determination of the equation of state (EOS) and the investigation of the liquid-gas phase transition of nuclear matter. Such information is needed for nuclear systems of different N/Z composition to constrain extrapolations of the EOS to the neutron-rich matter relevant to Type II supernova explosions, to neutron-star mergers, and to the stability of neutron stars.

Can Heavy Neutron-Rich Nuclei be Deformed? It is widely assumed that the n-p residual forces are mostly responsible for the emergence of nuclear deformation. The arguments can be convincingly tested only when the systematics of nuclear shapes far from stability are firmly established. Important data are energies and transition probabilities to low-lying collective states obtained by Coulomb excitation. A new tool for determining the degree of deformation can be provided by the specific shape of the longitudinal momentum distribution of the core residue after particle removal reactions from deformed projectiles. The exotic nuclei may also reveal unusual symmetries related to the deformations of higher multipolarities.

New Modes of Collective Motion: Standard approaches, such as the random phase approximation, break down in the case of "Borromean" nuclei whose excited states can only decay by emitting at least two (instead of one) particles. Available three-body methods, such as solving the Faddeev equation, usually consider the residual nucleus as an inert core. Such methods are to be supplemented by an improved treatment of microscopic dynamics and antisymmetrization. The strength functions of the collective response can be quite different from what is routinely seen in normal nuclei. Systematic studies of giant resonances and low-lying collective modes in loosely bound neutron-rich nuclei will allow one to establish exchange contributions to the classical sum rules, which express the general properties of nuclear matter in the response to external fields. Such information may further our understanding of collective motion in neutron matter, currently a hotly debated issue.

How do Mean-Field Models Evolve with N/Z? The basis of the nuclear shell model is that the mean field and its associated single-particle energies determine nuclear dynamics. Does this concept still apply to very neutron-rich nuclei near the drip lines? If so, what are the single-particle energies near the drip line and how well can they be extrapolated from the properties of nuclei near stability? There are several specific mechanisms that are important to quantify. As the neutron single-particle energies approach the Fermi surface and become loosely bound in neutron-rich nuclei, the orbitals become more closely spaced. This reduces the shell gap and sometimes allows shell inversion where the deformed configuration has a lower energy than the normal spherical configuration. This change in the shell structure is already known in nuclei near ^{11}Be and ^{32}Mg. It is not known whether such shell inversions exist in heavier nuclei. A possible change in the spin-orbit potential in a very neutron-rich environment is another factor that will influence shell gaps.

4 Nuclear Astrophysics

Nuclear processes underlie the creation of the elements and the evolution of stars. They define the successive stellar burning stages and drive the violent nova, supernova and X-ray bursts we observe in the Cosmos. A recent summary of the role nuclear science plays in astronomy and astrophysics is given in Opportunities in Nuclear Astrophysics, a white paper based on a town meeting held at the University of Notre Dame in June 1999 [21].

There has been considerable progress toward understanding nuclear processes in the Cosmos. The reactions by which stars generate energy and synthesize the elements are known qualitatively, but many detailed predictions conflict with astronomical observations. Such discrepancies are not surprising, since many of the nuclear properties and reactions involved have not been measured, but have instead been extrapolated from available data or modeled theoretically. The RIA facility can address these discrepancies and will allow most of the astrophysically interesting nuclei to be produced and studied. This capability is now more important than ever since new observational, experimental and theoretical tools are becoming available.

In most cases, one needs nuclear reaction rates, nuclear masses, energy levels, or lifetimes for unstable nuclei that can only be reached via reactions with rare isotope beams. For such measurements, the RIA facility will provide an unparalleled arsenal of re-accelerated and fast fragmentation beams.

Other phenomena whose elucidation requires extensive new nuclear physics information obtainable at RIA include:

The Nature and Evolution of Supernova Explosions: Information on the rates of electron capture and β-decay in the hot, dense environments of stellar cores is of crucial importance. These rates affect the evolution of the stellar cores in Type II supernova explosions and (perhaps) the light curves of the Type Ia supernovae used to determine the nature of the cosmic expansion.

The Site of the r-Process: About half of the heavy elements are made in the r-process, yet whether the r-process occurs in Type II supernovae, neutron star mergers, or in some other astrophysical environment is presently not known. Indeed, new abundance data for old metal-poor stars indicate that there may be more than one such site. The information on nuclei that participate in the r-process is currently not sufficient to accurately describe the r-process and the elemental abundances it synthesizes, or to provide detailed information on the site of the r-process.

The Nature of X-Ray Bursts and Pulsars: These events occur in binary stellar systems involving a matter-accreting neutron star. On the surface of the neutron star, hydrogen and helium burn via the rp- and αp-process powering bursts and synthesizing heavier elements that are incorporated into the crust of the neutron star and affect its observable behavior. The rp- and αp-processes proceed via proton and α-particle capture on proton-rich nuclei in combination with β^+-decays, but the rates of these processes and the masses of nuclei around the proton drip line are not known well enough to make accurate predictions of energy generation and nucleosynthesis. Electron capture rates on neutron-rich nuclei are needed to predict the composition change of the neutron star's crust in these scenarios.

The Nature of the Neutron-Rich Matter Found in Neutron Stars: Measurements of the isospin dependence of the nuclear compressibility will constrain the nuclear equation of state for neutron-rich nuclei.

The Isotopic Distribution of Cosmic Rays Arriving at

Earth: High-energy nuclear reaction data are needed to interpret this distribution which in turn will provide clues to the origin and generation of cosmic rays.

5 Test of the Standard Model

Tests of the standard model and of fundamental conservation laws require high precision experiments with high intensities. This is a special challenge when radioactive nuclei are involved.

CP-Violation: CP violation remains one of the most important open questions in fundamental physics. The observed cosmological baryon asymmetry from the big bang cannot be explained with the CP violating mechanisms within in standard model. Extensions to the standard model predict additional CP violating observables. Measuring the atomic electric dipole moment especially in heavy nuclei is a sensitive test for CP-violation and the radioactive isotope ^{223}Rn is one of the best candidate [3].

Parity Violation: search for parity violation is a test for physics beyond the standard model. Again, heavy nuclei are the most promising candidates and Fr, if available at sufficient intensities, should be more sensitive to parity violation than the current measurement with Cs. The predicted intensities of RIA should push the sensitivity to 0.1% [3].

6 Present Status

The nuclear physics community in the United States continues to work hard to make RIA a reality. Since the 2002 DOE/NSF long range plan a RIA users group and a RIA steering committee was formed. A yearly RIA summer school is being organized. All these efforts are coordinated via a site independent website [22].

A group of representatives of the RIA Users community met with the Director of the DOE Office of Science, on November 19, 2002 in order to outline some of the major scientific and intellectual themes underlying RIA research, with an emphasis on those that relate to important challenges and thrusts that cut across the disciplines of modern science [23].

A significant R&D effort continues to push the project forward. A workshop on the experimental equipment was held in March 2003 in Oak Ridge [24] and a workshop to determine R&D priorities for RIA was held in August 2003 in Washington D.C [25].

The next and most important step has to be authorization for a conceptual design report.

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