Scientific Opportunities

with an

Advanced ISOL Facility

NOVEMBER 1997

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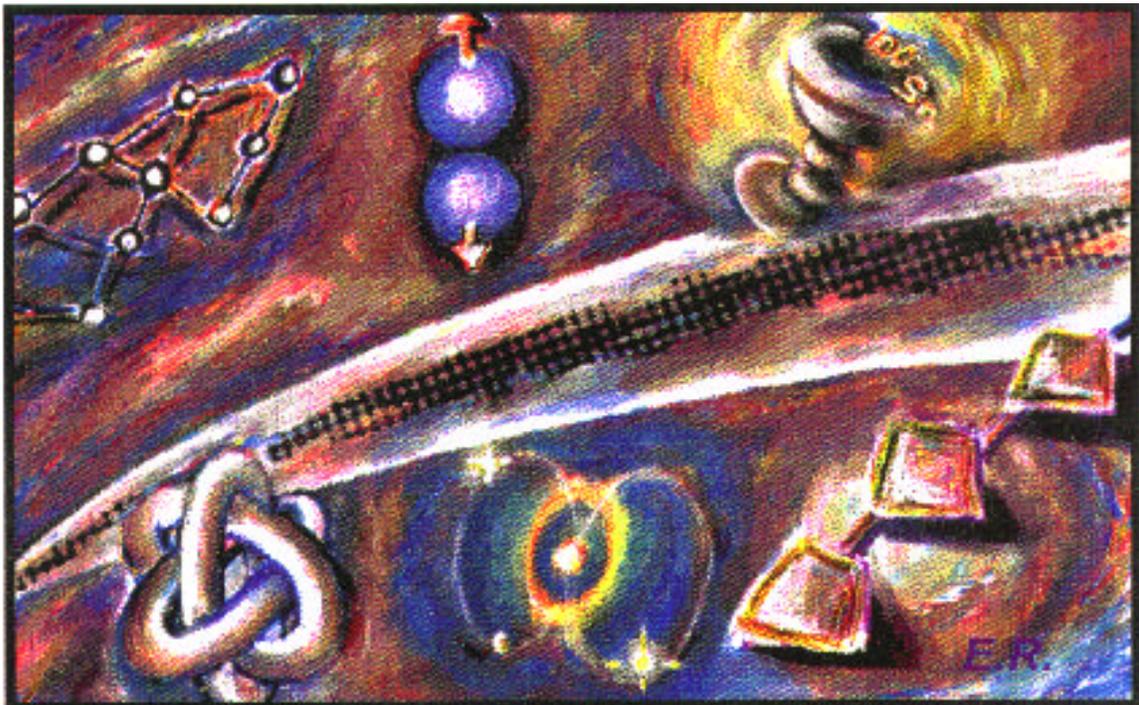
Preamble

This Report* summarizes the scientific case and the need for the construction of an advanced ISOL (Isotope Separation On-Line) facility. This major new research facility, which the 1996 DOE/NSAC Long Range Plan for Nuclear Physics identified as the highest priority for major new construction by the DOE, would be dedicated to providing a variety of high intensity, high-resolution accelerated beams of short-lived radioactive ions for a range of new science opportunities.

The initiative builds on the experience and excitement that the research community has developed over nearly a decade in radioactive beam studies. These studies are documented in various conferences, discussions, and White Papers. This summer, from July 30 - August 1, 1997, a Workshop was held at Columbus, Ohio on the Science for an Advanced Radioactive Beam Facility of the two-accelerator ISOL-type. The Workshop attracted 150 people and included more than 60 talks on the physics opportunities that would be provided by such a facility. These talks serve as a basis for this Report which has been prepared, following the Workshop, by the Panel listed at the end of this document.

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* The Report is written, for the most part, at a level that should be accessible to a broader audience, specialists as well as non-scientists. Some technical jargon, of course, is unavoidable without expanding the length unduly. For those unfamiliar with the field, terms that are commonly used or which are critical to following the text are explained in a Glossary at the end.

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Executive Summary

This Report presents the scientific case for an advanced, two-stage accelerator facility of the ISOL (Isotope Separation On-Line) type to provide intense, high-quality beams of short-lived, unstable (radioactive) nuclei for research in nuclear physics and related fields in the US. The opportunities offered by beams of exotic nuclei for research in the areas of nuclear structure physics, nucleosynthesis and nuclear astrophysics, and for critical tests of fundamental symmetries, are both timely and exciting. The enormous worldwide activity in the construction of different types of radioactive beam facilities reflects the strong scientific interest in the physics that can be probed with such beams. The need for advanced facilities of the ISOL-type is clear and several countries are embarking on proposals that either constitute such facilities or are upgradable into them.

At the present time, the US has no funded project for a next-generation ISOL facility. Yet, an opportunity to explore the exciting areas of physics discussed in this Report is available if acted on expeditiously. Construction of such a facility will be essential if the US is to have a world leadership role at the forefront of this broad new area of science. Such a course of action is in concert with the recommendations in the 1996 Long Range Plan for Nuclear Physics by the Nuclear Science Advisory Committee (NSAC) to the US Department of Energy and the National Science Foundation. The construction of an advanced ISOL facility should be pursued with the utmost vigor.

The new research addresses questions of key importance to our basic understanding of nuclei. Nuclei occupy the center of every atom and comprise over 99.9% of its mass. They are the building blocks of the matter around us. Through this research we will endeavor to achieve a full understanding of the nucleus as a many-body system built of protons and neutrons and governed by the strong force; an exploration of the origins of the chemical elements and their role in shaping the reactions that occur in the cataclysmic events of the cosmos; and tests of the limits of validity of the Standard Model, the fundamental theory that currently best represents our understanding of the laws and fundamental symmetries in Nature.

The key themes and challenges of research with exotic nuclei are:

- **The Nature of Nucleonic Matter**

- **The Origin of the Elements**

- **Tests of the Standard Model**

The study of **nucleonic matter**, that is, of the atomic nucleus and the interactions of the protons and neutrons of which it is composed, is a fundamental facet of our search to understand the universe. The study of unstable nuclei embraces many new aspects of this quest. It focuses on the exotic properties of loosely-bound quantum systems, often with new geometries, such as nuclei with giant halos or skins of neutron matter, and on regions of nuclei with special structure and symmetries. The new physics involves coupling between nucleons that are bound inside the nucleus and those that are moving freely, yet unexplored interactions between nucleons in the nuclear medium, and different reaction processes involving unstable nuclei. We expect to encounter new phases of nuclei such as novel types of nuclear superfluidity, new shell structure, and new collective modes. With access to exotic nuclei we can, for the first time, fully explore the very limits of nuclear existence, that is, the edges of the nuclear landscape itself. The ultimate goal is the understanding of the nucleus as a finite many-body quantum system. Nuclei far from stability are crucial to this endeavor since they allow us to amplify and isolate particular aspects of the interactions between nucleons. Using what we learn from these nuclei we can then return to the nuclei of the world around us and understand them far better than ever before.

Nuclear Astrophysics studies will focus on key stellar processes central to the synthesis of the elements in stars and to cataclysmic stellar explosions. Many of these elements are crucial to life and geologic processes. Many of the nuclear reactions in stellar environments, particularly in violent explosive events, involve proton and neutron capture processes that are sensitive to both the structure of the unstable nuclei involved and to the temperatures, densities, and timescales of explosive stellar events, such as supernovae. Studying unstable nuclei thus impacts both our understanding of the synthesis of the elements and the nature of the stars and their evolution as well.

The nucleus provides an ideal laboratory for precision tests of the ***Standard Model***, a venue in which to search for its limits of validity as well as for possible extensions to it, and to study violations of such fundamental concepts as parity and time reversal conservation in the electroweak interaction.

Ion beams are also important in a large variety of applications to medicine and industry. Beams of radioactive nuclei greatly expand the scope of such applications. For example, if a radioactive source is needed for implantation, such beams offer a large choice of half-lives, decay types, and energies, which can be used to control the depth, intensity, and location of implantation. This has obvious implications for doping of semi-conductors, medical therapy, and studies of the wear of materials. Moreover, when radioactive nuclei decay, the number of protons in the nucleus (and hence the element) changes. Thus one can introduce time-dependent chemical changes into a sample. In medical applications, one of every three hospitalized patients in the United States undergoes a nuclear medicine procedure, with a total value estimated at 7 billion to 10 billion dollars per year. More than 36,000 diagnostic medical procedures that employ radioactive isotopes are performed daily in the United States.

We now have extensive background, gained at on-line isotope separators and at first-generation ISOL and Projectile Fragmentation facilities, which provides the community with experience in both the production and utilization of radioactive beams. In addition, a vigorous program of R&D directed at the technical issues which must be met at a high intensity advanced facility is well under way. The technical tools for the construction of such a facility are in hand. In fact, several concepts for facilities capable of producing the beams required to carry out the physics program outlined in this Report have already been presented. The time for construction of an advanced ISOL facility has clearly come.

I. The Landscape of Exotic Nuclei

An Overview

The nucleus is the core of the atom. Containing more than 99.9% of the atom's mass, the nucleus defines its center and determines through its electrical charge the chemical nature of the atom. Atoms in turn, based on their chemical properties, form the manifold of molecules, compounds and materials which surround us, and from which we ourselves are made.

Nuclei came into being through cataclysmic events in the evolution of the universe: light nuclei were created within a few minutes after the Big Bang, heavier nuclei were, and still to this day continue to be, produced in stars, the cauldrons of the cosmos. In our quest to understand the fundamentals underlying the physical world that we live in, and the origins of its formation and evolution, it is essential to have a full understanding of the atomic nucleus. The process of heavy elemental synthesis involves unstable nuclei at every stage. Therefore, to understand the origins of the elements that surround us and that are critical to both material and life processes, we need to study unstable nuclei.

We enter a new realm when descending into the microscopic world of the nucleus. There are four fundamental forces of Nature, the gravitational force, the electromagnetic or Coulomb force, the strong force, and the weak force. While the chemical properties of atoms and materials are determined by the relatively simple structure of the electromagnetic force, when approaching the distance scales given by the size of the nucleus, the weak force and the strong nuclear force come into play. The weak force that governs the processes that transmute short-lived nuclei into each other and ultimately into stable nuclei, is important but, as its name implies, it is responsible for only minor rearrangements of the nuclear system. It is the strong force that holds nuclei together and determines the characteristics of nuclear binding and thus the overall nuclear landscape.

Nuclei are composed of protons and neutrons, together called nucleons. The nucleons themselves have sub-structure, quarks and gluons, with the gluons holding the quarks together in a tightly bound entity. The resulting picture yields the attractive force between nucleons as the residue of the quark and gluon interactions. The nucleon-nucleon force is further altered when these particles cohabit inside the nucleus. Together, these ideas underlie the successful phenomenological model of nuclei as composites of nucleons interacting via an effective nucleon-nucleon force. Inside the nucleus, this force binds nucleons into orbits which resemble the orbits of electrons around the central nuclear core. Sets of these orbits that correspond to similar nucleon energies and radii group together to form shells, analogous to the electronic shell structure of atoms.

Nuclei come in a large variety of combinations of protons and neutrons. However, due to the underlying forces and symmetries of the laws of Nature, not all combinations are possible. Figure 1 illustrates, in a map spanned by the number of protons on one axis

and the number of neutrons on the other, the landscape of those nuclei that we presently think might exist.

This landscape shows several thousands of nuclei that are expected to be bound by the strong force. Of these, fewer than 300 are stable: These are marked in black. While the other nuclei are bound against the release of protons and neutrons, they are not completely stable: they are subject to internal transformations (generically known as β-decay) in which a proton changes into a neutron or vice versa. Some of the unstable nuclei are long-lived and can be found on Earth, some are man-made, while thousands more are
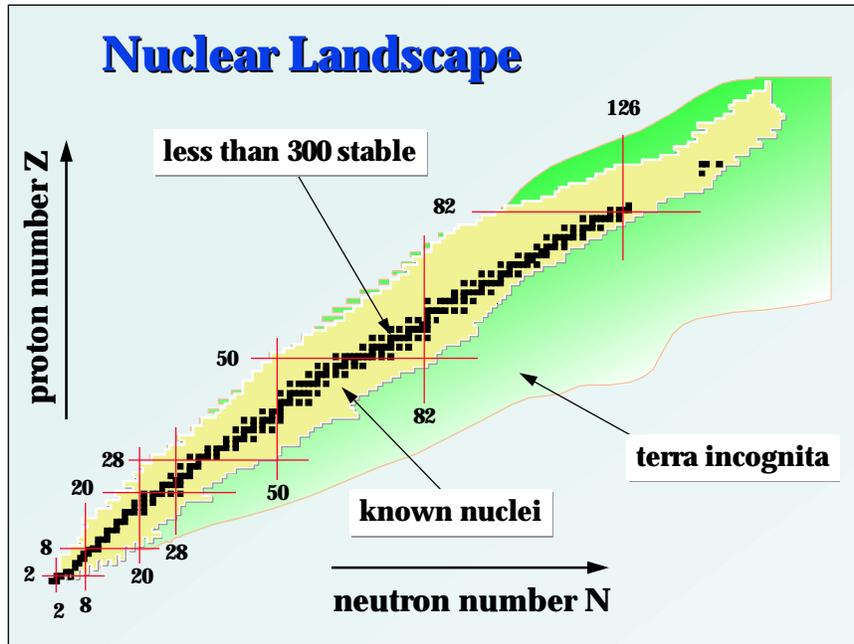
Fig. 1 Map of bound nuclear systems as a function of the proton number Z (vertical axis) and the neutron number N (horizontal axis). This nuclear landscape forms the territory of radioactive nuclear beam physics. The black squares show the nuclei that are stable, that is, non-radioactive, or those long-lived, with half-lives comparable to or longer than the age of Earth. There are fewer than 300 such species. These nuclei form the "valley of stability". The yellow color indicates man-made nuclei that have been produced in laboratories and that live a shorter time. By adding either protons or neutrons one moves away from the valley of stability, finally reaching the drip lines where the nuclear binding ends because the forces between neutrons and protons are no longer strong enough to hold these particles together. The nuclei beyond the drip lines emit nucleons very quickly to form nuclei with combinations of protons and neutrons for which the strong interaction is able to cluster these nucleons together as one nucleus. Many thousands of radioactive nuclei with very small or very large N/Z ratios are yet to be explored. In the (Z,N) landscape, they form the "terra incognita" indicated in green. The proton drip line is already relatively well delineated experimentally up to Z=83. In contrast, the neutron drip line is considerably further from the valley of stability and harder to approach. Except for the lightest nuclei where it has been reached experimentally, the neutron drip line is estimated on the basis of nuclear models -- hence it is very uncertain due to the dramatic extrapolations involved. The uncertainty in the limit of nuclear stability is illustrated by showing the unknown drip line as a dashed curve.

The red lines show the magic numbers known around the valley of stability. However, since the structure of nuclei is expected to change significantly as drip lines are approached, we really do not know how nuclear shell structure evolves at the extreme N/Z ratios.

yet-unexplored species. Consequently, of the multitude of nuclei that may exist and that were formed at one point or another in violent stellar explosions, only a few have survived. To understand the nucleus, we need to explore and study not only the phenomena that stable nuclei present, but also those out towards the limits of nuclear existence. These investigations will pose a great experimental challenge, but, as in any physical system, such studies at the extremes will provide important insights -- into the structure and dynamics of nuclei, on the underlying symmetries of Nature, and towards a new understanding of the nucleus as a fundamental many-body system governed by the strong interaction.

The basic contours of the valley of stability, shown in Fig. 1, are well understood. In concert with the Pauli Principle, which does not allow two identical nucleons to occupy the same orbit, the strong force favors symmetry between protons and neutrons. Thus, at least among light nuclei where the Coulomb force is weak, the most stable nuclei, those in the bottom of the valley of stability, have approximately equal numbers of neutrons and protons. If additional nucleons are added, they occupy outer, less-bound, orbits. At some point, the so-called proton and neutron drip lines, protons and neutrons, respectively, can no longer be kept in the nucleus -- they literally drip out. The exact locations of these boundaries are far from clear and their complete delineation awaits a full quantitative understanding of the nuclear system. The proton drip line is closer to stability than the neutron drip line since the Coulomb force repels the electrically charged protons from each other as well. This difference between adding a proton or a neutron leads to quite different phenomena on the two sides of stability.

The uncharted regions of the N-Z plane can answer many important questions. Primary is what are the very limits of nuclear existence: How many protons and neutrons can be clustered together by the strong interaction to form a bound nucleus? The boundaries of the nuclear realm are especially uncertain on the neutron rich side where the span of nuclei separating the known nuclei from the most exotic species is quite long. The nuclear landscape also has, or may have, a third terminus -- in the heaviest nuclei that might exist. The binding of these nuclei is dictated by the interplay between the repulsive Coulomb force between protons and the attractive strong nuclear interaction. We do not know where the mass border will be: different model predictions exist. But studying nuclei heavier than discovered to date is needed to make such predictions quantitatively reliable.

Closely related to these questions of which nuclei exist is: What are the properties of very short-lived exotic nuclei, especially those with extreme ratios, N/Z, of neutron to proton number? We have been able to study in the laboratory only a limited fraction of the nuclei away from stability, but even this tantalizing sampling has revealed surprising results and new perspectives. Indeed, some of our long-standing and cherished ideas of nuclear behavior may reflect only the microcosm of the nuclear landscape that lies along the valley of stability. For example, it is known that certain numbers of protons and neutrons, called magic numbers, have special stability. Nuclei with these numbers are themselves called magic, or closed shell, nuclei and have long served as key landmarks along the nuclear landscape (see Fig. 1). A fundamental question for nuclear structure is

whether the magic numbers are universal as originally thought, or whether they change in certain regions far from stability, as we now suspect, or perhaps disappear altogether.

An important characteristic of many-body systems in a variety of sub-fields of physics, is the fact that the interactions between their constituents in the physical medium that they constitute can be different from what it is in free space. We have developed successful interactions for free nucleons, but a critical issue for our understanding of nuclei is what is the nucleon-nucleon interaction within the nucleus. Nuclei having a very large
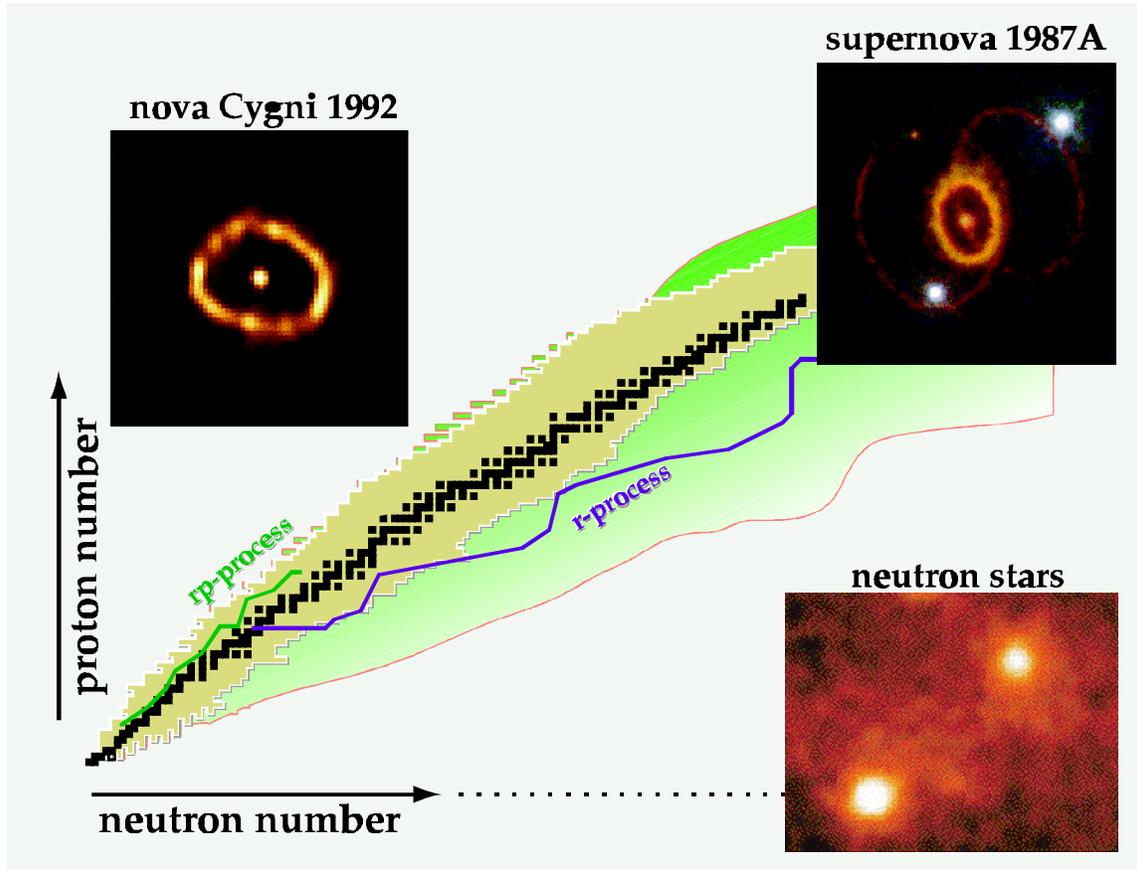
Fig. 2 Astrophysics on the nuclear landscape. The nuclear landscape discussed in Fig. 1 is reproduced here with the addition of landmarks relevant to nuclear astrophysics. The green and purple lines drawn on the landscape represent paths along which synthesis of nuclei is believed to occur in explosive cosmological events. Understanding the nuclear physics underlying these paths is a basic goal of accelerator nuclear astrophysics. The rapid-proton-capture, or rp-process (green line), is believed to occur in novae or X-ray bursts, while the rapid-neutron-capture, or r-process (purple line), may occur in supernova explosions. Photographic images of the remnants of such dramatic explosive events, taken by the Hubble Space Telescope, are shown near the respective paths. The image of Cygni 1992 was taken in May 1993, 467 days after the nova event; the ring is the edge of a bubble of hot gas ejected into space by the explosion. The image of supernova 1987A was taken seven years after the explosion was seen on earth. The central ring is ejecta from the explosion, while the two outer rings are thought to be due to the explosion's shock wave traveling through material which had previously left the progenitor star as a stellar wind. The image of a neutron star represented at the extreme neutron rich corner of the nuclear landscape is somewhat more whimsical, but the study of very neutron rich nuclei may improve our understanding of the crusts of neutron stars.

neutron excess provide a sensitive laboratory in which to study this question in an environment very different from that encountered in stable nuclei.

Nuclei play a critical role in the universe and, in turn, astronomical processes create the elements. The oxygen we breathe, the carbon on which life forms are based, and other light elements, are made continuously in stellar factories, while elements heavier than iron are produced in violent stellar explosions. The resulting elements are then dispersed into the universe and are later formed into new stars and planets. We are, therefore, all stellar debris. The astrophysical processes -- for example, the so-called rp-process and r-process -- dominating both the energy economy of stars and the synthesis of nuclei in violent stellar events depend sensitively on the properties of unstable nuclei. That is, in typical scenarios for nucleosynthesis, the outcome depends on both stellar parameters (e.g., density, chemical composition, and temperature) and on nuclear properties (e.g., probabilities of certain nuclear reactions, and nuclear lifetimes). As illustrated schematically in Fig. 2, unstable nuclei pave the highway along which material is transported up in proton and neutron number in the process of nucleosynthesis. Nova and supernova explosions have time scales which are so short that most of the unstable nuclei which are produced do not have time to decay back toward the region of stability but rather become links in a chain of reactions that leads to the production of the heavier nuclei. Therefore, the experimental study of explosive nucleosynthesis must include measurements of reactions involving short-lived radioactive species. Radioactive nuclear beams allow such measurements and will therefore have a catalytic effect on astrophysics studies of such environments.

The properties of nuclei near the neutron drip line are important in another cosmic context. We may ask if there is any nuclear existence beyond the neutron drip line. The answer is yes, indeed, for the cosmos offers up a realm of distant neutron stars which are a form of stable neutron matter. These giant "nuclei" having masses comparable to that of the sun squeezed into radii of only about 5 miles, are bound by gravity, an interaction which can safely be neglected in describing normal nuclei. But their surface regions are essentially pure low density neutron matter of which the outer reaches of neutron drip line nuclei are miniature paradigms. Hence these exotic nuclei are important for our understanding of neutron stars as well.

Exotic nuclei play a special role in tests of the best theory of Nature that we currently have -- the Standard Model, which describes the basic constituents of matter and their interactions. The wide diversity of unstable nuclei allows one to choose special ones that optimize specific measurements. These might be nuclei with special symmetries, such as having equal numbers of protons and neutrons, or the heaviest nuclei, in which effects of the electroweak interaction are enhanced due to the large nuclear charge. A nuclear landscape showing examples of unstable nuclei of importance for fundamental studies is shown in Fig. 3.

Finally, radioactive beams and intense sources of unstable nuclei provide opportunities for interdisciplinary research and for practical applications -- to other fields

of science such as condensed matter and atomic physics, to electronics and the properties of semiconductors, and to the bio-medical sciences -- in particular, to diagnosis and therapy of a wide variety of diseases. Radioactive beams allow one to implant carefully selected ions in semiconductors to alter their properties; they allow implantation of atoms whose chemical properties will change over time as the nuclei at their core decay; they allow studies of wear and abrasion in industrial processes; they allow precise imaging of the body and expand by orders of magnitude the choice of radioactive isotopes for therapeutic applications so as to maximize treatment while minimizing radiation exposure to the patient.
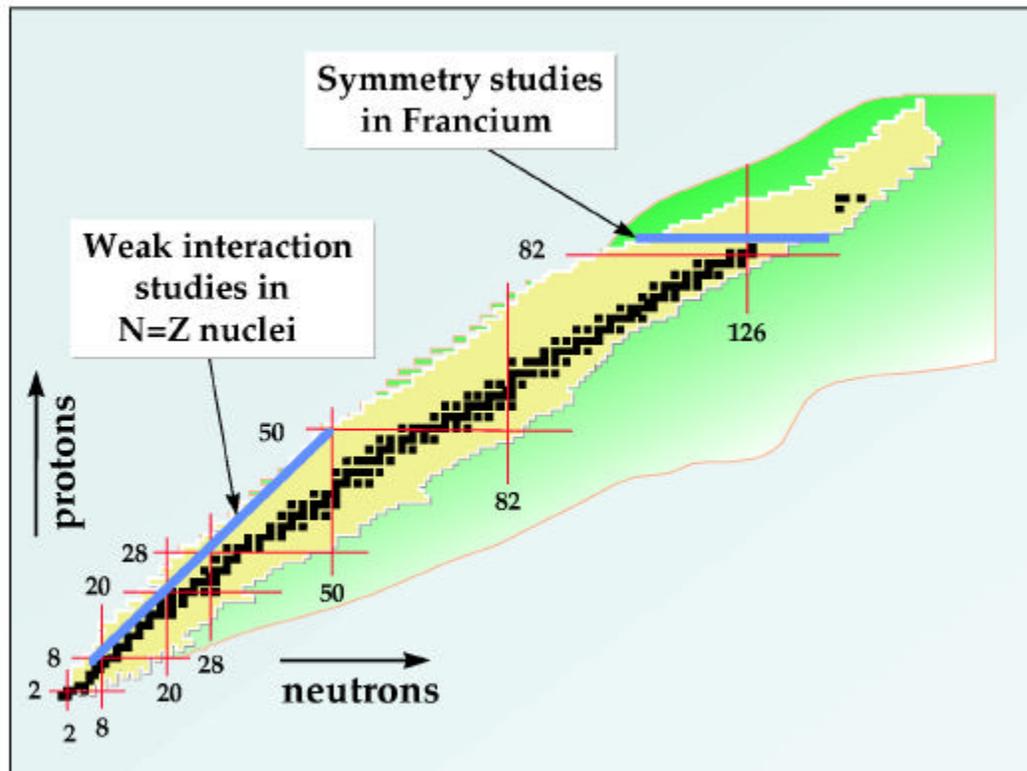
Fig. 3 Nuclides of high interest for fundamental symmetry studies. Well understood nuclear and atomic systems are required in order to allow the reliable observation of subtle effects that are direct manifestations of the fundamental forces acting in these systems. The N=Z region provides a fertile ground for studies of the weak interaction because of the simple nuclear structure of these nuclei which allows specific components of the interaction to be isolated. Francium has the simplest atomic structure amongst the heavy elements. This makes it ideally suited to study effects of parity and time-reversal violation at low energy which are often greatly enhanced in heavy systems.

Just as we recognize the need to probe and exploit the new, uncharted territory of exotic nuclei, the technology to do so is at hand. With techniques that allow the production and acceleration of beams of short-lived, unstable nuclei -- nuclei that themselves are already away from stability -- our horizons will be substantially extended.

In the following sections, we will briefly explore some of the exciting physics offered by exotic beams, in a wide variety of areas such as the exploration of the limits of nuclear existence (the drip lines and the superheavy nuclei), nuclear structure, the quantum mechanics of exotic systems, nuclear astrophysics (focusing on energy generation in stars and on the origins of the elements), tests of fundamental symmetries of Nature and of the Standard Model, as well as applications of exotic nuclear beams to interdisciplinary studies, to practical applications, and to medical diagnostics and therapy.

II. Nuclear Structure: The Nature of Nucleonic Matter

New Aspects of Nuclear Structure With Exotic Beams

Our understanding of nuclear structure as we know it today is largely based on a limited set of nuclei -- those near the valley of stability and, to a certain extent, the proton rich nuclei. As we will discuss in some detail below, there are theoretical reasons (and emerging experimental evidence) to suspect that nuclei can be far different entities away from stability. When considering the properties of exotic nuclei near the drip line, the unique new feature that enters is the weak binding of the outermost nucleons. It takes only a small amount of energy -- a minor jiggling of the nucleus -- to free these nucleons. For weakly bound nuclei, entirely different effects and new types of interactions among nucleons appear and may become dominant. Nuclear densities, nuclear sizes, nuclear symmetries, and nuclear excitations may be quite unlike those we have encountered until very recently. Even the underlying shell model -- the standard microscopic underpinning for our understanding of nuclear structure -- seems to be in need of revision if it is to encompass all the nuclei that exist rather than the subset that are stable. Moreover, the most neutron rich nuclei that we expect to be able to reach are likely to have outer regions, where only neutrons exist, that comprise a new form of matter -- neither normal nuclear matter nor free nucleons.

The mutual interactions between nucleons within the nucleus create a net force field. These ideas are embodied in the basic theory for nuclear structure, namely the Shell Model, and the force field is described mathematically by a construct called the shell model potential in which the nucleons move. In addition to this potential, Mayer and Jensen, in their Nobel Prize winning work, proposed adding a second interaction between the orbital motion of a nucleon and its spinning motion about its own axis -- the "spin-orbit" force which favors with lower energy those nucleons that orbit and spin in the same direction. This force is analogous to one that would exist if the motion of the earth around the sun depended on whether the earth rotates on its axis E-W or W-E. With the gravitational force it doesn't matter: in the nucleus it matters very much. There are additional forces between nucleons in the nucleus that are not contained in the shell model potential description. One of these forces, dubbed the pairing interaction, favors the coupling of like-nucleons going in opposite directions but in the same orbit. This confers on many nuclei a property analogous to that normally associated with solids, namely superconductivity, in which pairs of nucleons move in concert like the so-called Cooper pairs of electrons in cooled solids. One of the main objectives of nuclear structure studies is to gain insight into the nature of strongly interacting nuclear systems and the effective forces that act between the nucleons in the nuclear environment. Only in this way can we develop the foundations of a microscopic many-body theory of nuclei.

While existing data on nuclei may seem abundant, they are also seriously limited in scope, and our current understanding is incomplete and inadequate. A number of studies on stable and near-stable (mostly neutron rich) nuclei already suggest the fact that we do

not understand some of the most basic features of the shell structure underlying nuclear physics. For example, studies of nuclei as diverse as ^{32}Mg, ^{44}S, and the Zr and Sr nuclei with approximately 100 nucleons, show that even the benchmark magic numbers do not carry their usual implications of stable spherical and inert shapes. Magicity is fragile when one leaves the familiar confines of stable nuclei. By extending these studies to exotic nuclei, we can amplify and more easily isolate those components of the effective interaction that depend on the ratio of the number of neutrons to protons. This gives a way of studying the so-called "isospin" degree of freedom, which is a measure of the proton-neutron symmetry in nuclei. Then, we can return to stable nuclei to test these effective interactions and to improve our understanding of their binding, their shapes and configurations, their single particle shell structure, and their collective excitations.

Specific questions that need to be asked and answered are: What is the N/Z behavior of the nucleon-nucleon force and the spin-orbit force? What is the form of the pairing interaction in weakly bound nuclei? How does the overall nuclear force change when the density of nucleons changes? We know that there are differences between the interactions of free nucleons and nucleons in normal nuclei. But, what about nucleons in the diffuse outer region of nearly pure neutron matter in exotic nuclei with large neutron excesses? The questions we will be able to address are relevant not only to nuclei themselves but are important for theoretical consideration of the properties of extended nuclear matter and neutron droplets and hence for understanding the critical surface crust region of neutron stars.

As we have stated, the main conceptual challenge is the fact that near the drip lines, nucleons are very weakly bound: A proper theory must take into account all the possible orbits of these low energy quasi-bound nucleons, that is, it should treat the "particle continuum" of unbound orbits. As a result, many cherished approaches of nuclear theory such as the conventional shell model and the pairing theory must be modified. The closeness of the particle continuum impacts two aspects of the behavior of such nuclei. Firstly, particles (or pairs of particles) can scatter back and forth into the particle continuum. Secondly, nucleons can simply leave the nucleus altogether. While we can understand the motion of a single particle which breaks free into the continuum, the multi-particle situation that we encounter in near drip line nuclei is not solved. But there is also a splendid opportunity: the explicit coupling between bound states and continuum invites a strong interplay and cross-fertilization between nuclear structure and reaction processes between nuclei. Many methods developed by reaction theorists can now be applied to structural aspects of loosely bound nuclei.

Neutron rich Nuclei

Neutron rich nuclei are likely to exhibit many new and exotic phenomena. Theory predicts this and first experiments already allow us glimpses of it. What makes neutron rich nuclei so unusual? Firstly, they have very large sizes -- as implied by their weak binding. Secondly, they are very diffuse; their properties are greatly dominated by surface

effects. Thirdly, they are very superfluid: the close-lying particle continuum provides a giant reservoir for scattered neutron Cooper pairs. So, roughly speaking, they are large fuzzy superfluids.

On the neutron rich side of stability we have already used radioactive beams to discover the existence of nuclei with nucleonic distributions extending to huge distances. We will be able to better delineate the uncertain limits of stability going toward the neutron drip line. Furthermore, shell structure itself is likely to be substantially different than near stability. Hence, collective excitations may have different manifestations and may evolve differently with N and Z compared to their behavior near stability. Finally, new manifestations of pairing phases involving bound and unbound orbits are predicted.
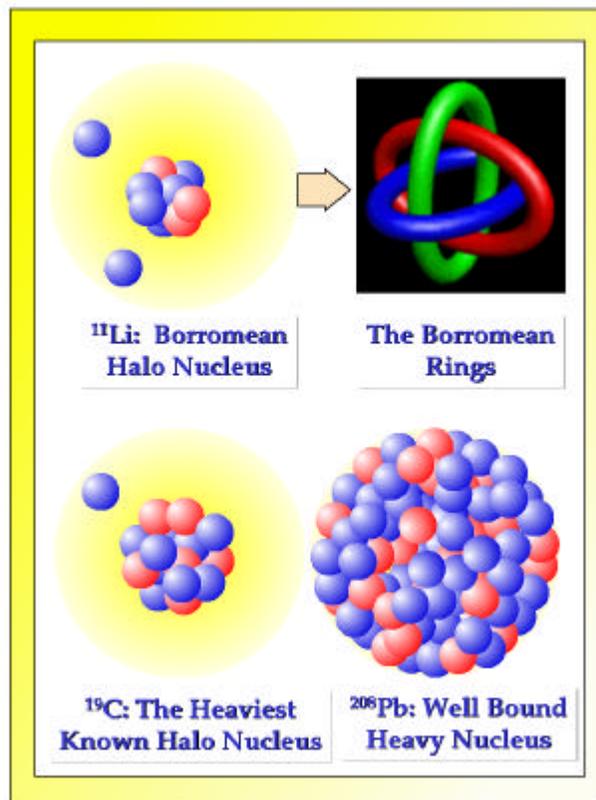
Fig. 4 Loosely bound halo nuclei such as ^{11}Li and ^{19}C are unique few-body systems. A paradigm of the unexpected phenomena and unusual configurations that may occur in the vicinity of the neutron drip line is the nucleus ^{11}Li (3 protons and 8 neutrons), understood as a three-body halo consisting of two neutrons and a well bound ^{9}Li core. Interestingly, while all three constituents of ^{11}Li form a bound system when placed together, the nuclear potential is not strong enough to bind any two of them separately. Hence the name Borromean nuclei. The heaviest neutron rich carbon isotope ^{19}C has 6 protons and 13 neutrons. That is, it has six more neutrons than the naturally occurring ^{13}C. ^{19}C is the heaviest neutron halo nucleus known. Due to very weak binding, the last neutrons in ^{11}Li and ^{19}C are spread throughout a volume whose size is nearly as large as that occupied by the far heavier nucleus ^{208}Pb. The spreading of the most weakly bound neutrons to distances so far from the nuclear core would not be allowed if the nucleus were governed by classical laws of motion; it occurs due to the effects of quantum physics.

Halo Nuclei

With the next-generation of radioactive beam facilities, we will be able to expand our access to the neutron drip line from the region roughly below carbon to nuclei as heavy as the most neutron rich isotopes of sulfur (roughly ^{52}S, a nucleus with 16 protons and 36 neutrons). Just before the neutron drip line, neutrons occupy orbits outside the nuclear core in states that are spatially extended and, from Heisenberg's uncertainty principle, have low kinetic energy. These states, called neutron halos, have radii that are up to several times that of the core. An artist's conception of halo nuclei is shown in Fig. 4. In the most famous halo nucleus, ^{11}Li, the two outermost neutrons orbit a ^{9}Li core at large distances. Figure 5 shows the neutron radii, and the differences between neutron and proton radii (inset), extracted from experiments in which isotopes of sodium were scattered from carbon nuclei. The increase of the neutron spatial extension with increasing neutron number is clearly visible.

Nuclei with two neutrons in their halo such as ^{6}He and ^{11}Li can be viewed roughly as three-body systems made up of a densely packed core and two extra neutrons. This is supported experimentally by the preponderance of reactions in which these three fragments emerge. The three-body problem has a fascinating place in quantum mechanics with a history that goes back to the theoretical interpretation of the helium atom. The two-neutron halos add novel features to the three-body problem. They are the first examples in Nature of systems that have the "Borromean" property, in which the nucleus is no longer bound if any one of its three components is torn away. [The name derives from the heraldic emblem of the medieval princes of Borromeo, three rings interlocked in such a way that removal of any of the rings will make the remaining two fall apart (see Fig. 4).] Also, theoretical studies suggest that some Borromean systems may have weakly bound excited states with extremely large radii -- perhaps approaching close to atomic dimensions.

A particularly interesting application of slow beams of halo nuclei is sub-Coulomb barrier reactions in which the long tail of the halo wave function could interact with a target at energies well below the Coulomb barrier when the cores of the nuclei are still well separated. This is expected to give interesting information on the radial distribution of the halo and, perhaps, on whether the nucleons can be induced to oscillate against the core. Predictions are conflicting: some find enhancement, others hindrance, of the reaction probability. Using high efficiency detector systems these types of reactions can be investigated with beam intensities between 10^4 - 10^5 particles/sec. Present facilities provide intensities for neutron rich beams which are several orders of magnitude lower in the energy range required for these experiments. A next-generation ISOL facility, however, will provide beams of, for example, ^{11}Li or ^{30}Ne, that will allow detailed studies of these reactions for the first time.

Moreover, by using reactions involving a halo nucleus as the projectile in which several nucleons are transferred between the participants, one can investigate the structure of new heavy nuclei located on the neutron rich side of the valley of stability which are not

produced in fission reactions. These multi-nucleon transfer reactions are strongly influenced by the underlying reaction Q-values, which for reactions with stable projectiles (e.g., ^{136}Xe) are usually very negative, resulting in very small reaction yields. This situation changes drastically when intense neutron rich beams (e.g., ^{142}Xe) will be available. There is no hindrance due to the Q-values even for the transfer of up to six neutrons. The optimum transfer probability for many systems will be in the ground state region, thus allowing the study of pairing correlations at low energies. Together with a high efficiency γ-ray detector array, nuclear structure information for nuclei produced via such six-neutron transfer reactions can be obtained with reaction rates exceeding 10^3 events/hr.
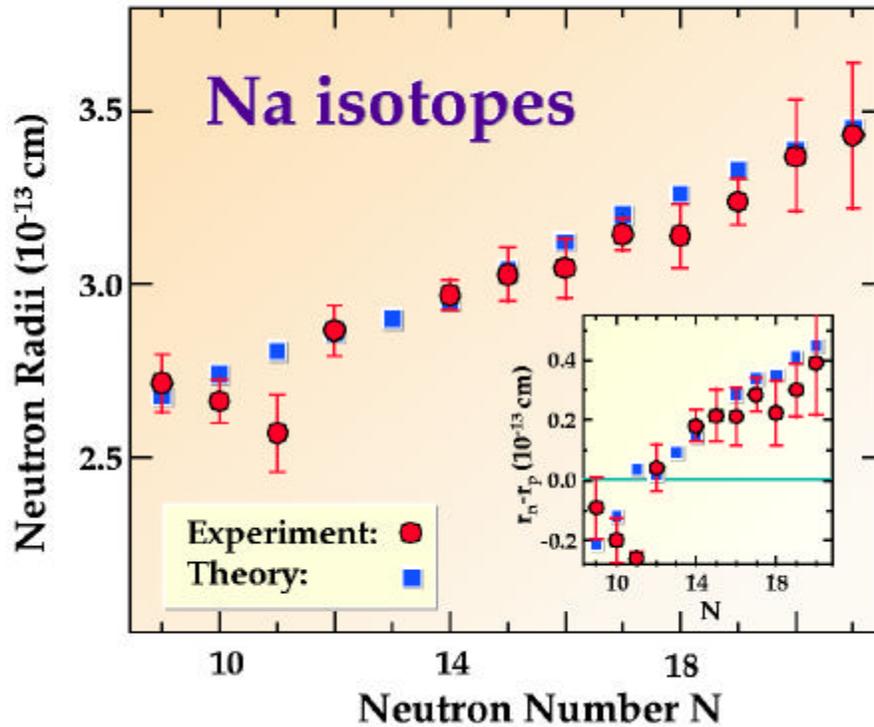
Fig. 5 Experimental (red dots) and calculated (blue squares) neutron radii for the Na isotopes (Z=11). Calculations were performed with a technique known as the relativistic self-consistent Hartree-Fock-Bogoliubov theory. The experimental and calculated differences between neutron and proton radii, $\Delta r_{np} = r_n - r_p$, are shown in the inset. The smooth increase of neutron radii and Δr_{np} for N>11 presents evidence for a neutron skin surrounding a normal core nucleus. The interesting discrepancy between theory and experiment at N=11 has been attributed to the effect of proton-neutron pairing in this N=Z nucleus. The data in this Figure are taken from T. Suzuki *et al.* [Phys. Rev. Lett. **75**, 3241 (1995)] while the calculations are from G.A. Lalazissis *et al.* [preprint nucl-th/9710013].

Recently, a new method has been developed for studying the rate for capture of nucleons that has special relevance for halo nuclei. In this method, one studies the reversed process of the breakup of nuclei in the strong electric field of a heavy nucleus. The measurement of such reaction rates is especially useful in studying the properties of weakly bound systems. This method has also been found particularly useful in the study of nuclear reactions that occur in stellar burning, for example in the sun where the by-products of these reactions also give rise to the emission of solar neutrinos.

Distributions of Nucleons

In heavier, neutron rich nuclei, the separation into a core and valence nucleons seems less justified. However, even in these nuclei the large N/Z ratio and the weak neutron binding implies the existence of a neutron skin (i.e., an excess of neutrons at large distances). Figure 6 displays calculated densities for two A=100 nuclei: one on the proton rich side of the valley of stability, ^{100}Sn (50 protons and 50 neutrons, N/Z=1) and one neutron rich nucleus, ^{100}Zn (30 protons and 70 neutrons, N/Z=2.33). For ^{100}Sn the proton and neutron densities are almost identical (proton and neutrons occupy the same shell model orbitals). In ^{100}Zn, however, both a neutron skin and pronounced diffuseness in the neutron density is clearly seen. In such a system the surface region extends deep into the nuclear interior and exhibits orders of magnitude changes in densities. A very interesting aspect of nuclei far from stability is an increase in their radial dimension with decreasing particle separation energy. Figure 7 presents the calculated differences between the average neutron and proton radii. The neutron skin is manifested by a rapid increase in neutron radii when moving toward the neutron drip line. While the interaction between nucleons in the nuclear interior is strongly influenced by their surroundings (in-medium effects), for the skin neutrons the effect of the nucleonic environment is much weaker. This situation is a challenge for a better modeling of the dependence of the effective nuclear force on the density of nuclear material and for experimental studies of nuclear interactions in the skin.

Pairing Correlations

Correlations between two particles that comprise a closely linked pair are of profound importance in many areas of many-body physics. The most familiar example is in superconductivity where the Cooper pairs of electrons lead to phenomena in condensed matter systems that are of immense practical importance. Less known but equally significant is the role of superconductivity or pairing correlations in nuclei. These correlations play a very special role in drip line nuclei where, contrary to the situation encountered close to the bottom of the valley of stability, the pairing force can no longer be treated as a small residual interaction. Rather, its effects on the nuclear binding of the outer nucleons become comparable in magnitude to that generated by the shell model potential. In fact, an increase in the magnitude of pairing correlations seems to be observed, on the proton rich side of stability, where we currently have greater access.

This is shown in Fig. 8. Of course, such effects could be much more dramatic on the neutron rich side of stability where the approach to the drip line is more gradual and where more neutrons are in weakly bound orbits.

That pairing correlations are important for weakly bound nuclei is suggested experimentally from studies of binding energies. Consider, for instance, the sequence of
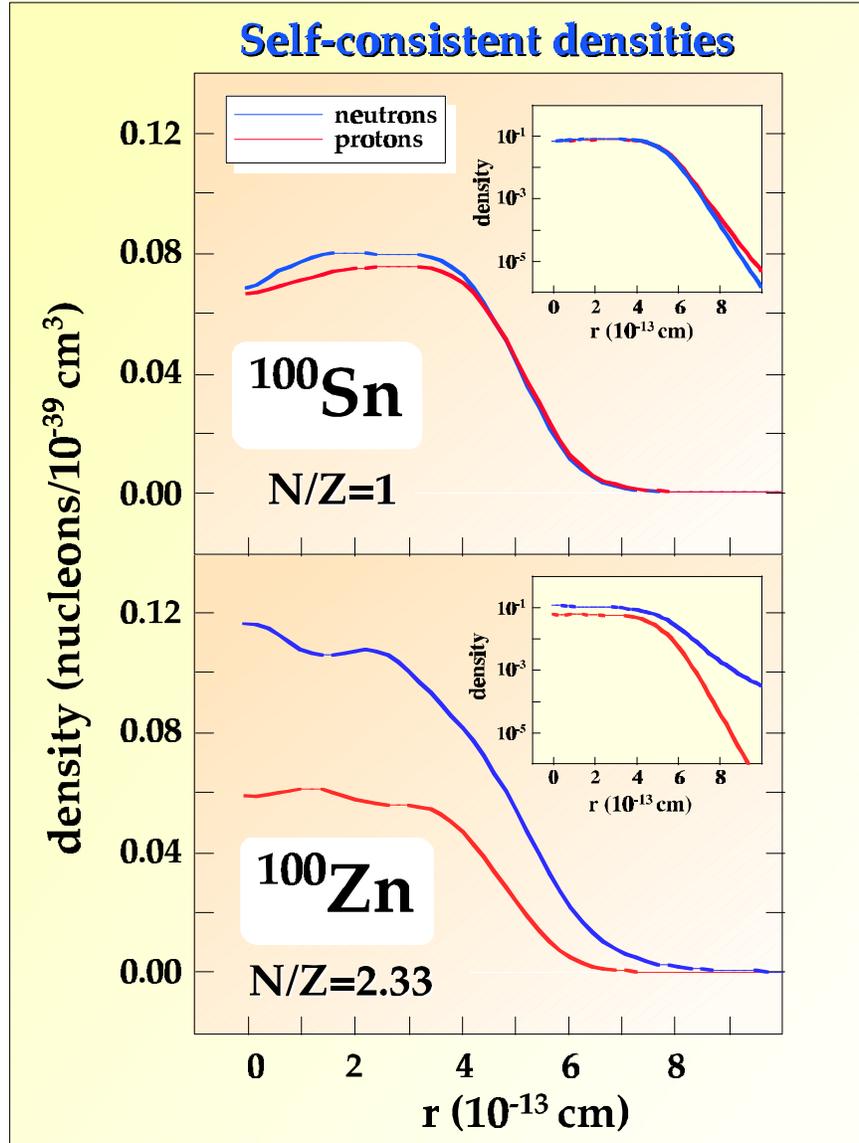
Fig. 6 Calculated densities of protons and neutrons in two extreme nuclei, each with 100 nucleons. The top panel shows the proton rich nucleus [100]Sn (Z=50, N=50), the bottom shows the neutron rich nucleus [100]Zn (Z=30, N=70). Note how the neutrons extend much further out in [100]Zn. This effect of a neutron skin is clearly seen in the logarithmic-scale plots in the insets. The small excess of neutrons in the interior of [100]Sn is compensated by the small excess of protons in the surface region. These calculations were done with an approach called the self-consistent Hartree-Fock-Bogoliubov theory. The diffused neutron density in [100]Zn gives rise to a very shallow shell model potential.
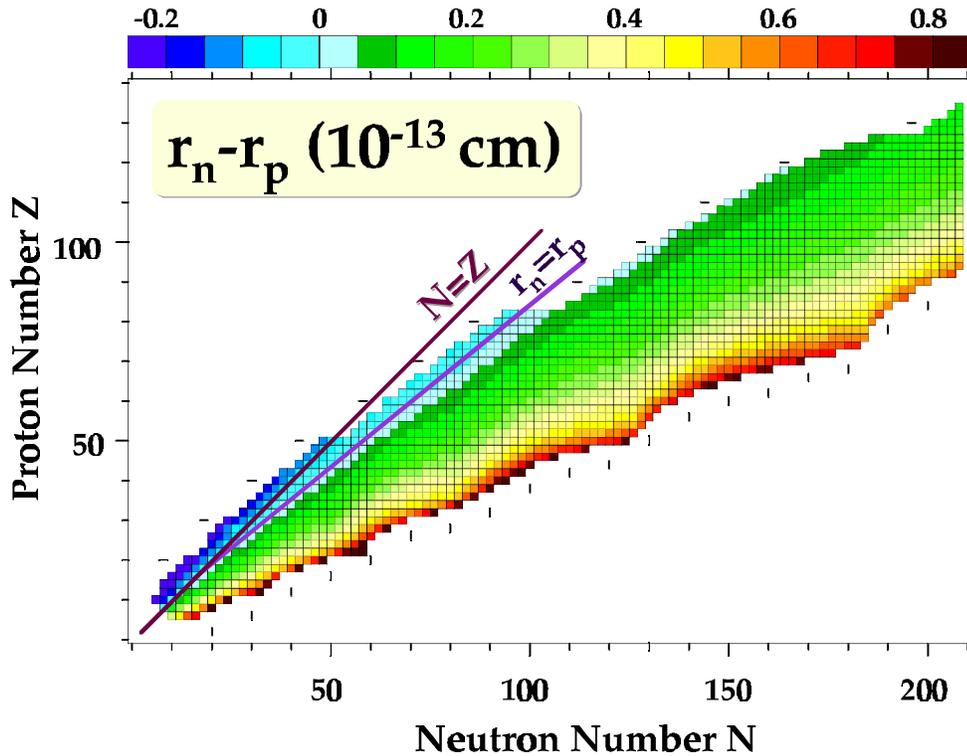
Fig. 7 Difference between neutron and proton rms radii, Δr_{np}, calculated in the spherical self-consistent Hartree-Fock-Bogoliubov theory, by J. Dobaczewski et al. [Z. Phys. **A354**, 27 (1996)]. The color codes are spaced by 0.05×10^{-13} cm. The valley of stability lies close to the line r_n-r_p in light nuclei and then bends towards the dark-green-colored boxes in heavier nuclei. It is seen that the influence of shell effects (sudden changes in color) on Δr_{np} is weak: the large neutron-proton attraction renders the radii of both types of particles as similar as possible, even in semi-magic systems where only one species is subjected to a strong shell effect. However, there is a gradual but significant trend from the proton drip line towards the neutron drip line. Very close to the neutron drip line, there is a sharp increase in neutron skin caused by weak binding: this is a local effect, strongly dependent on N. The line of equal neutron and proton radii, Δr_{np}=0, deviates from the N=Z line for heavy nuclei due to the Coulomb repulsion for protons.
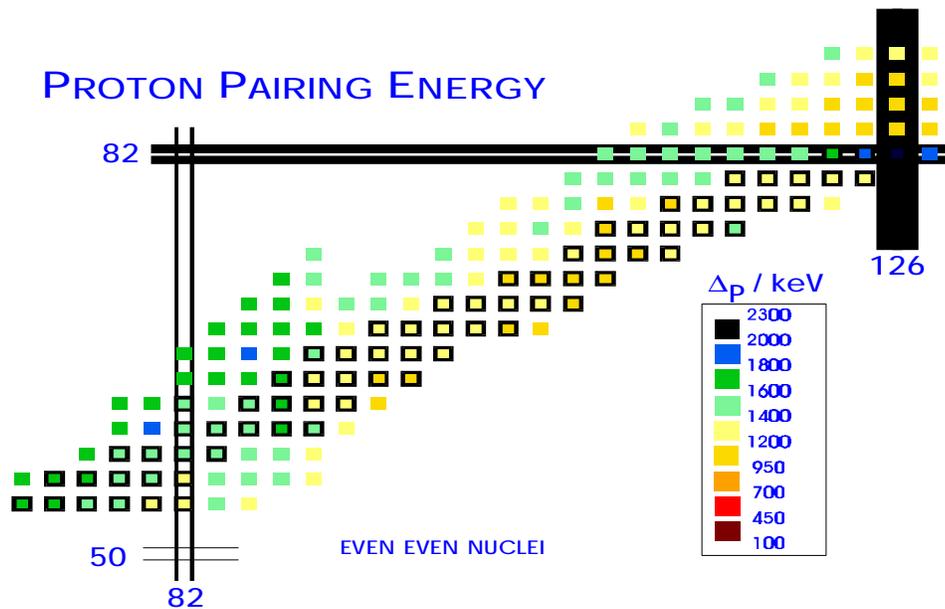
Fig. 8 Landscape of experimentally deduced proton pairing energies for a number of nuclei with even numbers of protons and neutrons that are located from tin (Z=50) to just beyond lead (Z=82). The pairing energies, Δ_p, are indicated (in keV) according to the color coded legend. With a few exceptions, especially near [208]Pb, the general trend for the pairing energy is an increase towards the left as the proton drip line is approached, demonstrating the importance of pairing correlations near the drip lines. The figure is taken from T. Radon *et al.* [Multiturn Mass Measurement Group Meeting, Rauischholzhausen, Germany, June 1997]

helium isotopes. The nucleus ^{4}He (α-particle) has the strongest binding per nucleon of any nucleus. However, its heavier neighbor, ^{5}He, is neutron-unstable. By adding another neutron one arrives at the Borromean system ^{6}He which is bound due to the increase in neutron pairing energy. And then the pattern continues: the next isotope, ^{7}He, is neutron-unstable while the still heavier ^{8}He is bound. (^{8}He is also the heaviest bound He isotope: the doubly magic nucleus ^{10}He decays by emitting neutrons). Although pairing is not the full story here, it evidently plays a major role.

Surprisingly, very little is known about the pairing force. Up to now, the pairing interactions employed are usually designed to reproduce data on actual nuclei, whereas interactions deduced microscopically from effective nucleon-nucleon forces are seldom used. Actually, schematic models of pairing perform remarkably well when applied to nuclei in the neighborhood of the stability valley (where, as pointed out above, pairing can be considered as a small correction). However, this may no longer be true for weakly bound neutron rich nuclei. The main questions we face pertaining to the pairing force are: What is its microscopic origin and how does the range over which the force acts depend on the density of protons and neutrons in the nucleus and, especially, on the surface? How can properties of the pairing force be tested? These questions are of importance not only for nuclear physics but also for nuclear astrophysics and cosmology. For instance, a better understanding of the density dependence of the nuclear pairing interaction is important for theories of superfluidity in neutron stars. Because of strong surface effects, weakly bound nuclei are perfect laboratories in which to study the basic properties of neutron pairing. An experimental observable that may probe the character of the pairing correlations is the probability of reactions in which a pair of neutrons is transferred between projectile and target nuclei.

Shell Structure Far From Stability

The structure of the nuclear potential (that is, the shape and strength of the force field experienced by the nucleons) is expected to change significantly as the limit of nuclear stability is approached on the neutron rich side. Due to the systematic variation in the spatial distribution of nucleonic densities and the increased importance of pairing, the average nucleonic potential should become more diffuse. This would result in a new shell structure characterized by different sequences of energies and different magic numbers, or no magic numbers at all. Magicity as a concept is tenuous and perhaps variable at the neutron rich extremes of the nuclear world.

The weakening of shell effects in drip line nuclei would manifest itself in the energy required to separate the last two nucleons from the nucleus. These separation energies, denoted S_{2n}, are illustrated in Fig. 9 for nuclei with N=80, 82, 84, and 86 calculated in a self-consistent model. These separation energies imply that the large N=82 magic gap in single particle energies, which is clearly seen in nuclei close to the stability valley and to the proton drip line, is expected to gradually disappear when approaching the neutron drip line.

The predicted behavior of experimental observables related to shell gaps, such as two-neutron separation energies, depends very much on the effective interaction used. This is illustrated in Fig. 10 which shows separation energies calculated in the tin isotopes. Calculations agree well in the region when experimental data are available but they quickly diverge farther from stability. It should be noted, however, that the microscopic models known to reproduce isotopic trends (labeled SkP, SLy4, and FRDM in the figure) give more consistent predictions. Nevertheless, the predicted location of the neutron drip line
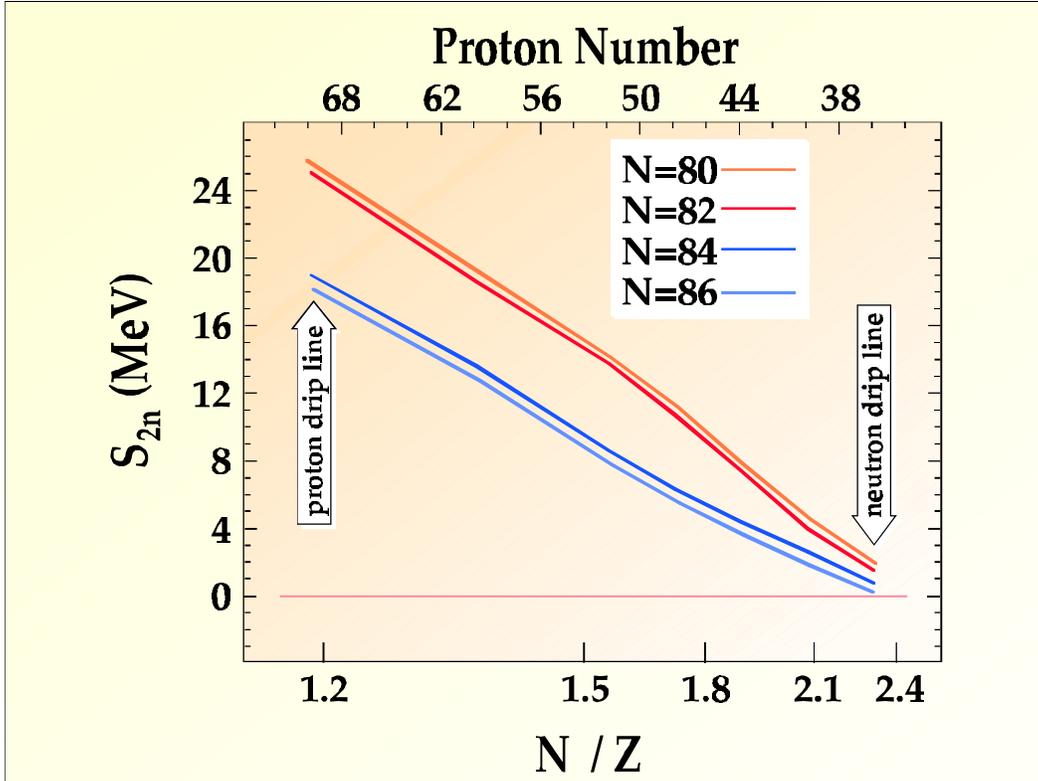
Fig. 9 Two-neutron separation energies for spherical nuclei with neutron numbers N=80, 82, 84, and 86 and even numbers of protons calculated in the self-consistent Hartree-Fock-Bogoliubov theory as a function of the proton number. The arrows indicate the approximate positions of the neutron and proton drip lines for small and large proton numbers, respectively. The large N=82 magic gap, clearly seen in the nuclei close to the stability valley and to the proton drip line, gradually closes down when approaching the neutron drip line. These calculations are taken from J. Dobaczewski *et al.* [Phys. Rev. **C53**, 2809 (1996).]

for the Sn isotopes depends strongly on the effective interaction used and it varies at least between N=118 and N=126.

Changes in shell structure in very neutron rich nuclei are expected to have important ramifications for the basic excitation modes of these nuclei as well. This can be seen by comparing the energies of shell model orbits in Fig. 11 -- the normal sequence on the left and possible scenarios for single particle energies near the neutron drip line in the middle and right panels. Here, we see the disappearance of the magic numbers 50 and 82

which have been cornerstones of our understanding of nuclear structure for half a century. But the figure reveals other effects of equal significance. The order and energies of the levels within a shell are completely different. Since collective excitations in nuclei depend sensitively on the particular orbits that can be occupied, the manifestations and evolution with N and Z of coherent excitations modes may be different than we have observed to date.

How can we study the structure of these neutron rich nuclei? What are the key experimental quantities? We have already discussed nucleon separation energies in relation to shell quenching. Discontinuities in separation energies can also serve as signatures for shape changes in nuclei when one or two nucleons are added. Shell structure in exotic nuclei can be studied in a variety of other ways as well. Both single particle energies and effective interactions between nucleons may be extracted from experiment by two approaches. The first involves the comparison of data with calculations with the shell model for many nuclei, especially in regions where nearly all states are known. This has been done for light nuclei. For heavier nuclei such spectroscopy becomes difficult. The energies and interactions are then better determined by the alternate approach -- from the spectra of nuclei in the vicinity of closed shells. Single particle energies can be determined best from nuclei with a single nucleon added to or removed from a magic nucleus. Phenomenological nucleon-nucleon interactions are best investigated in systems with two nucleons outside a closed shell nucleus. In both cases, we can use reactions in which one or two nucleons are transferred between projectile and target (in either direction). Since unstable nuclei do not live long enough to be useable as targets these reactions would exploit the technique of inverse kinematics in which the roles of target and projectile are interchanged. For example, a beam of ^{132}Sn can be used to bombard light targets. Single nucleon transfer reactions such as (d,p), (p,d), (t,α), which traditionally could only be used for the spectroscopy of near-stable nuclei, once again become very powerful tools to identify the energies of a particle outside a closed shell. These experiments are most sensitive for beams of 6-10 MeV/nucleon which will be available from an advanced ISOL facility. Effective nucleon-nucleon interactions can be determined from the spacings of energy levels corresponding to the energies of two particles outside doubly magic cores. Most such data comes from the vicinity of ^{208}Pb, with fragmentary information from other, less ideal, closed shell nuclei such as ^{40}Ca, ^{48}Ca, ^{88}Sr and ^{90}Zr. ^{132}Sn is an excellent closed shell nucleus and would again provide new experimental information. In particular, it would confirm whether the residual interactions obtained from nuclei near stability may indeed be extrapolated to the neutron rich regime. Experiments to measure effective interactions would be done much as for the single particle states, except that the beams would differ from ^{132}Sn by one nucleon: ^{133}Sn, ^{131}Sn, ^{133}Sb, or ^{131}In. The transfer reactions will then populate levels based on these particle states coupled to the additional nucleon.

Beam intensities of short-lived nuclei near the peak of the fission fragment distribution, such as ^{132}Sn, will approach about one particle nanoampere(nA) and allow measurements in times comparable to those with stable beams and targets. Studies across a shell to even more neutron rich nuclei will have to rely on considerably smaller beam
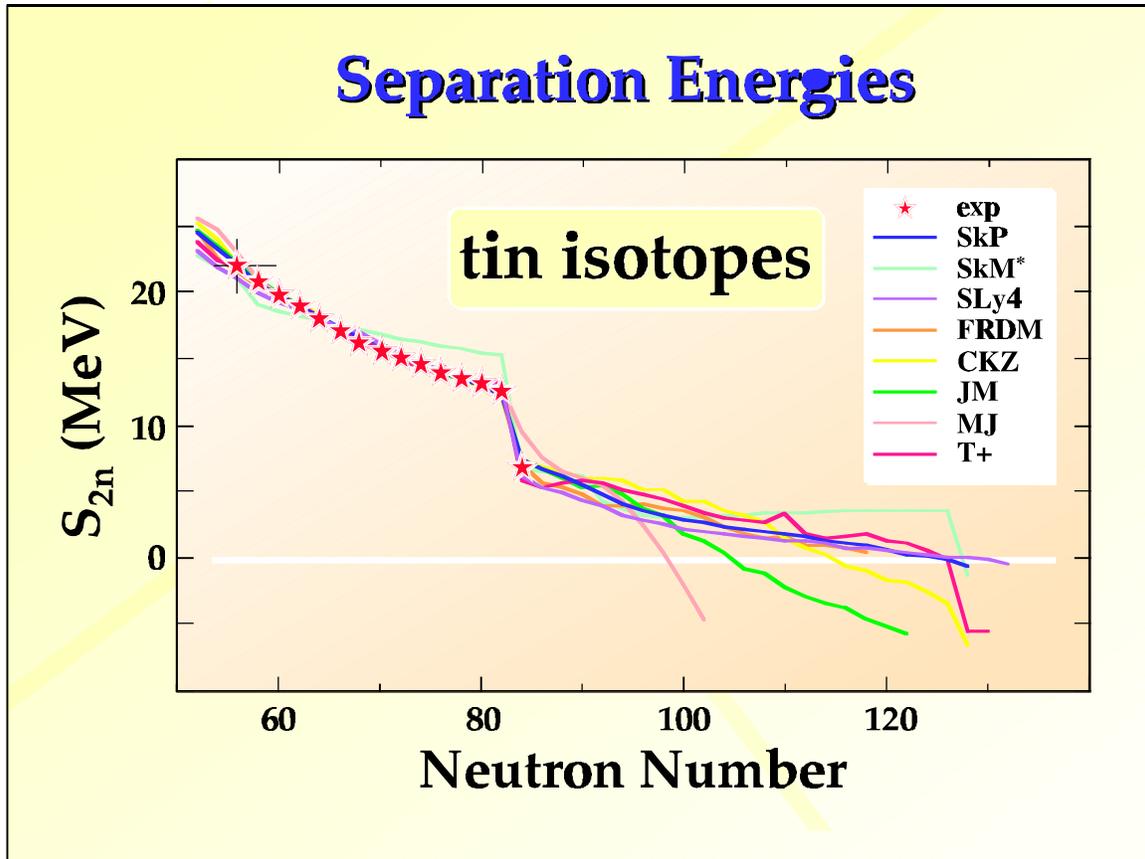
Fig. 10 Separation energies and the neutron drip line from recent microscopic calculations and phenomenological formulas. Experimental (stars) and calculated (lines) two-neutron separation energies S_{2n} are given for the Sn isotopes. Calculations range from the self-consistent Hartree-Fock-Bogoliubov approach with effective interactions SkP, SkM*, and SLy4, the microscopic-macroscopic finite-range droplet model (FRDM), to the phenomenological mass formulae by Comay-Kelson-Zidon (CKZ), Jänecke-Masson (JM), Masson-Jänecke (MJ), and Tachibana et al. (T+). Calculations agree well in the region where experimental data are available but they diverge far from stability. It should be noted, however, that the microscopic models known to reproduce isotopic trends (SkP, SLy4, and FRDM) give more consistent predictions.
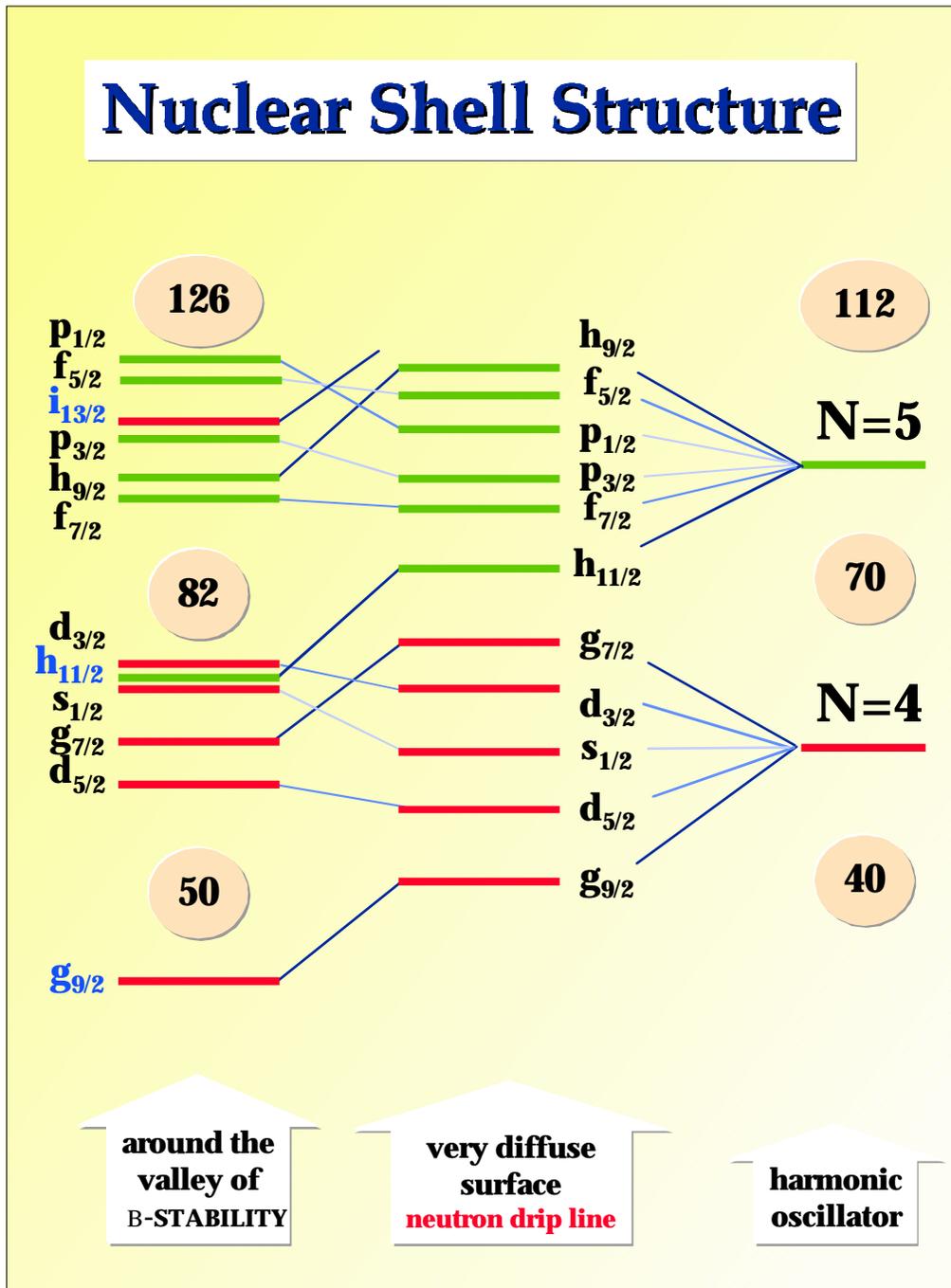
Fig. 11 Left: Shell structure characteristic of nuclei close to the valley of stability. Middle: New shell structure characteristic of very shallow single particle potentials in drip line nuclei. It corresponds to a more uniform distribution of orbits with the same parity and to a sequencing of orbits within a shell that is very different from the normal ordering seen near stability. In the absence of a spin-orbit splitting (a significant reduction of spin-orbit coupling in neutron rich nuclei has actually been predicted by some calculations), this single particle spectrum is expected to approach the limit of the spherical harmonic oscillator (shown in the right panel), in which the clustering of levels reaches an extreme.

Fig. 12 data — even-even nuclei from Er (Z=68) to Hg (Z=80). Each box: top (red) = energy in keV of first 2+ state; middle (brown) = E(4)/E(2) ratio; bottom (green) = B(E2).

Z \ N	104	106	108	110	112	114	116	118	120	122	124
80	366 / 2.97 / 1.94	405 / 2.67 / 1.37	413 / 2.43	416 / 2.50	423 / 2.50	428 / 2.49					
78	155 / 2.70	163 / 2.68 / 3.95	192 / 2.56 / 2.98	266 / 2.53 / 2.60						470 / 2.36	
76	132 / 3.09 / 3.62	127 / 3.15 / 3.81						219 / 2.75	300		
74	106 / 3.24					143 / 3.09					
72				98 / 3.29	107 / 3.26						
70			84 / 3.31								
68	77 / 3.31										E(2) / E(4)/E(2) / B(E2)

Blue lettering in the diagonal stable-nuclei swath spells: N U C L E I and S T A B L E.

Fig. 12 A portion of the nuclear landscape showing the even-even nuclei from Er (Z=68) to Hg (Z=80). In each box up to three numbers are shown. These are experimental values for the most basic quantities that tell us the overall structure of a nucleus, namely, the energy (in keV) of the first excited state (with spin and parity 2^+), the ratio of the energies of the first 4^+ and first 2^+ levels, and a quantity, B(E2: $2^+_1 \rightarrow 0^+_1$), which measures the strength of the γ-ray emission transition from the 2^+ level to the 0^+ ground state. (The quantity is given in units called electron-barns squared). The stable nuclei are denoted by the blue diagonal swath. For these stable nuclei, and most proton rich nuclei, extending quite far from stability, all three of these essential clues to structure are known experimentally. For neutron rich nuclei the opposite is true. In fact, there is not a single neutron rich nucleus in this entire region, even only one nucleus beyond stability, where all three quantities are known. Two or more nuclei away from stability, virtually nothing is known.

intensities. Meaningful measurements of these reactions that have, at most, cross sections of millibarn size, could still be done for important selected cases down to 10^3 beam particles per second, for, say, ^{140}Sn.

Another area where direct reactions using radioactive beams in inverse kinematics can be of particular importance is sub-Coulomb pick-up and stripping, where the incident particle energy is actually below the energy classically required to overcome the electrical or Coulomb repulsion between projectile and target nucleus. It has been demonstrated for the case of the nucleus ^{208}Pb that, at sub-Coulomb energies, light ion induced stripping and pick-up reactions provide a direct measure of the structure of the single particle states (their "wave functions") and thus can trace their radial distribution. This is so because the particles follow trajectories which do not depend on the ambiguities of nuclear potentials but only on the well known Coulomb force.

The interest in nucleon distributions in neutron rich nuclei has certainly been stimulated by the discovery of neutron halo nuclei, and a modification of the above reaction may also be useful to quantitatively measure thin neutron tails. For light nuclei, one possibility is to measure sub-Coulomb transfer by bombarding a heavy nucleus with a halo nucleus at low energy. This procedure has been demonstrated with the (^{13}C, ^{12}C) stripping reaction showing that, with reasonable assumptions about the ^{13}C wave functions, the same information is obtained in ^{209}Pb as in the sub-Coulomb (d,p) reaction. Again the range of beam intensities can extend from nA down to about 10^5 particles/sec.

Historically, much of our basic understanding of nuclear systems has been derived from the knowledge of their ground state properties. Information on the spins, parities, and electromagnetic moments of the ground states of odd-mass and odd-odd nuclei can also provide direct information about their single particle nature and, hence, about possible modifications to the nuclear potential. The low lying excited states of even-even nuclei can be probed with techniques such as Coulomb excitation, inelastic scattering, and β-decay. Such studies investigate the way the nucleus reacts to gentle perturbations as manifest in characteristic collective motions such as vibrations and rotations of the nucleus as a whole. Coulomb excitation in inverse kinematics can probe collective excitations in nuclei even with beam intensities as low as 10^3 particles/sec. If one has well-collimated beams, such experiments can place the target inside a hole through the γ-ray detector, thus assuring very high detection efficiency.

Of course, the study of neutron rich nuclei has always been and will remain difficult. Such nuclei are not easily reached with reactions that fuse lighter, stable nuclei (since these have smaller N/Z ratios). Indeed, as shown in Fig. 12, nearly nothing is known even about the first nuclei beyond stability on the neutron rich side in the entire Z=68-82 region. Hence, even modest forays into new territory with radioactive beams can bring important data into play. It is striking to recall that the nucleus ^{214}Pb was discovered by Hahn and Meitner in 1909 but it took until 1996 for the discovery of the very next Pb isotope, ^{215}Pb. RNB studies can allow us to rapidly extend these frontiers. Sometimes the simplest-to-obtain data can provide clues to changes in structure that may emerge more fully as one approaches closer to the drip lines.

In this context an analysis of experimental trends in terms of structurally significant quantities can be revealing: One such quantity, which reflects the importance of the proton-neutron interaction among valence nucleons, is the simple product of the number of valence protons N_p times the number of valence neutrons N_n. Figure 13 (top) gives a typical example -- a plot of the ratio of the energies of the two lowest excited states (with angular momentum and parity 2^+ and 4^+) in nuclei near mass number A ~ 170. While the plot of
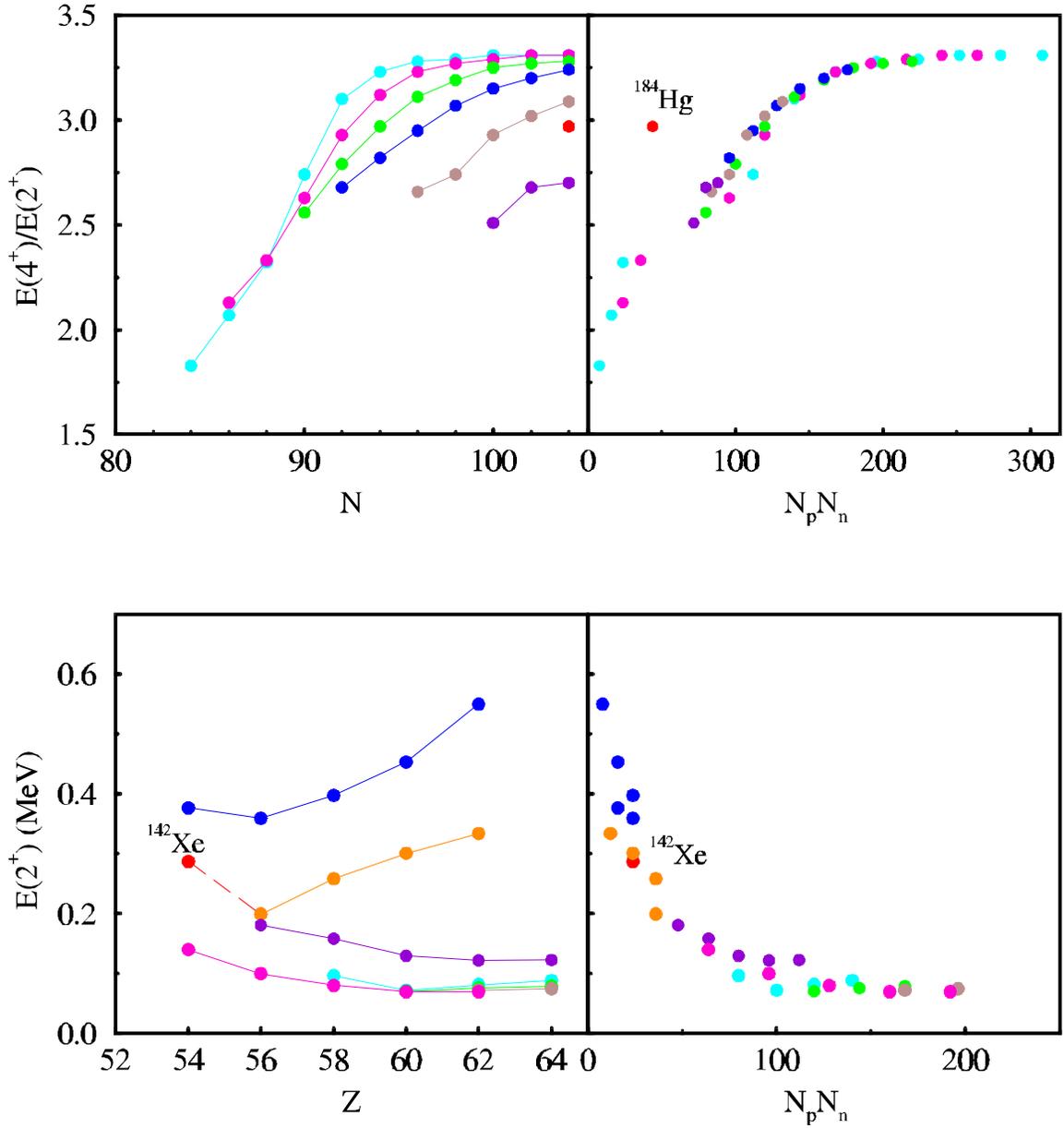
Fig. 13 Two examples of so-called normal and N_pN_n plots of basic experimental data that tells us the structure of even-even nuclei. The top plot shows the energy ratio of the first two excited states, of spin and parity 4^+ and 2^+ for Z=66-82, while the lower panel shows the 2^+ energy itself, for a set of nuclei with A~130-160. On the left in each panel is a normal plot, either against neutron or proton number. Here the data points are widely scattered and present a complex picture. On the right, exactly the same data are plotted against the product of the number of valence protons, N_p, times the number of valence neutrons N_n. This product simulates the number of proton-neutron interactions of the outermost nucleons. The idea behind the plot is that this interaction is so important that one might expect the data to be a smooth function of its overall strength. Indeed, the data do follow a smooth and compact trend. In fact, the simplicity of these plots reveals anomalous nuclei (such as ^{184}Hg) that would be hard to identify in a normal plot. The lower panel shows how the N_pN_n scheme can transform the process of extrapolation in estimating the properties of new nuclei into the much safer one of interpolation.

nuclear observables against neutron number shows a wide spread, a plot of the same data against the product N_pN_n reveals a simple, compact envelope of data points.

These correlations can amplify deviations from normal behavior. Such deviations may signal changes in magic numbers, competition with exotic configurations, or quenching of shell structure altogether. This is, in fact, exemplified in Fig. 13 (top), which shows one deviant data point whose anomalous value is not at all apparent in the normal plot on the left. Once recognized, though, this anomaly is easy to interpret -- it is related to a special deformed (or intruder) configuration in the nucleus ^{184}Hg. N_pN_n correlations have another property of special interest for the study of exotic nuclei. Predictions for such nuclei in normal plots against N, Z or A necessarily involve extrapolation from existing trends. In contrast, the N_pN_n product for exotic nuclei is often less than for known nuclei in the same region. Hence, one can use the safer method of interpolation within an already known trendline as illustrated in the lower panel of Fig. 13. For example, to estimate the energy of the 2^+ state in ^{142}Xe in the normal plot on the left entails substantial guesswork and it is unlikely that one would have anticipated the specific kink in the systematics that is observed for this nucleus. On the right, the observed energy is identical to that obtained by simply reading off the curve at the appropriate N_pN_n value.

An especially important region of moderately neutron rich nuclei is that of the heaviest nuclei -- the actinides, near mass number 250. These nuclei have large numbers of valence nucleons and hence are among the most collective nuclei that we can study. The interplay of shell structure and large Coulomb effects determines just where the most stable and the most deformed nuclei are. We can almost but not quite reach them now. However, with radioactive beams, we can actually home in on the nuclei near ^{250}Fm and ^{252}Cf that are calculated to have among the most elongated ellipsoidal shapes in the entire region.

Finally, another important experimental manifestation of shell quenching in neutron rich nuclei may be its influence on stellar nucleosynthesis. Very neutron rich nuclei cannot be reached experimentally under present laboratory conditions. On the other hand, these systems are the building blocks of the astrophysical process of rapid-neutron-capture (the r-process -- See Section III): the separation energies, decay rates, and neutron capture cross sections of these nuclei are the basic quantities determining the path and rate of the nucleosynthesis of heavy nuclei. Consequently, one can actually hope to learn about very neutron rich systems by inverting the problem and studying the r-process component of the solar system abundances of heavy elements to infer the properties of the unstable nuclei along the r-process path. Recent r-process calculations illustrated in Fig. 14 indicate that a quenching of the shell effects at N=82 and N=126 can lead to dramatic improvements between the calculated abundances of nuclei around A=118, 176, and above 200 with experimentally determined abundances of nuclei produced in the r-process.
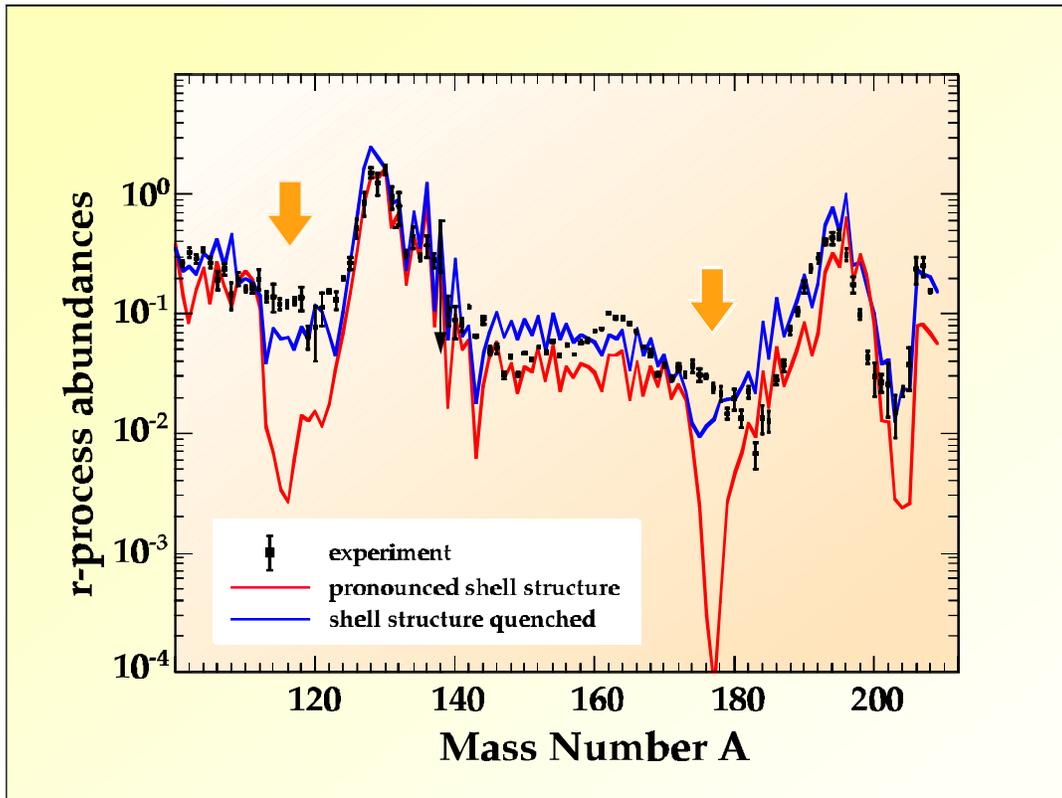
Fig. 14 The very neutron rich drip line nuclei cannot be reached experimentally under present laboratory conditions. On the other hand, these systems are the building blocks of the astrophysical r-process; their separation energies, decay rates, and neutron capture cross sections are the basic quantities determining the results of nuclear reaction network calculations. Consequently, one hopes to learn about properties of very neutron rich systems by studying the r-process component of the solar system abundances of heavy elements. The black squares with error bars indicate the experimentally deduced r-process abundances for nuclei with mass numbers greater than A=100. The theoretical abundances, marked by red and blue, were obtained in the recent r-process network calculations Pfeiffer et al. [Z. Phys. **A357**, 235 (1997)]. They are based on microscopic mass formulae which assume that the spherical shell gaps towards the neutron drip line are either similar to those in stable nuclei (red curve) or significantly quenched (blue curve) as suggested by the calculations shown in Fig. 9. It is seen that calculations that incorporate a quenching of magic gaps at N=82 and N=126 greatly improve our ability to understand the experimental solar abundances of the elements around A=118 and 178, and above 200.

Exotic Collective Modes in Weakly Bound Neutron Rich Nuclei

Neutron halos and heavy, weakly bound neutron rich nuclei offer an opportunity to study the wealth of phenomena associated with the closeness of the particle threshold. We have learned that weakly bound nuclei are different; they have giant sizes, they are diffuse, they are strongly superfluid, and their shell structure is probably different. What are their collective behaviors? Can they -- for instance -- be deformed? Can they permit exotic shapes or excitation modes? The answer is likely to be positive. Some examples of such modes are shown in Fig. 15.

The presence of the spatially extended neutron skin gives rise to exotic low energy modes representing the relative motion of the skin (or halo) with respect to the more bound neutron-proton core. In the top image of Fig. 15 the core oscillates against the halo giving a so-called "pygmy" giant E1 resonance. At lower left, we see a deformed core embedded in a spherical halo distribution. Nuclei close to the neutron drip line such as the neutron rich sulfur isotopes are excellent candidates for these exotic shapes embodying different deformations for protons and neutrons. Finally, in the lower right illustration the halo and core density distributions oscillate against each other in angle -- a collective scissors-like mode.

The question of shapes in halo nuclei raises a fundamental issue of how we should think about the concept of a geometric description of weakly bound, low density, quantal objects. The issue is how to relate weak binding and deformation? Shape deformation is an extremely powerful concept provided that the nuclear surface can be properly defined. However, in the limit of very weak binding, the geometric concept itself of a single shape may be lost. That is, the shape of the halo might be determined by the spatial structure of the valence nucleons, independently of the shape of the core. The large halo radius effectively gives a spherical outer boundary. In heavier neutron rich nuclei the neutron skin and the nearby continuum of unbound levels allows for strong pairing. For nuclei a few nucleons or more inside the drip line, the binding is also larger. Hence, an important question is how will deformation be modified in the presence of enhanced pairing, and for greater separation energies? We do not know the answer to this question; the systematic investigation of the interplay between deformation and pairing in weakly bound neutron rich nuclei is one of the exciting avenues of physics which can be explored with exotic beams.

Proton Rich Nuclei

On the proton rich side, the proton drip line lies much closer to the valley of stability, and, therefore, we have the opportunity to reach the proton drip line for nearly all elements up to and even beyond lead. Near the proton drip line, many interesting physics questions will be explored. Among them are proton radioactivity and nuclear structure beyond the proton drip line; the effects of the proton-neutron interaction and the prospects for emergence of a new type of nuclear superconductivity; isospin breaking interactions and mirror nuclei; shell structure near magic particle number 50; novel new shapes; and the properties of nuclei important in the nucleosynthesis processes in stars. We address some of these opportunities here. Very proton rich nuclei are also important for tests of the Standard Model and studies of the astrophysical rp-process that will be discussed in the following Sections.

Proton Radioactivity and Structure near the Proton Drip Line

A phenomenon peculiar to extremely proton rich nuclei is proton radioactivity. In this phenomenon, proton emission is delayed by an almost counter-intuitive consequence

of the repulsive Coulomb interaction. Ironically, this interaction, which places the proton drip line much closer to stability than the neutron drip line, partially compensates by erecting a barrier that slows down the proton decay process. In these nuclei the protons are emitted with lifetimes ranging from seconds down to, say, a billionth of a second. The decay involves a process called quantum tunneling through the barrier created by the Coulomb force. Proton radioactivity thus creates a new possibility to study nuclei that are actually beyond the formal limits of nuclear existence. Rigorously speaking, these protons
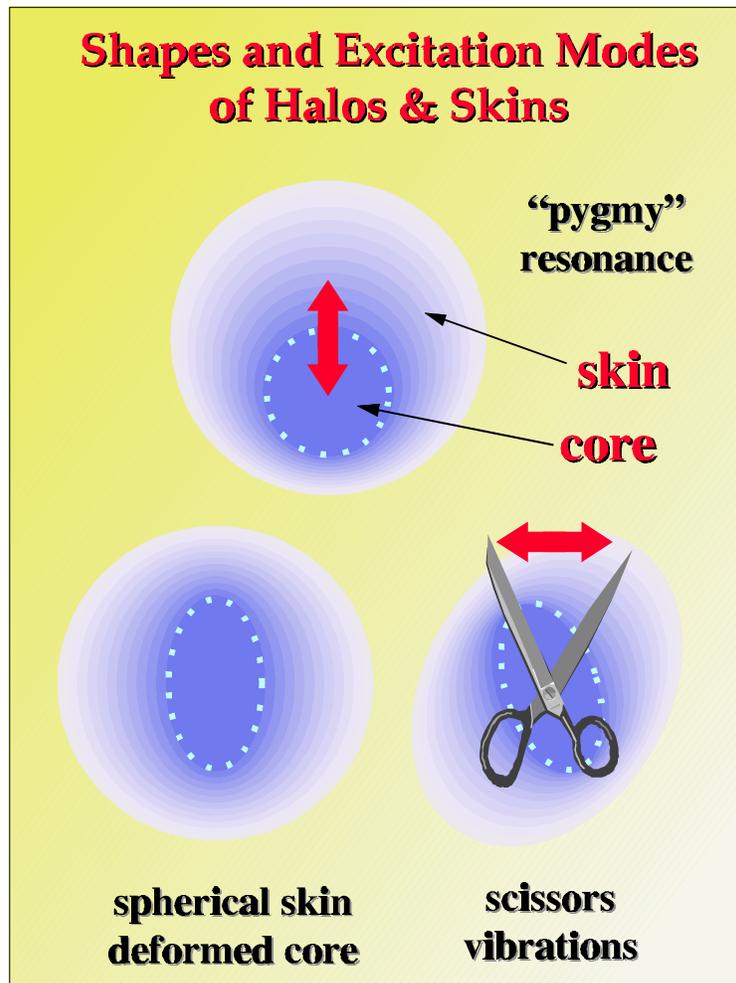
Fig. 15 Schematic illustration of collective modes associated with the neutron skin. The top left diagram shows vibrations of the neutron skin (or halo) with respect to the core (indicated by a light dotted line). This coherent mode is sometimes referred to as a "pygmy" resonance, in distinction to a collective mode in normal nuclei where all the protons and neutrons oscillate against each other. The lower left diagram shows a system with very different shapes of skin and core (here the core is ellipsoidal while the skin is spherical). The right diagram illustrates the angular vibrations of a deformed skin with respect to the deformed core (a so-called skin "scissors" mode).

occupy unbound levels: they lie in the particle continuum we have discussed earlier. The decay rates for these processes are sensitive to the quantum numbers and structure of the parent and daughter states. Structural information thus gleaned about the continuum will

provide valuable insights into effective interactions, pairing and nuclear shapes in this nether world that is neither bound nor free. One important aspect of this is illustrated in Fig. 16 which shows the relation between the experimental proton emission half-lives and the angular momentum of the emitted proton. In some regions of heavy nuclei that will only be accessible with radioactive beams, the parent nuclei are non-spherical. Proton radioactivity then entails tunneling of a proton through a deformed 3-dimensional barrier -- an opportunity to study a basic quantum effect found in many systems encountered in modern physics and technology.
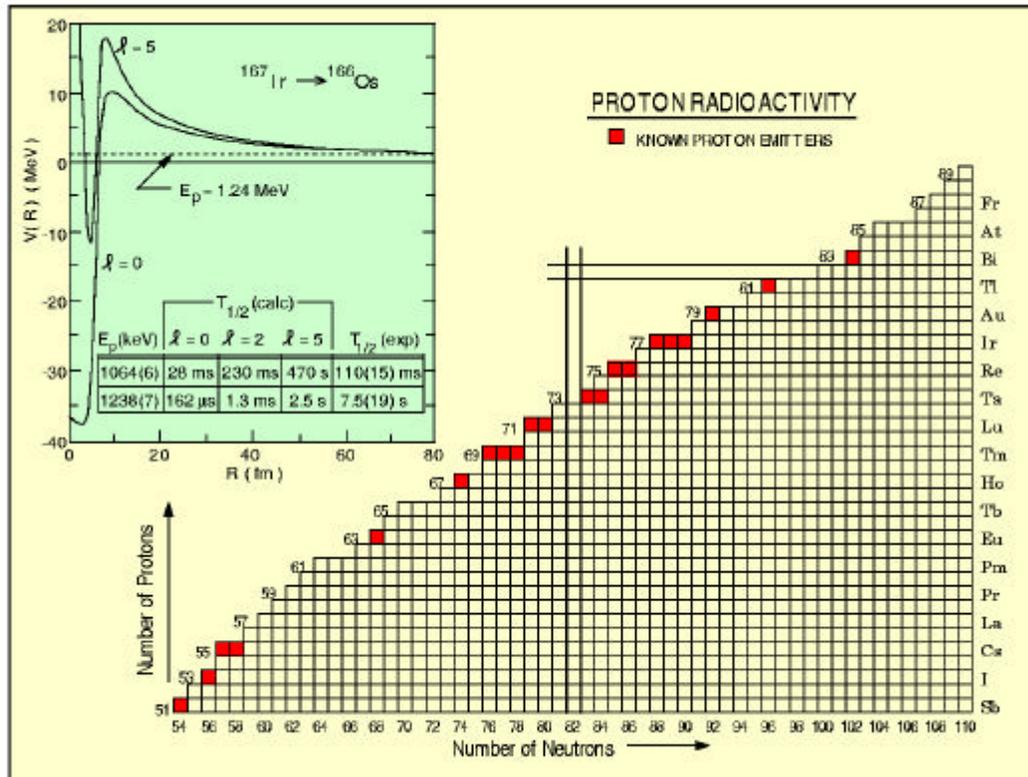
Fig. 16 Locations of known proton emitters at the proton drip line and a graphical representation of the potential barrier that the proton has to tunnel through when escaping from the mother nucleus. It is interesting that the barrier at the binding energy of the proton reaches out to about ten times the size of the nucleus (approximately 10^{-12} cm; note the deep pocket in the potential) before the proton is completely free. The insert also quantifies with the example of the ^{167}Ir nucleus the relationship between the proton emission half lives and the angular momentum of the proton. The higher the angular momentum, the higher the total barrier due to the contribution from the centrifugal force.

Short-lived radioactive beams will allow studies of nuclear levels and nuclear structure in the vicinity of the proton drip line for all elements at least up to lead. New techniques (such as the tagging of recoils in their ground states) and observation of their subsequent decays by γ-ray and particle emission) are providing powerful tools for these structure studies. Since unbound protons are temporarily held by the Coulomb barrier

before being emitted, this technique will allow nuclear structure studies and spectroscopy that actually extend beyond the proton drip line itself.

Near the proton drip line one also encounters very interesting cases of doubly magic nuclei namely, ^{48}Ni (Z=28, N=20), ^{56}Ni (N=Z=28), and ^{100}Sn (N=Z=50), corresponding to combinations of the neutron or proton numbers 20, 28 and 50. Since cases of well-studied doubly magic nuclei are rare indeed (above ^{48}Ca, there are only ^{132}Sn and ^{208}Pb) this offers another opportunity to explore the benchmarks of shell structure. It is important to assess the robustness or fragility of shell structure on this proton rich side of stability where neutron and proton numbers are similar, in order to compare with neutron rich systems where fragility appears, in part because of the highly unbalanced numbers of protons and neutrons.

Symmetries in N=Z Nuclei

The element tin with 50 protons forms the approximate boundary below which we are able to form and study nuclei with N/Z ratios of one or less. Since protons and neutrons in nuclei with N=Z can occupy the same orbitals, these nuclei have special symmetries. Shell model calculations point to the sudden importance of a unique type of proton-neutron interaction in N~Z nuclei. As we have explained earlier, a basic property of nuclei away from the N=Z line is that their protons (and neutrons) pair together to form Cooper pairs of like nucleons with a net angular momentum of zero (see parts (a) and (b) in Fig. 17). This common form of pairing profoundly affects the properties of the low-lying states in normal nuclei. However, if protons and neutrons occupy the same orbital in a nucleus, they can form the proton-neutron pairs shown in (c) and (d) of Fig. 17. The pair in panel (d) is special: it does not have angular momentum zero. It corresponds to a non-spherical Cooper pair that is actually donut shaped. The simplest system that manifests this type of pairing is the deuteron, an isotope of hydrogen with one proton and one neutron. The importance of this new form of pairing in many-nucleon systems is predicted to grow rapidly near nuclei with N=Z and leads to several exotic effects.

One of the most dramatic of these effects is the additional binding energy that is generated by the interaction of protons and neutrons when they move together or in spatially close orbitals. This additional binding energy is observed as spikes in the experimental binding energies of the N=Z nuclei. A plot of this so-called Wigner energy, extracted from the binding energies of the N=Z nuclei and their neighbors, is shown on the right in Fig. 17 for the light to medium-mass nuclei. Only shell model calculations that take both types of proton-neutron interactions (T=1 and T=0) into account reproduce experimental Wigner energies. Measurements of the Wigner energy in newly accessible N=Z nuclei thus will allow us to probe the nature, strengths, and effects of the proton-neutron interaction very sensitively.

A key issue is the extent to which the Wigner energy, which is rooted in the specific coupling of protons and neutrons in heavy nuclei similar to that which occurs in

the deuteron, dominates the structure of heavy N~Z nuclei. If such a coupling could exist among many pairs of nucleons in a nucleus, it would represent a new phase of nuclear superconductivity, not observed to date. Among possible experimental signatures of this phenomenon, besides the Wigner effect in binding energies, are: (i) an energy gap in the levels of odd-odd nuclei, similar to that observed at low energies in even-even nuclei; (ii) an enhanced probability to form an odd-odd nucleus by the addition to or removal of a deuteron-like pair to even-even nuclei in a nuclear transfer reaction; and (iii) the absence of the irregularities commonly observed in states of high angular momentum that are associated with the breaking of an ordinary nn or pp Cooper pair. These and other suggested signatures can only be investigated with the help of radioactive ion beams.
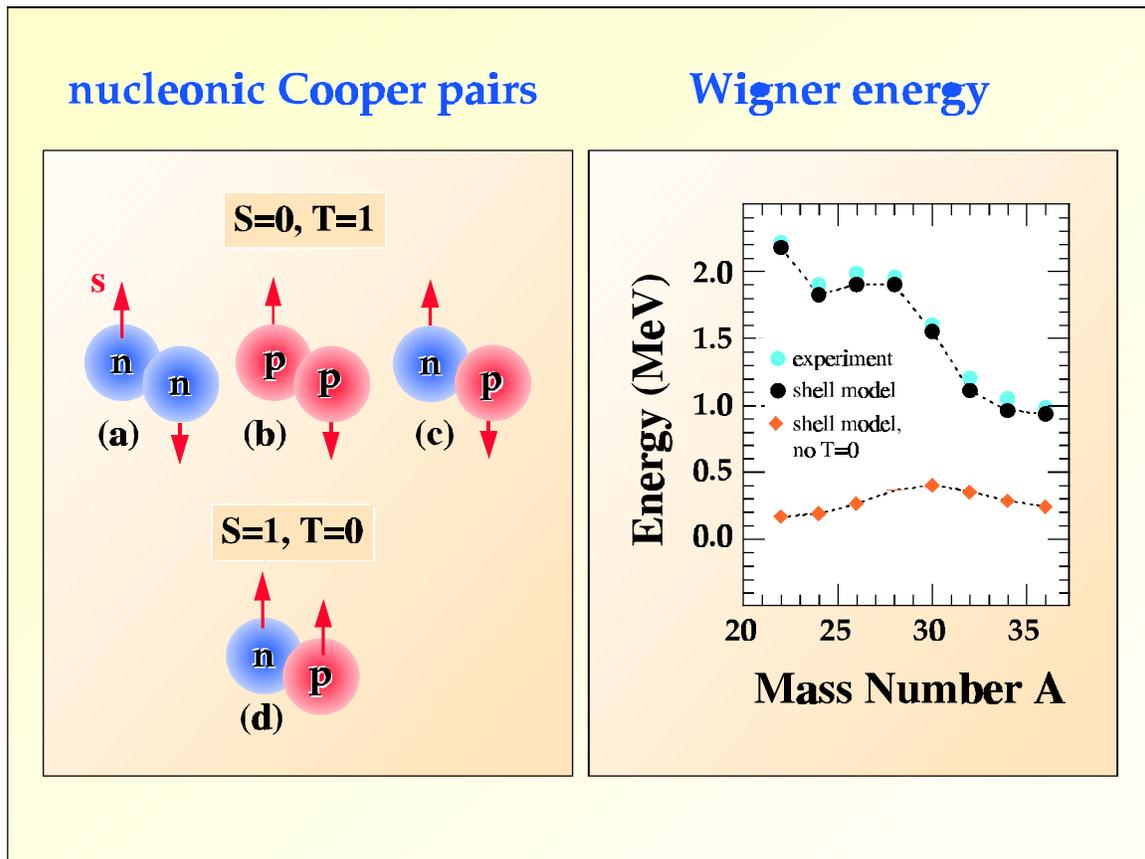
Fig. 17 Superconductivity in solids is a well known and well-understood phenomenon. It arises from the interaction between pairs of electrons moving in opposite directions. The superconducting state can be expressed as a freely moving collection (or "condensate") of these strongly correlated pairs (referred to as Cooper pairs). Less well known is that superconductivity is also realized in atomic nuclei. Here, strong correlations involving nucleon Cooper pairs also arise. In the nuclear domain, the strongest interactions involve pairs of nucleons that orbit the nucleus in opposite directions and so their net orbital angular momentum is zero. There are four types of these nucleon Cooper pairs, as shown in the left panel. Three of these consist of either two protons or two neutrons, or a proton and a neutron, coupled so that the spin directions of the nucleons themselves (red s) are opposite, giving a total spin angular momentum S of zero. The fourth combination, which occurs only for a proton-neutron pair, has the nucleon spins in the same direction (S=1). This type of pairing is a phase that is especially important for nuclei very near to the N=Z

line. To date, only the nuclear superconducting phases associated with Cooper pairs of like nucleons -- neutrons with neutrons (a) and protons with protons (b) -- have been discovered. Since the total spin of these pairs is zero, they are isotropic in shape. They also have a property called isospin, reflecting their proton-neutron symmetry. The pairs in (a) and (b) have another label, for their isospin, T=1.

 A unique aspect of nuclei with N=Z is that neutrons and protons occupy the same shell model orbitals. Consequently, due to the large spatial overlaps between neutron and proton wave functions, proton rich N=Z nuclei are expected to exhibit the superconducting phases that arise from the proton-neutron Cooper pairs (c) and (d). While the pair (c), with spin zero and isospin T=1, is isotropic (its spatial structure is the same as the T=1 p-p and n-n pairs), the pair (d), having spin S=1 and isospin T=0, is expected to be strongly anisotropic, with a donut-like shape.

At present, it is not clear what the specific experimental fingerprints of such proton-neutron pairing are, and whether the proton-neutron correlations are strong enough to form a static pair condensate. So far, the strongest evidence for enhanced proton-neutron correlations around the N=Z line comes from the measured binding energies. An additional binding (the so-called Wigner energy) found in these nuclei manifests itself as a spike in the masses of nuclei as a function of N-Z. The recent shell model calculations of W. Satula *et al.* [Phys. Lett. **B407**, 103 (1997)] account for the details of nuclear binding around the N=Z line. The right panel compares these calculations with the experimental binding (the Wigner energy) for N=Z nuclei. [For nuclei with N different from Z this energy is much smaller.] The magnitude of the Wigner term is well reproduced theoretically. On the other hand, if the proton-neutron (T=0) interaction is excluded from the calculations, the Wigner energy is dramatically underpredicted as seen by the lower theoretical curve.

At present, data on N=Z nuclei are very limited above A=60. Above A=84 it is almost non-existent. The expected terminus of bound N=Z nuclei is near ^{100}Sn. Therefore, a favorable region to search for this new superconducting phase of nuclear matter is in the N~Z nuclei located between ^{56}Ni (N,Z=28) and ^{100}Sn (N,Z=50) which have enough active nucleons outside closed shells to form many Cooper pairs. We will need radioactive beams to study these N=Z nuclei. Studies of the formation and decay of these nuclei are also important for tests of the Standard Model as discussed in Section IV.

Charge Independence of the Strong Force

A fundamental assumption in nuclear physics is that the nuclear force is approximately charge independent. This concept, sometimes called isospin symmetry, states that protons and neutrons behave similarly in nuclear systems and may be viewed as two states of one particle, the nucleon. This is manifest in the nearly identical spectra of levels observed in pairs of "mirror" nuclei, such as ^{27}Al (Z=13, N=14) and ^{27}Si (Z=14, N=13), that have interchanged numbers of protons and neutrons. Experimentally, studies of the energy spectra of mirror pairs near stability up to ^{55}Ni have in essence validated this symmetry. However, different spectra may show up in mirror pairs such as ^{17}Ne (Z=10, N=7) and ^{17}N (Z=7, N=10), when one of these nuclei is a halo nucleus, because the diffuse halo region is not matched in structure by the other nucleus closer to stability. Another example of the breakdown of mirror symmetry may occur in ^{48}Ca and ^{48}Ni; both of these nuclei are doubly magic but the latter is unbound. It will be important to experimentally investigate the role played by factors that break the isospin symmetry in heavy nuclei, such as the Coulomb force in the presence of weak binding, large deformations, or at high angular momentum.

The Approach to ^{100}Sn

The nucleus ^{100}Sn, which is the heaviest N=Z nucleus that is stable with respect to particle emission, has a very special role in nuclear structure. Firstly, ^{100}Sn is the only bound near-proton drip line nucleus studied so far that is likely to be doubly magic: it gives a rare opportunity to study magicity right at the limits of nuclear existence. Secondly, the energy levels in nuclei near ^{100}Sn define the single particle spectrum and the nuclear interactions around magic number 50, for both protons and neutrons. Thirdly, being the heaviest particle-stable N=Z nucleus, ^{100}Sn is perhaps the optimum place to study effects due to the breaking of isospin symmetry. Lastly, ^{100}Sn offers the best hope to obtain a precise strength estimate of certain transitions in β-decay called Gamow-Teller transitions and to probe models of the origin of the quenching of their strengths that has been observed.

Efforts to investigate ^{100}Sn and its immediate neighbors with stable-beam reactions have so far met with only limited success: Due to the proximity of ^{100}Sn to the proton drip line, it has a very small production cross section. Therefore, it was only recently that ^{100}Sn was identified at two Projectile Fragmentation facilities in Europe, and its mass was measured with a modest resolution. To date, less than 50 atoms of ^{100}Sn have been produced and firmly identified from these studies. No excited states of ^{100}Sn are yet known nor is its expected doubly magic character verified or disproved. Our ability to progress beyond these limited measurements depends critically on the availability of intense proton rich radioactive ion beams. For example, for beams such as ^{54}Ni or ^{63}Ga, production cross sections for ^{100}Sn can be up to thousands of times larger. Of course, the radioactive beam intensities most likely will be lower by at least as much. So, in both cases, production and beam rates for ^{100}Sn are likely not to exceed a few particles, maybe a few tens of particles, per second. This does not allow one to use doubly magic ^{100}Sn in, for example, direct reaction studies. However, certain classes of decay studies might be possible, with a technique called recoil nucleus tagging. In that case, the production reactions with radioactive beams will be far superior because of the many orders of magnitude higher signal-to-background ratio for ^{100}Sn compared to all the other nuclei produced in the fusion reactions. Because of this, radioactive beams will play a crucial role in structure studies of ^{100}Sn and the region of nuclei around it, as well as in other regions of the proton drip line.

Superheavy Elements

Another important and exciting frontier of nuclear stability that can be explored and extended with radioactive beams is that of the heaviest elements. The search for new elements has been an important theme in science for more than a century, since their atomic properties extend the Periodic Table to new species.

While most of the lighter and medium-heavy elements were discovered by chemical means, the heaviest elements, those beyond uranium (with nuclear charge Z=92), have been created in the last 50 years in nuclear reactions in the laboratory using either reactor neutrons or energetic ion beams. The Periodic Table as of 1997, is shown in Fig. 18. Elements up to Z=112 have now been discovered, using sophisticated and clever techniques to unambiguously identify them. These nuclei are usually produced in very small numbers down to perhaps two or three in very rare reactions, and the key to their identification is their characteristic nuclear decays. A chain of α-decays connects the original mother nucleus, say the mass 277 nucleus of element Z=112, with a known lighter nucleus, here the mass 249 isotope of element Z=100, fermium (see Fig. 18).

In addition to the discovery of new elements, the study of these heavy nuclei is of great interest from a nuclear structure point of view. The heaviest nuclei are the quintessential shell model nuclei in that their very existence arises solely from their shell structure. Nuclei with $Z > 104$ would fission instantaneously if they were charged liquid drops governed by classical physics. However, the nucleus is a quantum system and shell effects allow heavier elements to exist: indeed, calculations predict a rather extensive region of shell-stabilized superheavy nuclei.

According to recent calculations, confirmed by measurements, the valley of shell-stability extends from the deformed region around Z=108, N=162 towards the spherical doubly magic nucleus with 184 neutrons. However, we are not certain about its magic proton number. While earlier calculations yielded the value Z=114, modern models favor Z=126 or Z=120. The prediction that Z=126 is a magic proton nucleus is consistent with hints from experiment: The N_pN_n phenomenology (see discussion relating to Fig. 13) of certain transition strengths in the actinide (trans-uranium) region is much simpler when a shell closure at Z=126 is assumed.   While the discovery of new elements is exciting in itself, from a nuclear structure point of view it is obvious that exploring the structure of the heaviest nuclei along a chain of isotopes bears on many interesting and important aspects. Among them, of course, is the exploration of the location of the contour lines in Fig. 18 and elucidation of shell structure and closures. Reaching new elements will always be a formidable challenge whether with stable or exotic beams. But exploring the isotopes of, for example, lawrencium (Z=103), and thus extending studies into the neutron rich region not accessible with stable beam-target combinations, seems eminently feasible. It is known that the fusion reactions of ^{48}Ca beams with ^{208}Pb and ^{209}Bi targets have an unexpectedly high cross section (μb) when compared to the overall systematics. Radioactive beams of neutron rich calcium isotopes from ^{49}Ca to, possibly, ^{52}Ca, might then still be measurable with reasonable effort and expected beam intensities (10^6 to 10^9 particles/sec). This will provide important structure information for these heavy, strongly shell-effect dominated neutron rich nuclei and the overall properties of the heaviest nuclei. At the same time it will provide important new information on the fusion reaction process and on the formation of fused heavy compound nuclei by extending the systematics. This in turn might provide important guidance on reactions with stable beam-target

combinations. It is obvious that the availability of radioactive beams with quite different neutron-to-proton ratios will add new aspects to this very active area of research.

Fig. 18 Top: The Periodic Table of the elements as of 1997. It contains the heaviest elements synthesized thus far by man: Rutherfordium (Rf, Z=104), Dubnium (Db, Z=105), Seaborgium (Sg, Z=106), Bohrium (Bh, Z=107), Hassium (Hs, Z=108), Meitnerium (Mt, Z=109), and the recently discovered elements 110, 111, and 112 which do not have their final names yet. For the time being, they are dubbed unununilium, unununium, and ununbium, respectively, following a generic naming convention for the new chemical

elements [0=nil, 1=un, 2=bi, etc.] The transactinide elements have been extended up to element 112, but the chemical properties have been investigated only up to Seaborgium (M. Schädel *et al.* [Nature **388**, 55 (1997)]). The highlighted elements 107-112 form a chemical "terra incognita".

Bottom: Contour map of the calculated shell energy for the heaviest elements. (Shell energy is the difference between the total binding energy and the energy of the spherical nuclear liquid drop.) The darker the color, the greater is the binding. The self-consistent Hartree-Fock calculation of S. Cwiok *et al.* [Nucl. Phys. **A611**, 211 (1996)] clearly shows the presence of strong shell stability around the "doubly magic" superheavy nucleus Z=126, N=184 (upper question mark). This result markedly differs from recent macroscopic-microscopic approaches where the island of shell stability is concentrated around Z=114, N=184 (lower question mark). The experimental chain of α-particle decays that identifies the currently heaviest known element with Z=112 and N=165 is indicated. (S. Hofmann *et al.* [Z. Phys. **A354**, 229 (1996)])

An interesting related issue is the "fission" behavior of the very neutron rich heavy nuclei that can only be reached with radioactive beams. Fission is a process in which heavy nuclei break up into two major fragments. This can happen spontaneously or can be induced in nuclear reactions. But there is a hindrance to fission that needs to be overcome to pull the fragments apart. This is called the fission barrier. In processes involving very heavy nuclei, the cross sections are large (barns) so that even much lower intensity radioactive beams can be used (maybe down to a few tens to hundreds per second) to explore a new behavior of nuclear binding. In general, one would expect the fission barrier to grow with an increase of neutron excess. But the isospin symmetry of the nuclear force and the much stronger interaction between neutrons and protons than that between the neutrons or between the protons themselves, leads to a reduction of the fission barrier when moving away from stability towards the neutron rich isotopes. This intriguing behavior has not been studied yet, since it has not been possible to access the very neutron rich region, in particular for the heaviest nuclei, with fusion reactions. Radioactive beams open a window on this new research. Using, for example, a very neutron rich beam (say ^{146}Xe or ^{148}Cs), fusion reactions with a light neutron rich target such as ^{36}S or ^{48}Ca will populate fused, or compound, nuclei well beyond the valley of stability on the neutron rich side. An additional interesting aspect is that when these very neutron rich nuclei undergo fission, they will produce light neutron rich fragments not easily studied in the normal fission of, say, ^{238}U. This means that we will possibly gain access to fragment nuclei which are, themselves, very neutron rich and currently unavailable for study.

The discovery of elements heavier than those currently known would provide critical tests not only of nuclear models, but also of relativistic quantum chemistry. According to calculations which include a correct treatment of Einstein's special relativity, the inner-shell electrons are predicted to approach the speed of light as the atomic number of a nucleus grows to Z = 173. Relativistic effects actually occur at much lower Z values and cause deviations from the periodicity of chemical properties that characterize lighter elements and that is embodied in Mendeleev's Periodic Table of the elements. Indeed, an example of such effects has already been observed for the element Rf (Z=104), using single atom radiochemistry. Thus, study of the chemistry of the heaviest elements may lead to a revised version of the Periodic Table for the largest atomic numbers, a Table in

which the elements with Z=112 and Z=114, which are supposed to be in the same chemical families as mercury and lead, respectively, are predicted to be gases.

The experimental quest to synthesize nuclei with Z>112 and N~184 will not be easy, given the trend of decreasing probabilities for heavy nuclei to fuse, as observed up to Z=112. However, the good news is that superheavy nuclei are predicted to be more stable and longer-lived than those elements most recently synthesized. The long term perspective would be aided by the advent of beams of neutron rich radioactive nuclei from an advanced ISOL facility which, in combination with neutron rich targets, may provide a path leading to the predicted superheavy island. Experiments would almost certainly require significant advances in isotope separation and detection technology. But if they succeed in producing shell-stabilized spherical superheavy nuclei, they would represent a triumph of nuclear science.

III. Nuclear Astrophysics: Explosive Nucleosynthesis and the Origin of the Elements

Astronomy and nuclear physics are inextricably intertwined. Technological advances in observational astronomy and the need to better understand the underlying physics which controls astrophysical phenomena make the intersection of these two fields a vital area of research.

The initial "Big Bang" formed primarily hydrogen and helium. The principal energy sources in the universe are nuclear and all the remaining materials that we find in Nature have been synthesized from this hydrogen and helium through nuclear reactions either in quiescent stars (e.g., the elements carbon and oxygen on which life is based) or (for heavy elements) in cataclysmic stellar explosions. The synthesis of the elements thus takes place through a sequence of nuclear reactions in a variety of astrophysical environments, such as red giants, cataclysmic binary systems (such as novae and X-ray bursts) and supernovae. The resulting material is subsequently dispersed into the interstellar medium to be used in the condensation and formation of the next generation of stars and planets. These stellar sites and events are therefore the origin-sites for almost all of the heavy elements that we find in ourselves and in the world around us. In this way, we, and the world we live in, are all formed from stellar debris. The explosive events leading to the synthesis of heavy elements involve radioactive isotopes far from stability in a very direct fashion, and thus, as we discuss below, it is necessary to have intense beams of radioactive nuclei for studying and understanding the sequences of nuclear synthesis reactions that are crucial to life on this planet.

Forty years ago Burbidge, Burbidge, Fowler, and Hoyle laid out the foundations for this field in their seminal paper, describing a variety of nuclear reaction processes to reproduce the observed isotopic abundances (work which formed one of the main bases for Fowler's 1983 Nobel Prize). Except for hydrogen, helium, and lithium, all of the elements and isotopes which we find in our solar system were produced in stellar sites and then injected into the interstellar medium before our solar system was formed about four and a half billion years ago. Astronomical observations detect radioactive isotopes in the interstellar medium, on the surfaces of stars, and in exploding stars, demonstrating that this nucleosynthesis is continuing today.

Understanding our origins requires nothing less than a clear understanding of these nucleosynthetic processes, and one of the areas that we are just now becoming able to explore directly in the laboratory is the synthesis of isotopes that are normally formed in exploding stars such as novae, X-ray bursts, and supernovae. Gold, iodine, and the heavy nitrogen isotope ^{15}N, are examples of material which was synthesized in such stellar explosions. These explosions have time scales which are so short (typically shorter than a few seconds) that most of the radioactive isotopes which are produced do not have time to decay during the explosion. Therefore, any laboratory study of explosive

nucleosynthesis must necessarily include measurements of reactions involving short-lived radioactive species.

In a typical nucleosynthetic scenario, the outcome depends both on stellar parameters (e.g., density, chemical composition, and temperature) and on nuclear properties (e.g., reaction cross sections, β-decay rates, and masses). Current stellar models of these scenarios are based only on crude predictions for nuclear reaction rates and decay properties. Large sophisticated reaction network computer codes have been developed in recent years to predict, to simulate, and to understand energy generation and
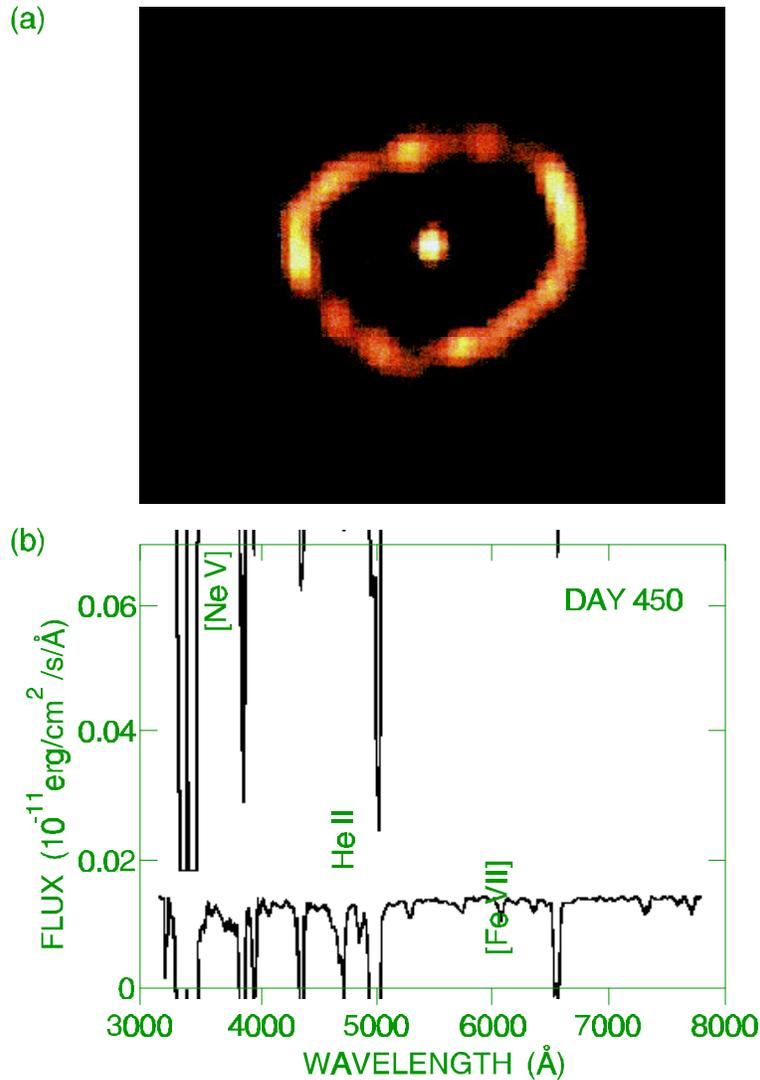
Fig. 19 In 1992 a stellar explosion was observed in the constellation of Cygnus the swan (Nova Cygni 1992). In a nova, an old, very compact star, called a white dwarf, blasts away material that has fallen on its surface from an accompanying star. The expanding shell from this explosion which took place about 10,000 light years away was photographed by the Hubble Space Telescope in 1994 (top). In these stellar explosions starting with hydrogen, helium, carbon, and oxygen a variety of heavier elements are formed within time scales of a few seconds. This synthesis of heavier elements is shown by the observation of the emission lines of the element neon (marked in blue) in the optical spectrum of this nova (bottom).

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nucleosynthesis in explosive events. However, the reliability of these calculations depends strongly on the nuclear input parameters. Studies of nuclear structure, nuclear reactions, and decay mechanisms for radioactive nuclei are, therefore, absolutely necessary. Radioactive nuclear beams allow experimental measurements of these nuclear reactions and decays and will therefore have a catalytic effect on astrophysics studies of such environments, by helping to understand both explosive nucleosynthesis and the time scales associated with energy generation in explosive events.

Explosive nucleosynthesis occurs when the stellar temperatures and densities are sufficiently high that successive reactions can form new nuclei faster than they decay. In this way, nucleosynthesis can march up the chart of the nuclides in a matter of seconds. This situation can greatly increase the rate of energy generation and the total amount of energy produced, and it can have a dramatic impact on the isotopic and elemental abundances produced (see Fig. 19). A classic example of this impact is the contrast in going from the normal carbon-nitrogen-oxygen (CNO) burning phase of stellar evolution to the HotCNO cycle, for which the amount of ^{15}N relative to ^{14}N increases by more than a factor of 1000. (The measured terrestrial ratio allows us to conclude that essentially all of our ^{15}N must have been made via the HotCNO cycle in nova explosions.)

rp-Process and Break-out from the HotCNO Cycle

One of the important open questions in explosive nucleosynthesis is the role of the rapid-proton-capture (rp)-process in which a sequence of proton capture reactions occurs in a stellar explosion, on a time scale of 100 seconds or less, producing nuclei on the proton rich side of the valley of stability starting from oxygen and going up to masses as heavy as zirconium, and perhaps even beyond. Open questions include the temperatures and densities for which the break-out from the HotCNO cycle to the rp-process will occur, what is the site for this process, how far along the proton drip line can this process proceed, and what are the important "waiting-point" nuclei along the rp-process path which will govern the rate of the process and determine the principal nucleosynthetic products. These waiting point nuclei have anomalously small proton capture cross sections since they are at the proton drip line: any momentarily captured proton almost immediately drips back out again before another proton can be captured. This effectively halts the rp-process at that element.

The time-scale for the rp-process outburst varies from 10 to 100 seconds. Within this period nuclei all the way up to ^{56}Ni, or even ^{96}Cd, can be made. A better determination of the actual time scale, the path through the nuclear landscape, and the terminus of the rp-process will depend on measurements of the masses and stability of nuclei up to and along the proton drip line in this region. Many of these nuclei are close to the N=Z line where special symmetries and unique nuclear correlations come into play (see section II). Waiting points in the rp-process occur at ^{14}O, ^{15}O, ^{24}Si, ^{34}Ar, and ^{56}Ni. These are shown in Fig. 20. At these waiting points, the sequence must wait to bypass this blockage via either a β-decay or a nuclear reaction in which an α-particle or two protons

are captured -- all of these mechanisms are much slower than the normal rp-process proton capture reactions. For example, as the rp-process proceeds beyond the last waiting point shown in Fig. 20, it encounters the unbound nucleus ^{69}Br, which can only be bypassed by waiting for the β-decay of ^{68}Se (with half-life of 36 seconds) or via a sequential pair of proton capture reactions that converts ^{68}Se into ^{70}Kr. The rate for this latter process will depend exponentially on the currently unknown disintegration energy of ^{69}Br to ^{68}Se. A variety of mass models gives a variation of Å1.5 MeV for this disintegration energy, and this corresponds to a variation in the stellar lifetime of the ^{68}Se waiting point of a factor of 10^4;
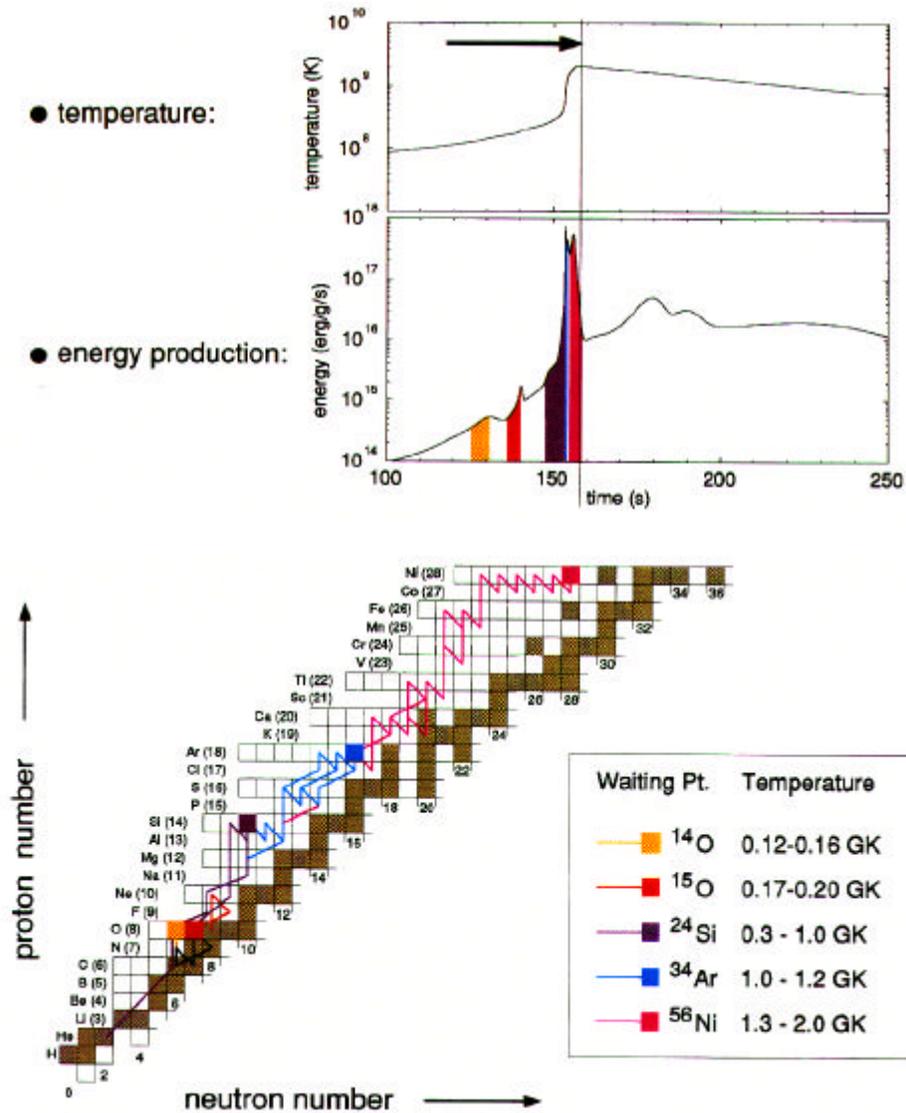
Fig. 20 A portion of the rp-process reaction sequence path along the proton rich side of the valley of stability from ^{14}O and ^{15}O up to ^{56}Ni. During an X-ray burst, at temperatures ranging up to Å2x10^{9}K, this entire sequence of reactions occurs in a time scale of only Å35 seconds. The legend gives temperatures in units (GK) of 10^{9}K. The top graphs show the variation of temperature and energy production as a function of time in seconds. [M. Wiescher, 1997].

experimental measurements of such masses and disintegration energies (at or near the proton drip line) are clearly crucial in sorting out the nucleosynthetic path and time scale.

Stellar X-ray bursts have been suggested as possible sites for high temperature (explosive) hydrogen burning via the rp-process. Even though the gravitational attraction of the neutron star which is at the core of the X-ray burst may permit only ≈0.1% of the synthesized material to escape into the interstellar medium, this might be sufficient to produce the as-yet-unexplained abundances of proton rich stable nuclei such as ^{74}Se, ^{78}Kr, ^{84}Sr, ^{92,94}Mo, and ^{96,98}Ru.

The accepted models for these explosive events are based on accretion processes involving a close binary system that includes a neutron star. The accreted material is continuously compressed by newly fallen material until it reaches sufficiently high density ($\approx 10^6$ g/cm^3) and temperature to trigger the rp-process nuclear reactions. This results in a thermonuclear runaway which reaches temperatures of up to 2 billion degrees Kelvin (see Fig. 20.) The rates of α-particle reactions on ^{14}O and ^{15}O are crucial in determining the temperature and density conditions associated with the break-out from the HotCNO cycle to the rp-process. Currently, these rates are estimated from indirect transfer reaction studies. However, these rates are very sensitive to small changes in the nuclear wave functions. A direct measurement of these reactions with radioactive beams is therefore essential. These measurements will be extremely difficult because of the low cross sections, resulting from Coulomb barrier inhibition, and will therefore require very sophisticated detector equipment. Typical beam intensities required for these studies are in the range from 10^7 - 10^{11} particles/sec.

Formation of the Heavy Elements: Neutron Capture Processes

Most nuclei with masses A³60 are formed in Nature by neutron capture processes which take place in two considerably different astrophysical environments: slow-neutron-capture (the s-process), which occurs in red giant stars such as Betelgeuse (α-Orionis), and the rapid-neutron-capture (the r-process), which occurs in supernova explosions such as the explosion observed in 1680, whose remnant "Cas A" is shown in Fig. 21. The distinction between the above two processes is made largely on the basis of the relative time scales for neutron capture and β-decay. If neutron capture is slower (the s-process), then the reaction path remains on or close to the line of stability since any radioactive nuclei produced will undergo β-decay before capturing the next neutron. For higher neutron densities the neutron capture can be much faster than β-decay and successive neutron captures will lead to neutron rich regions far from the valley of stability, by the r-process.

Due to its proximity to the valley of stability, the s-process can generally be studied much more easily than the r-process. However, along the s-process path there are a number of long-lived "branch-point" nuclei whose neutron capture reaction rates can not currently be measured. Since their β-decay rates and neutron capture reaction rates are

roughly comparable, an accurate measurement of the ratio for the two processes would be a very sensitive probe of the neutron density and temperature characteristics of the s-process. Therefore, one important program at a future ISOL facility should include measurements of these reaction rates. This might be done using radioactive beams in conjunction with the inverse (d,p) reaction in which the roles of target and projectile are interchanged. For some particularly long-lived isotopes, an alternate technique would involve using high purity radioactive targets which could be produced at such an ISOL facility and then irradiated off-line with neutrons at another facility; an example of this technique would be the formation of a target of ^{155}Eu which could then be used to measure the branching between the
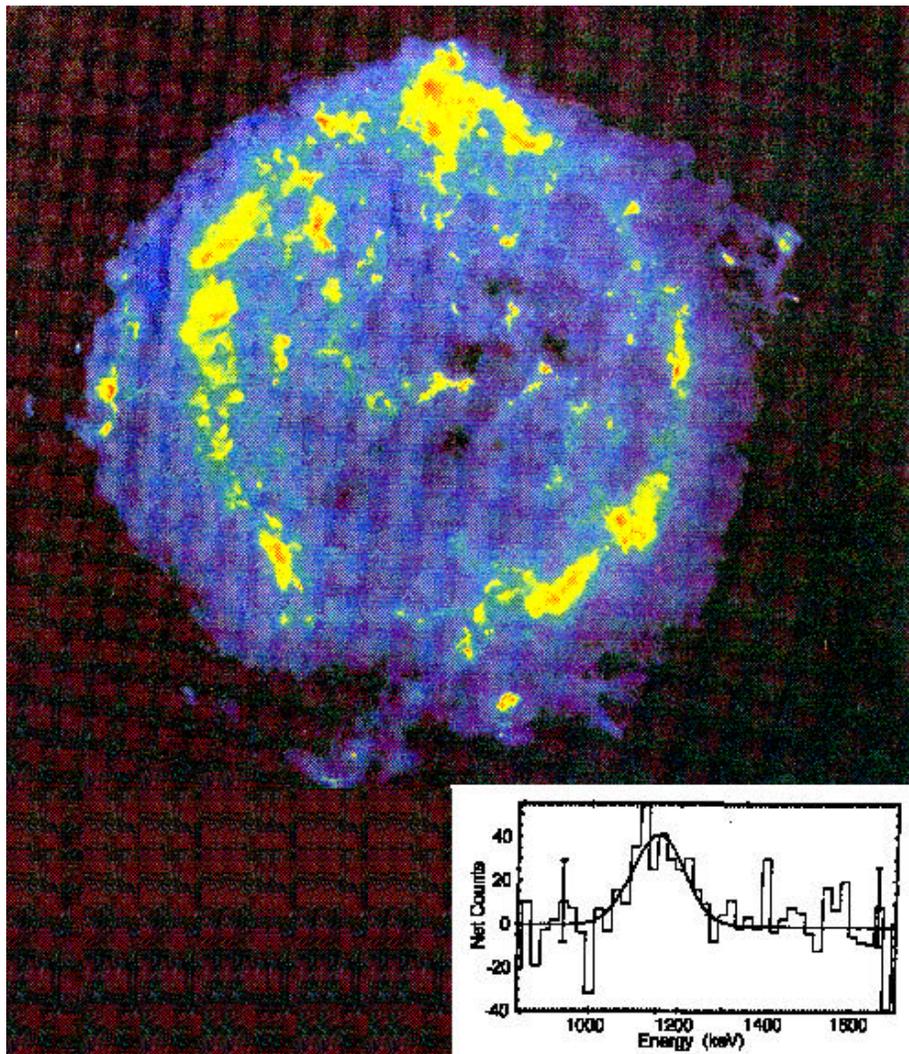
Fig. 21 The supernova remnant "Cas A". This stellar explosion was observed by Flamsteed in 1680. Approximately 300 years later, this image was measured using the Very Large Array (VLA) radio telescope in New Mexico. Recently it has received renewed attention as a result of the observation by the Gamma-Ray Observatory (GRO) satellite of 1.157-MeV γ rays from the decay of radioactive ^{44}Ti that was synthesized in that explosion. The inset displays the γ-ray spectrum measured using the COMPTEL detector on GRO: it is taken from Iyudin *et al.* [Astron. and Astrophys. **284**, L1(1994)].

production of ^{156}Eu via neutron capture on ^{155}Eu compared to the competing β-decay of ^{155}Eu to ^{155}Gd. Intensities of the order of 10^8 to 10^9 particles/sec should be quite adequate for such measurements, and because these radioactive nuclei are typically only 1 or 2 mass units away from stability, in general these intensities should be relatively easy to obtain.

The r-process was originally proposed to explain abundances of certain nuclei in the solar system. These nuclei could not be produced sufficiently in the s-process. However, at that time there was no direct evidence for the r-process. An important recent result has been the high resolution optical observations of a very old star in the Galactic Halo. These measurements showed that, while no s-process contributions have been detected in this star, the abundances of nuclei with 56-76 protons (Ba-Os) in this star are very well matched with the solar system r-process abundances. This result is shown in Fig. 22 and leads to several important conclusions. The lack of s-process elements suggests that this star condensed in the short time period between the explosive death of earlier massive r-process stars in the halo and the ejection of the initial s-process elements into the halo from lower-mass, longer-lived stars. The remarkable agreement between the r-process abundances in this ancient star and in our much younger solar system greatly increases the credibility of the determination the solar system r-process abundances. It has also been used to infer that the conditions in supernovae that lead to the production and ejection of r-process elements into the interstellar medium have been quite similar for billions of years.

Current theoretical models indicate that the site of the r-process is located just above the surface of a nascent neutron star. In this region, the enormous neutrino flux released in the gravitational collapse of the neutron star creates a neutron rich bubble. All the "iron-peak" nuclei (synthesized in the last gasp of energy generation just before the supernova collapse) are disassembled at the high temperature of this explosion(T ^{3} 10^{10} K), and their α-rich constituents are subsequently reassembled in the neutron rich environment of the neutrino bubble to create very neutron rich seed nuclei [such as ^{80}Zn (Z=30, N=50)]. These nuclei then undergo a rapid series of neutron captures all the way to A = 240 and beyond in just a few seconds (see Fig. 2). This process pauses only at waiting points associated with magic neutron numbers 50, 82, and 126 where the neutron capture rate is greatly reduced and the process must wait for several β-decays before proceeding. To better determine the r-process path and to better test and constrain the models for heavy element nucleosynthesis, what are needed now are measurements of β-decay lifetimes and neutron separation energies for nuclei along the r-process path, particularly at the waiting points associated with magic neutron numbers. In this context we need to remember that the neutron magic numbers may well not be the same far from stability as they are at or near the valley of stability. Mass and lifetime measurements can be made with beam intensities as low as 10^3 particles/sec. Measurements of the single particle levels in nuclei adjacent to important waiting points in the r-process [e.g., ^{131}Cd (Z=48, N=83)] will require beam intensities of at least 10^5 particles/sec.

The Links Between Nuclear Astrophysics and γ-ray Observational Astronomy

Recently the connection between astrophysics and nuclear physics has been enhanced by the opening of the field of γ-ray astronomy and the detection of γ rays from the decay of the unstable nuclei originating in explosive nucleosynthesis. By-products of nucleosynthesis such as ^{56}Ni and ^{44}Ti can provide valuable clues to the nature of the explosive process itself. The interpretation of such γ rays requires knowledge of the cross sections for the nucleosynthesis of these nuclei, as well as their β-decay lifetimes. For example, the current range of ^{44}Ti half-lives [46–67 years] corresponds to roughly a factor
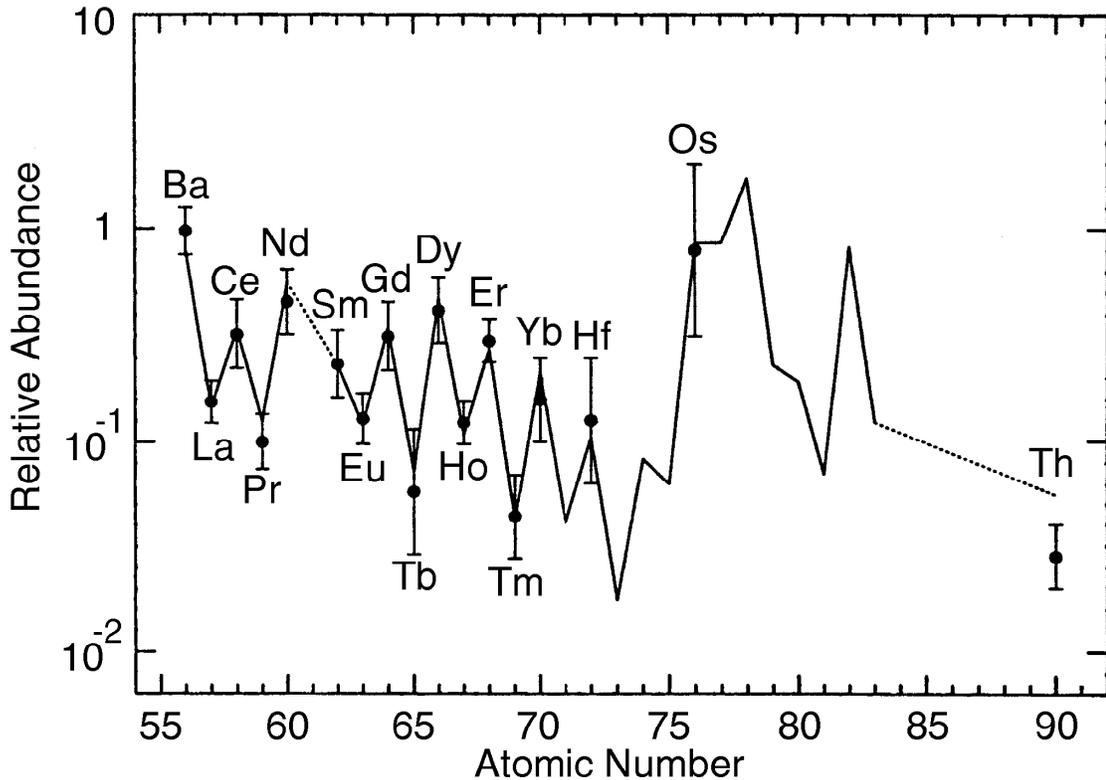
Fig. 22 Comparison of r-process elemental abundances in a 12 to 15 billion year old star in the Galactic Halo (dots) and in our solar system (solid line). The remarkable agreement between the two sets of abundances implies a universality in r-process nucleosynthesis. Either the r-process is the same in all supernova regardless of the size or age of the initial star, or perhaps there is only a narrow mass range for those supernovae which contribute to the r-process elements in the interstellar medium. The figure is taken from Sneden *et al.* [Ap.J. **467**, 819 (1996)].

of 3 variation in the amount of ^{44}Ti that must have been produced in the supernova explosion called Cas A. The most important reaction in understanding this synthesis is proton capture on ^{45}V producing ^{46}Cr: any direct study of this reaction will require a beam of radioactive ^{45}V which has a half-life of only half a second. With the more sensitive and higher resolution γ-ray observatories which are scheduled to be launched within the next 5-10 years (e.g., the European Space Agency's INTEGRAL satellite,

scheduled for 2001), this interconnection between nuclear physics and γ-ray astronomy can only continue to get stronger.

The key to understanding the cataclysmic explosions which we observe in our Milky Way and in external galaxies is the study of nuclear reactions far from the valley of stability. By providing the means to measure nuclear reaction cross sections involving short-lived nuclei, the masses of isotopes far from stability, and the decay modes and lifetimes of isotopes at the neutron and proton drip lines, an advanced ISOL radioactive beam facility will offer a unique opportunity for pushing our understanding of these reactions and their influence on the synthesis of nuclei and the generation of energy and nucleosynthesis in exploding stars. This information will allow us to determine the conditions of temperature and density for the origin of the elements which we find in and around us.

IV. Tests of the Standard Model

The Standard Model describes the world in terms of its basic constituents and their interactions. The basic constituents are three families of elementary particles, collectively called fermions, with each family composed of pairs of particles known as quarks and leptons. The fundamental forces acting between them (electromagnetic, weak, strong, and gravitational) are considered to originate in processes whereby complementary particles, called bosons, are exchanged between them -- for example, the strong force is due to the exchange of gluons between two quarks. These constituents and interactions are listed in Fig. 23 which also gives an illustration of physical systems where these interactions are most evident.

Critical to testing the Standard Model is verification that there are, indeed, three and only three families of fermions, and that the interactions between these fermions are the same as those envisaged in the Model. All experimental observations presently available are essentially in agreement with the Standard Model. It is nevertheless deemed incomplete because of the large number of parameters which must be inserted in an ad-hoc fashion to match observations. An example is the masses of the elementary particles themselves which are determined solely by experiment. In addition, a complete theory should attain a unified treatment of the electromagnetic, weak, strong, and gravitational forces. The present Standard Model falls short of these goals, and an advanced ISOL RNB facility presents unique opportunities to test and perhaps extend it with unprecedented accuracy and flexibility.

The Standard Model includes a unified treatment for both electromagnetic and weak interactions. Much of its development is the result of a large number of high precision nuclear physics experiments. Low energy nuclear physics experiments provide the most stringent determination of many parameters in the Standard Model and are a sensitive probe of possible extensions to it. This is due in part to the complementarity of these experiments to high energy physics experiments; but it is also due to the very large diversity in nuclear systems available which allows one to choose a nuclear state whose properties will select or enhance a specific decay channel which can then be studied to high accuracy. For reasons having to do with symmetries of the strong force and the consequent features of nuclear structure, the nuclei that provide the cleanest window into the fundamental nature of the interactions involved often lie far from stability. A typical case involves nuclei with equal numbers of protons and neutrons -- the N=Z nuclei discussed earlier -- whose special structure (proton-neutron symmetry) allows very fast transitions to take place while other nuclear effects remain small. Another example concerns experiments which are basically atomic in nature. They involve laser excitation of electron energy levels, but where the effects increase rapidly with the charge of the nucleus. Radioactive beams are useful, for example, in providing intense sources of the heaviest alkali atom francium, whose nucleus is unstable. A major challenge for experimental studies of fundamental interactions or conservation laws is therefore to obtain high intensity sources of the appropriate isotopes, prepared in the specific form best

suited to the particulars of the experiment. This is where a high intensity radioactive beam facility becomes essential.

The remainder of this section will deal with a number of tests of specific components of the Standard Model. The physics sought in these different types of experiments can be classified under three main headings:

a) The relative strength of the various interactions in the Standard Model. Radioactive beams play an essential role in assessing the weak interaction. The strength of one component of this interaction, the so-called vector part, is specified by a parameter G_V. A high-accuracy determination of G_V is extremely important and leads to precise tests of the "three-generation", or three-family, aspect of the Standard Model. These experiments exploit the special features of very fast ("superallowed") β-decays between states with angular momentum and parity 0^+.

b) Limits on possible extensions to the nature of the electroweak interaction used in the Standard Model. This interaction has a special mathematical form known as Vector-Axial Vector (or V-A). However, this choice of interaction is not mandated a priori but is driven by non-observation of effects that would point to additional components of the electroweak interaction. Experiments with radioactive beams can greatly advance the sensitivity to other components.

c) Precision measurements of low energy manifestations of violations or breakdowns of fundamental symmetries such as parity or time-reversal.

Strength of the Weak Interaction and Tests of the Standard Model

The charged weak interaction has been determined experimentally to have a Vector-Axial Vector structure. The Vector component of the interaction is particularly interesting in that the theory tells us that it should be conserved (this is the CVC or Conserved Vector Current hypothesis), in analogy to the conservation of electromagnetic currents. This implies that G_V is the same for the decay of complex nuclei as it is for the decay of an UP quark into a DOWN quark. It is possible, by selecting the proper nuclei, to find decays that isolate the Vector component and therefore allow a high accuracy determination of G_V at the quark level.

In particular, β-decay transitions from 0^+ to 0^+ states must be of pure Vector character from conservation of angular momentum. If the initial and final states involved in the decay transition are also "isobaric analogue states" of each other, that is, if they are identical except for the change of a proton into a neutron in the same orbit, then the nuclear structure effects become relatively simple to calculate. Such decays are called superallowed 0^+ to 0^+ β transitions and represent a particularly successful example of tests of fundamental physics using low energy nuclear physics. Nine superallowed β-decays from ^{10}C to ^{54}Co have been precisely measured: their strengths are now known to about 1

part in a thousand. These values are used to test the CVC hypothesis mentioned above and provide the most precise value of G_V (see Fig. 24).

The quarks that lie behind the Standard Model are mixed when acted upon by the weak interaction. This means that, for example, the UP quark will decay not into a pure DOWN quark but into a state which is a mixture of the DOWN, STRANGE, and BOTTOM quarks. This weak mixing between the three families of quarks is determined by a matrix called the "Cabibbo-Kobayashi-Maskawa (CKM) quark mixing" matrix. The CKM matrix must have a property called unitarity for a three family Standard Model to be valid. The largest element of the top row of the CKM matrix relates to the mixing of UP and DOWN quarks. It is determined most precisely by combining G_V from 0^+ to 0^+ superallowed decays with the decay properties of particles called muons. While the agreement among the precise 0^+ to 0^+ data strongly confirms the CVC hypothesis, the unitarity test of the CKM matrix deviates from unity by more than two standard deviations. This discrepancy in what is one of the most basic tests of a three-generation Standard Model has led to much theoretical speculation. If this situation is confirmed, it would have serious implications for physics beyond the Standard Model.

3 Families of Elementary Particles (Fermions)

	up	charm	top
charge +2/3			
quarks			
charge -1/3	down	strange	bottom
	electron neutrino	muon neutrino	tau neutrino
charge 0			
leptons			
charge -1	electron	muon	tau

Fundamental Interactions

Gravitational   Electromagnetic   Weak   Strong
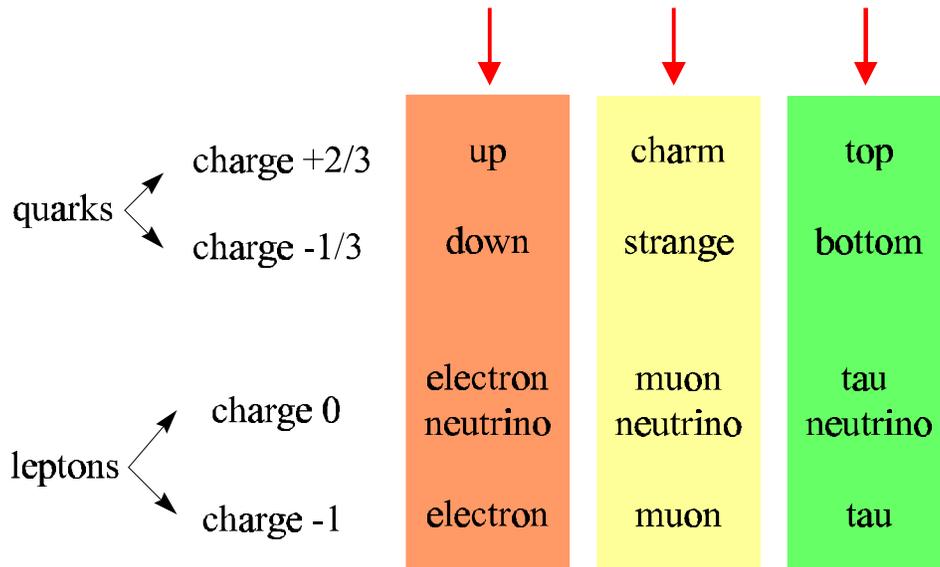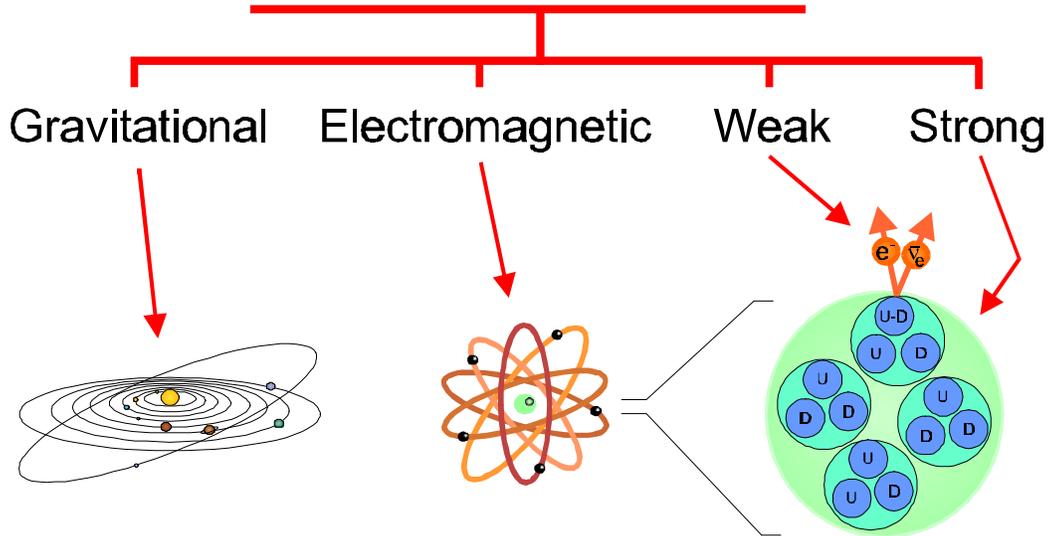
Fig. 23 The three generations of fermions and the fundamental interactions in the Standard Model. The Standard Model describes the world around us as made up of fermions interacting together via the fundamental interactions. These interactions work by exchanging particles named bosons (for example, the photon, in the case of the electromagnetic interaction). The figure sketches examples of phenomena associated with the different interactions such as the orbits of the planets in the solar system, the electronic cloud around an atom, β-decay, and the binding of nucleons inside a nucleus which are primarily due, respectively, to the gravitational, electromagnetic, weak, and strong interactions. The weak and electromagnetic interactions are now unified within the Standard Model, and aspects of this resulting "electroweak" interaction can be probed to high precision with radioactive nuclei.

The largest error in these tests is not experimental, but comes from the uncertainty in small nuclear charge and radiative corrections that must be applied to the experimentally measured β-decay intensities. The charge correction in particular is under much scrutiny. The only experimental handle available to constrain this correction comes from weak β-decay branches to excited 0^+ states. These transitions are normally forbidden but become possible via the above mentioned charge correction. The small number of excited 0^+ states energetically available for the nine precisely measured cases limits the quality of this test. However, a next-generation radioactive beam facility will provide experimentalists with sufficient yield on the heavier superallowed 0^+ to 0^+ decays such as ^{62}Ga, ^{66}As, ^{70}Br and ^{74}Rb to perform such measurements on these isotopes. The advantages here are twofold: the charge corrections have been recently calculated to be much larger for these heavier nuclei, and the higher energy available in the β-decay process will allow several excited 0^+ states to be fed at a measurable level. In addition, measurements in nuclei with higher atomic numbers Z could further constrain systematic deviations in the charge correction that depend on the magnitude of the nuclear charge.

These difficult measurements will, however, require precise determination of the half-lives, weak branching ratios and energies of these heavy N=Z superallowed β-emitters. Precise measurements of the first two quantities will require not only sufficient yield, but also very clean sources, which are best obtained with a high resolution mass separator. Precise measurements of decay energies for these nuclei will best be done by direct mass measurement of the parent and daughter nuclei using the newly developed Penning trap mass spectrometry technique. In this case, the very small number of ions required to perform a high accuracy mass measurement would more than offset the losses incurred by injecting these short-lived isotopes into the Penning trap mass spectrometer.

Limits on Extensions to the Standard Model

A general expression for the angular correlation between different particles emitted in β-decay was formulated 40 years ago. The (V-A) structure of the charged weak-interaction was then determined by the observation (or non-observation) of the different possible contributions to the total angular correlation. This form of the charged weak interaction is not a theoretical prediction of the Standard Model but an experimental fact.

Very precise measurements of angular correlations can, therefore, reveal contributions beyond (V-A). The difficulty here again lies in finding the nucleus which will exhibit the proper decay, preparing it in a way best suited for the observable to be determined, and then performing the experiment. In general, the nuclei of interest lie close to the N=Z line. In this vicinity one can choose specific types of decay transitions called pure Fermi transitions, mixed Fermi/Gamow-Teller transitions, or pure Gamow-Teller transitions which are well suited to look for specific physics beyond the Standard Model such as the so-called scalar interaction, right-handed currents, and tensor interactions, respectively.

The various observables require the observation of one or many of the following quantities: the momenta of the β-particle and the neutrino, their respective energies, and the initial and final polarizations of the nuclei and particles emitted. The neutrino momentum and energy are not directly observable and therefore the analysis is often carried out in terms of the momentum and energy of the recoiling nucleus.

Innovative techniques such as observing particles (protons or α-particles) emitted from the recoiling nucleus have been used to alleviate background problems. The
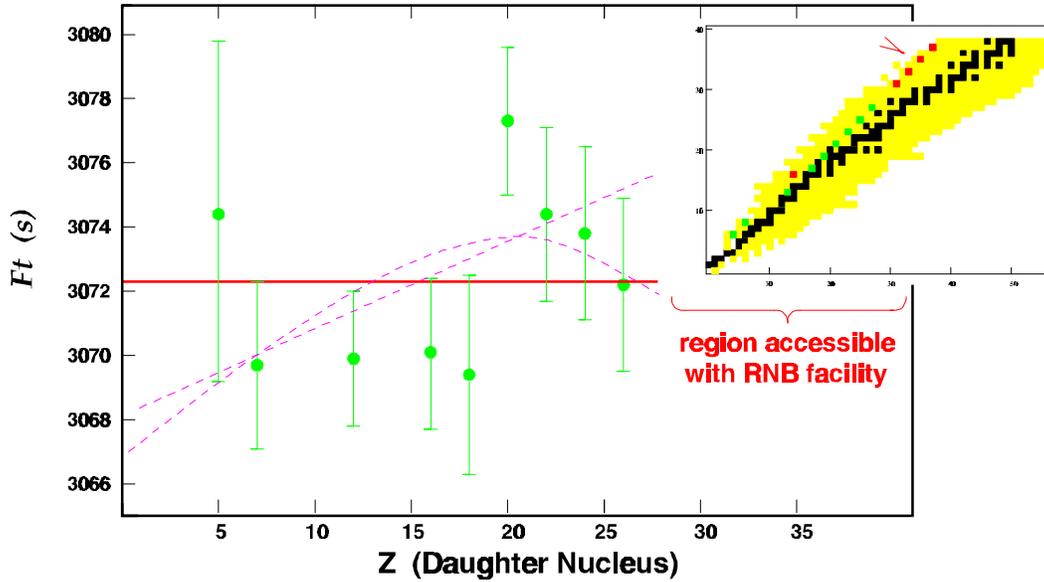
Fig. 24 Normalized strength (Ft-value) for pure Fermi decays along the N=Z line. The excellent agreement between these nine high precision measurements confirms aspects of the Conserved Vector Current (CVC) hypothesis while providing the most precise value of the weak vector coupling constant. However, when this result is combined with data from medium- and high energy experiments, it leads to results which do not agree with the Standard Model predictions. This might be a sign for new physics. Possible corrections, linear and quadratic, in the effects of the nuclear charge (see dashed lines), have been proposed to resolve this discrepancy. Data on heavier pure Fermi β-emitters (shown in red in the inset) would clearly pinpoint (or rule out) the need for such corrections. These experiments will become possible with the intensities available at a full powered RNB ISOL facility.

availability of high intensity and high purity radioactive samples from a next-generation radioactive beam facility will allow us to improve the limits obtained from these methods. Strong sources of ^{32}Ar and ^{36}Ca, for instance, which decay primarily through Fermi transitions, would allow measurements of the electron-neutrino angular correlation by measuring the Doppler-broadened energy distribution of the β-delayed protons. This information could then be used to put constraints on the scalar component of the weak interaction and on extensions to the Standard Model. Other experiments now being performed such as the observation of the polarization of β-particles emitted from polarized nuclei would also benefit from the increased intensity. The increased source strength would allow modifications to the geometries being used to reduce systematic errors.

These measurements provide tight constraints on specific extensions of the Standard Model where the more direct approaches of high energy physics have no sensitivity.

The most significant improvements in this field are, however, expected when new technologies now emerging are applied to the isotopically pure, high intensity beams that will be available at a full powered radioactive beam facility. One such new technology that will allow the preparation of intense and pure radioactive sources, highly polarized, and with near zero thickness, is the laser atom trap.

Laser atom traps come in a variety of forms but the most successful at trapping radioactive atoms has been the magneto-optical trap. This atom trap (see Fig. 25) uses a combination of a weak static magnetic field and six laser beams counterpropagating along three axes to obtain three-dimensional confinement of a specific isotope. Presently, atom traps achieve efficient trapping only for alkali species. Radioactive isotopes of Na, K and Fr have now been trapped in amounts approaching 10^5 atoms. This is still far below the results obtained for stable atoms where densities of about 10^{10} per cm^3 have been obtained, but has allowed preliminary work towards full scale β-decay angular correlation measurements to be performed. Experiments proposed with such a scheme include searches for a scalar interaction in the decay of ^{38m}K, a search for right-handed currents in the β-decay of polarized ^{37}K and ^{21}Na, and search for time-reversal invariance, and tensor currents in the decay of polarized ^{82}Rb. All these experiments will benefit from the maximum beam intensity achievable.

While the atom traps provide an ideal environment for this type of measurement when the radioactive parent is an alkali, Nature also presents many other candidates equally well suited to this type of study in nuclei which do not happen to be easily captured in a magneto-optical trap. For these species, a different kind of trap, an ion trap, could be used as a confinement device. Ion traps are not sensitive to the atomic structure of the isotope to be captured and can be used for essentially any atomic species. Their main disadvantage in this application is that the confining electromagnetic field will perturb the trajectories of the charged particles being studied. This can, however, be used to advantage in geometries where the channeling of the β-particles allows detectors to be located farther from the source, without loss in efficiency, limiting multiple scattering problems.

Other types of experiments will also benefit from the increased beam intensity and purity. For instance, high intensity beams of ^{14}O would be ideal to measure the shape of the β spectrum and the branching ratio of the decay to the ground state of ^{14}N, allowing an improved test of β-decay theory. The production of proton rich light nuclei would also allow, because of the unusually large decay energies available, a thorough and unprecedented study of the distribution of Gamow-Teller strength and of the discrepancies between the values extracted from β-decay studies and from measurements using other techniques (hadronic probes). This issue is very interesting since it bears on stellar nucleosynthesis, the calibration of neutrino detectors, and our understanding of nuclear
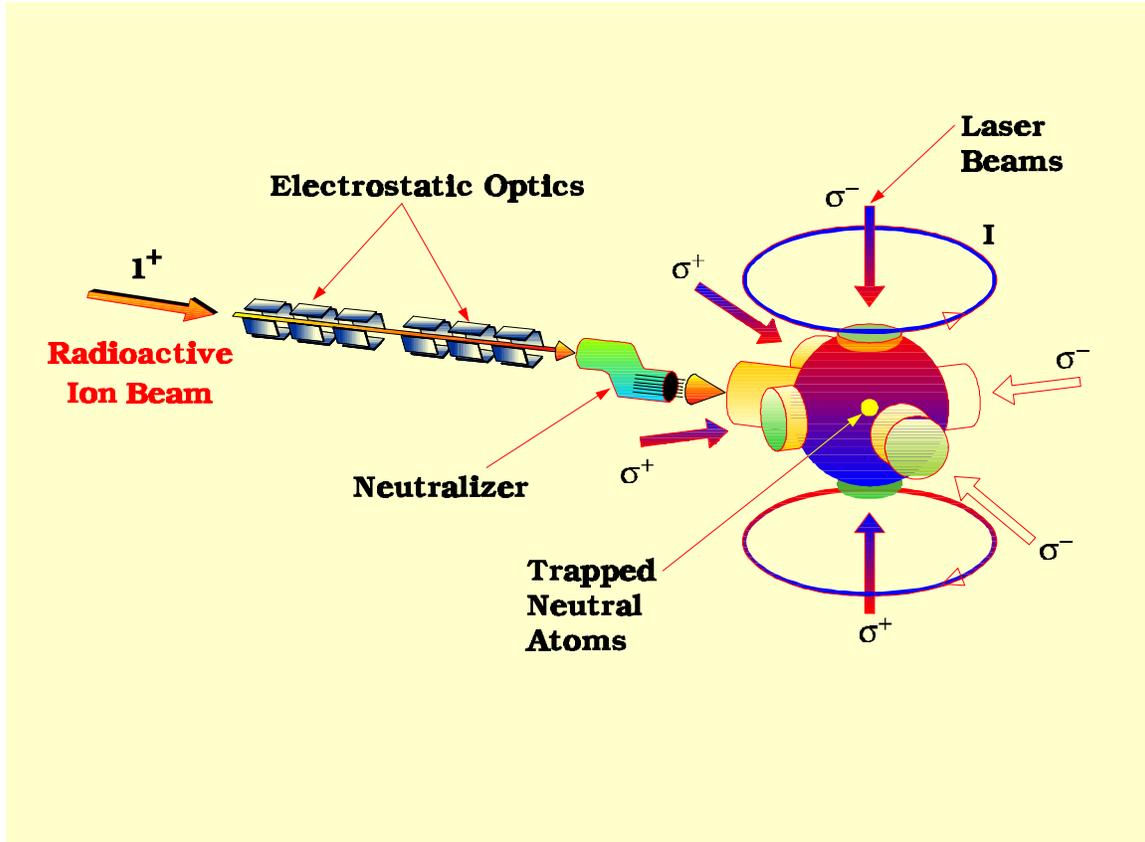
Fig. 25 Schematic layout of a neutral atom trap. The trap shown is a magneto-optical trap which uses a combination of a weak magnetic field and six intersecting polarized laser beams to trap and capture radioactive atoms. These atoms are obtained by neutralization and thermalization of a low energy radioactive ion beam. Once captured in the trap these ions become an ideal source for high precision studies.

structure. In particular, beams of 100-1000 atoms per second of ^{32}Ar, ^{33}Ar, ^{36}Ca and ^{37}Ca would yield important information.

Precision Measurements of Parity and Time-Reversal Violation

In the above paragraphs we pointed out that the observation of the properties of particles emitted in β-decay is a competitive means of obtaining information on the fundamental electroweak interaction. Manifestations of the electroweak forces are also visible in the bound electrons orbiting the nucleus. These effects are subtle and require careful examination but can provide information either not available by other means or in an energy regime very different from the direct searches at high energy.

Experiments that study the violation of left-right symmetry (parity violation) in atoms have recently provided a much-publicized independent window on electroweak physics. The interactions between a nucleus and the surrounding electrons are dominated by electromagnetism. However, the exchange of elementary particles called Z^0 bosons

between the electrons and the nucleus is also allowed, although rare. This exchange gives rise to weak parity mixing in the atomic shells. The tiny effect has recently been measured with an experimental accuracy of about 0.5% in ^{133}Cs. It depends very strongly on the charge Z of the nucleus. Hence, heavy atoms offer more sensitive tests. Alkali atoms are particularly simple in their atomic structure, eliminating a source of uncertainty, and francium offers a particularly attractive case, being the heaviest alkali. Parity violating effects are expected to be some 18 times larger in Fr than in Cs, where the highest experimental accuracy has been achieved. Since Fr has no stable isotopes, such experiments would, therefore, benefit from intense sources of Fr from an advanced ISOL facility.

Atomic structure uncertainties can be reduced substantially by studying parity violating effects in different isotopes of a given element. This would probably best be done on a series of francium isotopes inside a laser trap. Preliminary conservative estimates indicate that a 1% uncertainty (to compete with the accuracy available from other methods) would require about 10^8 trapped atoms. Initial tests indicate that the efficiency of trapping atoms from a beam may be around 10^{-4} per second with a lifetime on the order of 1 second. Improvements in trapping efficiency and storage time by one order of magnitude are perhaps reasonable to anticipate. To achieve 1% accuracy would require a beam of about 10^{11} atoms per second. An advanced ISOL facility would provide a number of Fr isotopes at intensities in the range of 10^{10} - 10^{11} per second. This is a factor of almost 100 more than available at the best existing facilities and would bring a very exciting level of precision within reach.

Another low energy manifestation of electroweak physics in an atomic system is the anapole moment. The nuclear anapole moment is an electromagnetic moment generated by the parity violating weak nucleon-nucleon interaction. It corresponds to a toroidal current in the nucleus. Its effect is confined inside the nucleus and is therefore felt only by an electron whose orbit penetrates the nucleus. In the previous paragraphs, we saw that the direct exchange of Z^0 particles between the nucleons and electrons that come in the vicinity of the nucleus induces a small but measurable parity mixing in the electron cloud. The electromagnetic interaction of this electron cloud with the nuclear anapole moment will create an atomic parity violation signal that depends on the total angular momentum. There is evidence for such a term in the latest high precision measurements of atomic parity non-conservation in ^{133}Cs. Further experiments are definitely needed to confirm this exciting result but also to further explore this new means of studying the poorly understood nucleon-nucleon weak interaction.
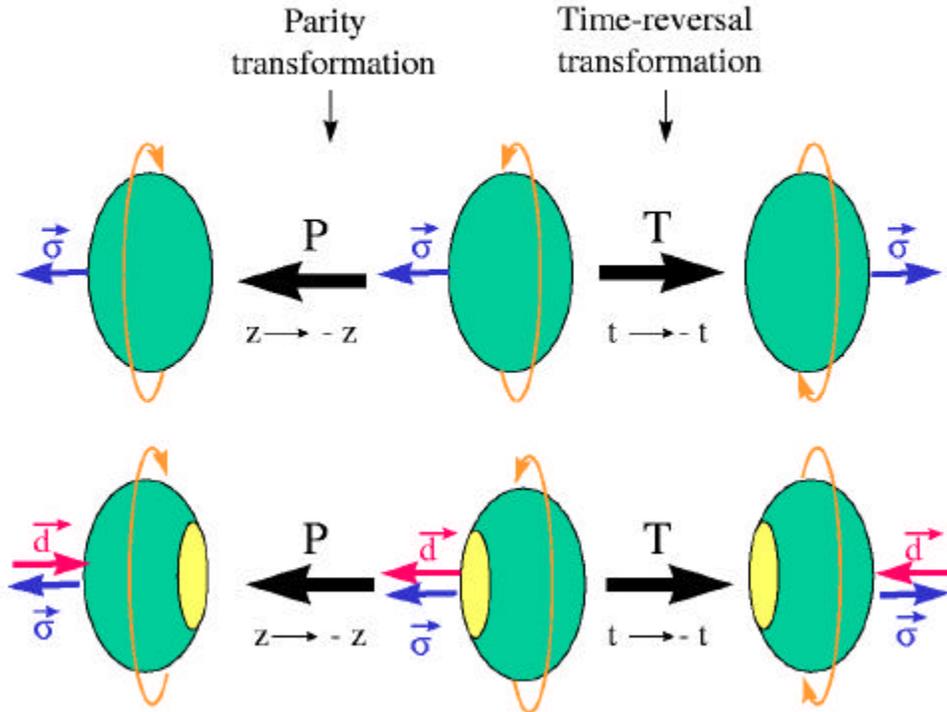
Fig. 26 Violation of parity and time-reversal symmetry by an Electric Dipole Moment (EDM). The top row shows a nucleus (center panel) with a magnetic dipole moment σ. When acted upon by a parity transformation (left on figure) or a time-reversal transformation (right on figure) we obtain the same physical object (rotated by 180 degrees on the right panel). Thus, a magnetic dipole moment obeys both time-reversal and parity conservation. The center panel of the bottom row shows a nucleus with an EDM d (the yellow cap represents a region with extra electric charge creating the EDM) and a magnetic dipole moment. Both parity and time-reversal transformations result in a different physical system (they cannot be brought back to the original by a simple rotation). The existence of an EDM therefore requires breaking of both parity and time-reversal symmetry.

Both the atomic parity non-conservation and the anapole moment discussed above require parity violation but not time-reversal violation. It is known, however, that both symmetries are violated in the Standard Model. The combination of these violations allows the existence of non-uniform distributions of charge (electric dipole moment or EDM) of the electron or other fundamental particles (see Fig. 26) which have never been observed. The Standard Model does not accommodate an electron EDM larger than about 10^{-37} e-cm -- about 10 billion times smaller than present experimental limits. But many, if not most, models beyond the Standard Model allow an experimentally observable electron EDM. Thus, observation of any EDM larger than 10^{-37} e-cm would be proof of new physics beyond the Standard Model. Some models predict EDMs in the range of 10^{-28} - 10^{-31} e-cm -- about 1 - 4 orders of magnitude below the current limit. An experiment with this sensitivity would be desirable.

An EDM can be detected by placing a spinning particle in an electric field and noting a difference in energy when the electric field lines are aligned and anti-aligned with the direction of spin of the particle. The valence electron in a neutral atom will also see the electric field. If one chooses an angular momentum 1/2 state of a very heavy atom, relativistic effects can greatly enhance the external field seen by the valence electron. The enhancement factor for Tl is about 580 and for Fr it is about 1150 -- larger than any other atom that has been used for such experiments.

All experiments searching for an EDM are essentially studies of an atomic clock in an electric field. A change in the clock frequency upon reversal of the electric field relative to the spin direction of the atom is the signature for an EDM. Improvements in these experiments largely follow improvements in atomic clock technology. The next generation of atomic clocks will achieve orders of magnitude higher precision using laser trapping and cooling. The same holds for EDM experiments. This increased precision comes from the much longer measurement time in a trap. In addition, the slow atoms and the tremendous control of both internal and external degrees of freedom achievable in traps provides much better suppression of systematic effects than has been possible with current experiments.

Francium is easy to trap (three different isotopes have already been trapped) and has a higher sensitivity to an EDM than any atom previously used. There is a practical limit of about 10^9 atoms that can be trapped and cooled -- a limit that can be reached with stable atoms but, at present, not with francium which has no stable isotopes. Until now these disadvantages have outweighed francium's attractions, but all that changes at a modern ISOL facility because beams of 10^{11} Fr/s assure that there will be as much francium available as can be loaded into a trap. Francium traps which capture into the trap 0.3% of the atoms produced in a radioactive source have been operated and simple engineering improvements can raise this efficiency at least an order of magnitude. An experiment using trapped francium atoms to observe an electron EDM can reach sensitivities in the 10^{-30} e-cm region, and perhaps beyond. An advanced ISOL facility will therefore make it possible to search for a permanent electron EDM with a thousand times the sensitivity of present experiments, far into the range of values allowed by most models that contain physics beyond the Standard Model.

The nucleus can also have an EDM and recent calculations indicate that octupole (pear-shaped) deformations may enhance this nuclear moment by as much as a factor 2000 over the best measurements to date. An experiment to measure the nuclear EDM of trapped ^{225}Ra, which has a strong octupole deformation, might significantly improve the present experimental limits on the nuclear EDM. Here again, as in the case of the Fr EDM measurement, an advanced ISOL facility is needed to provide sufficient source intensity of these radioactive isotopes.

Other Opportunities

Other studies of the fundamental interactions are possible with radioactive beams. As an example, if such beams are polarized, (that is, all the nuclei in the beam spin in the same direction) then one might be able to study the nucleon-nucleon weak interaction which is the most poorly understood part of the total weak interaction. This interaction can be observed as a parity mixing between nuclear states. In this case one looks for a nucleus with simple shell structure and closely spaced levels of opposite parity but the same total angular momentum. If there is an interaction between these two states (parity mixing) and if one of the levels has a normally inhibited transition that is enhanced by the parity mixing, this provides the kind of amplification factor that is characteristic of many tests of fundamental symmetries with nuclear physics techniques. The decay of the level is observed to look for evidence of parity admixing.

Related measurements have been performed on a few systems such as ^{14}N, ^{18}F, ^{19}F and ^{21}Ne where transfer reactions with polarized stable beams were used to populate and polarize the states of interest. In most cases the polarization achievable and resulting source intensity were limited. With accelerated polarized radioactive beams, large numbers of these nuclei could be excited to the level of interest following which the angular distribution of the decays is observed with respect to the polarization axis. One of the significant advantages of this method is that it would allow one to study transitions in mirror nuclei such as ^{19}F and ^{19}Ne. The symmetry in the nuclear wave functions would then allow an unambiguous separation of components that depend on whether the neutrons and protons act in concert (constructively) or not (destructively) when both results are combined.

V. Multidisciplinary Physics and Societal Applications

Ion beams are important in a large variety of applications to other fields of science, to industry, and to medicine. Beams of radioactive nuclei greatly expand the scope of such applications. There are several generic reasons for this. First, in applications where a radioactive source is needed (for example, as an implanted ion in a lattice of atoms), radioactive beams offer an enormous choice of half-lives, decay types (β, α, positron, etc.), and energies. Secondly, the energy and intensities of radioactive beams can be used to control the depth, intensity, and location of implantation. This has obvious implications for doping of semiconductors, for medical therapy, and for studies of the wear of materials by introducing tracers at controlled depths. Clearly, the availability of radioactive beams from an ISOL facility that are low, and precisely variable, in energy will be particularly valuable. Thirdly, when radioactive nuclei decay, they change the number of protons in the nucleus and hence the element and its chemistry. Thus, by implantation, one can introduce time-dependent chemical changes into a sample.

Low energy beams of radioactive ions are therefore the basis of a variety of cutting-edge scientific programs in fields outside of nuclear physics as diverse as materials science, chemistry, medicine, and monitoring of material properties. A medley of applications, such as doping into selected lattice sites for studying the properties of semiconductors, doping of crystals or of manufactured materials for tribological (wear-related) studies, or the production of isotopes for diagnostic or clinical medical studies, are already in use. The enhanced assortment of isotopically pure beams available from an advanced ISOL facility will introduce exciting new possibilities in which the best possible isotope can be selected for a particular application from the variety of isotopes available, each of which has its own specific nuclear properties. The increased energy range of accelerated radioactive ions from such a facility also will lead to a wider range of implantation depths as well as to programmable depth profiles. This section very briefly describes a few examples of many possible applications.

Applications to Materials Science — For materials science the advent of beams of radioactive ions allows a variety of studies varying from the doping of materials to techniques for studying the environment of a radioactive probe ion implanted as an impurity into materials such as semiconductors. The general method for probing the vicinity of a specific lattice site is depicted in Fig. 27. The electric or magnetic field gradient can be measured at a site in the host material by implanting the appropriate radioactive probe nucleus to interact with the electric or magnetic fields of the surrounding lattice structure. The information is transmitted to outside the lattice by the decay characteristics of the radioactive ion. An assortment of such techniques including perturbed angular correlations, Mössbauer spectroscopy, and emission channeling is presently in use at radioactive ion beam facilities. For example, the perturbed angular correlation technique obtains information on the lattice environment through the observation of the electric or magnetic hyperfine interaction between the nuclear moment of the probe nucleus and the magnetic field or electric field gradient induced by the

surrounding lattice structure. This information on the hyperfine interaction is transmitted by γ-γ coincidence measurements from the decay of the radioactive probe ion.
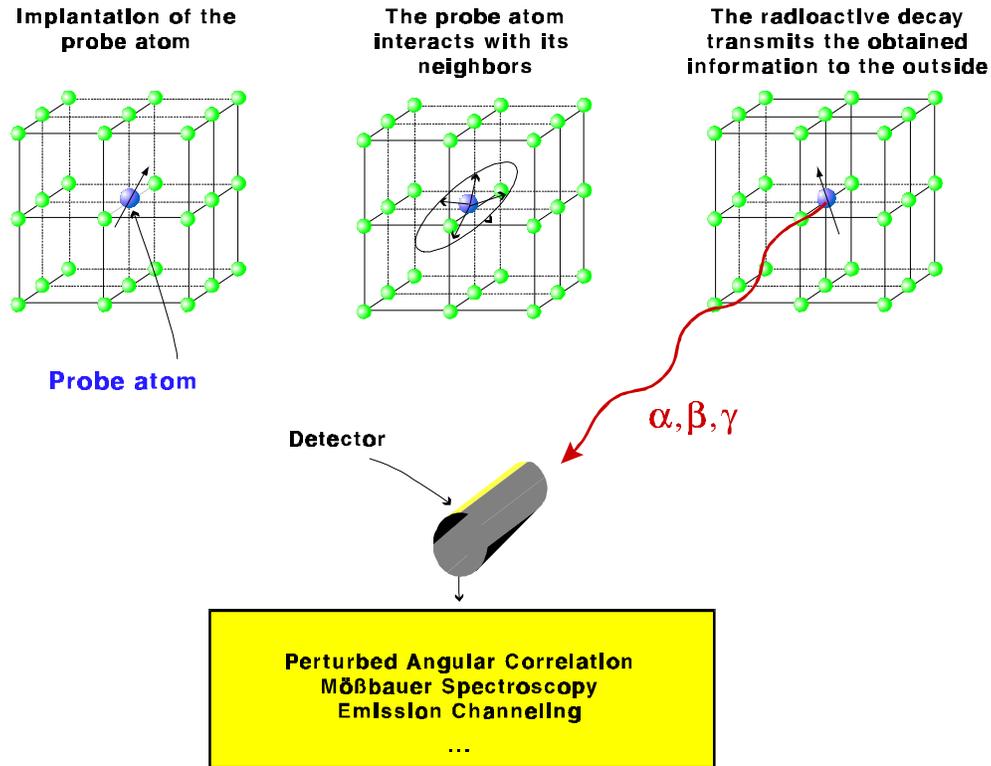
Fig. 27 Schematic depiction of the implantation of a radioactive atom in an atomic lattice (left-hand portion) its interaction with the lattice atoms (center portion), followed by "communication" of information about the details of the crystal structure by its radioactive decay (right-hand) portion. The information on the electric and magnetic fields of the lattice site of the radioactive ion can be obtained by an assortment of techniques such as perturbed angular correlations, Mössbauer spectroscopy, and emission channeling.

Sometimes it is impossible to implant a desired isotope into a lattice because of chemical incompatibility. Here, radioactive beams provide a solution through time-delayed chemical transformations. An example is the implantation of ^{107}Ag in a CdTe crystal. Obviously, however, Cd itself will be easily accepted into CdTe. With a radioactive beam facility radioactive ^{107}Cd ($T_{1/2}$ = 6.5 hr.) can therefore be implanted into a CdTe crystal (as shown in Fig. 28). After the radiation damage is annealed, ^{107}Cd will decay to the stable silver isotope, ^{107}Ag, forming a p-type doped CdTe crystal desired.

The proposed new ISOL facility will provide a greater variety of radioactive probe ions further away from stable nuclei with a diversity of half-lives, longer decay chains, and indeed new types of radiation (e.g., medium mass α-emitters). Nearly all combinations of probe atoms and host lattices will become possible, since pure radioactive isotopes can be produced (with variable energies) and implanted within seconds into any host lattice. The increased beam energy will allow an increased range of implantation depths leading, for example, to deep diffusion studies in which the α-particle energy distribution from the

decay of implanted α-emitters is studied as a function of time. Coulomb excitation plus recoil implantation also can extend Mössbauer studies to materials where solubility is not possible. At present, semiconductors are studied, for example at CERN's ISOLDE facility, using radioactive ions. In the future such studies may be expected to be extended to address a myriad of topics in superconductors and ceramics.

Applications to Nuclear Medicine — One of every three hospitalized patients in the United States undergoes a nuclear medicine procedure, with a total value estimated at 7 billion to 10 billion dollars per year. More than 36,000 diagnostic medical procedures that employ radioactive isotopes are performed daily in the United States. Most of the radioisotopes presently used for nuclear medicine are produced by reactors or small accelerators. The advent of a large ISOL facility would not only allow a greatly increased variety of carrier free, i.e., isotopically pure, radioisotopes, it also would allow a new class of intermediate-mass α-particle emitting nuclides, such as ^{149}Tm, to be utilized for radionuclear therapy. Previously it has been possible to synthesize only a handful of very heavy or very light α-particle emitting isotopes.

Positron emission tomography (PET) is a technique in which a positron emitting radionuclide is introduced into biological tissue. A positron emitted from a nucleus annihilates with an electron in the surrounding material producing a pair of 511 keV γ-rays, whose detection can be used to precisely define the location of the decay. This technique has been used for blood flow studies, glucose metabolism, amino acid utilization, and receptor binding of neurotransmitters in living human patients. Still largely a research tool, PET promises to have important clinical applications to heart disease, cancer detection, and cerebral dysfunctions. Also PET is the only method of obtain absolute radioactivity concentrations in vivo. By employing positron-emitting isotopes of elements used for other types of radiotherapy, it is possible to extract deposited doses quantitatively. For example, positron emitting ^{83}Sr ($T_{1/2}$ = 32.4 hours) can be used to monitor the uptake of the radioisotope ^{89}Sr used in bone metastasis.

A variety of positron-emitting isotopes are currently produced by small accelerators to be used for PET. However, often the positron-emitting isotope of the element of interest is too short-lived for clinical use or research. It decays before it can be used. For example, the longest lived positron-emitting isotope of phosphorus, ^{30}P, has a half life of only 2.5 minutes. However, arsenic has similar chemical properties as phosphorus and could therefore be used as a surrogate for phosphorus. There are positron-emitting arsenic isotopes with half-lives in the range of hours, which could be produced carrier free by an ISOL facility for PET research.

Atoms of a variety of elements have been captured at the center of fullerenes (buckyballs), a circular lattice of 60 or 84 carbon atoms (depicted in Fig. 29). Therefore, one can imagine using fullerenes to transport a selected radiation to a specific biological site by capturing the appropriate radionuclide in a fullerene. Applications to cancer therapy are

Transmutation Doping
of CdTe
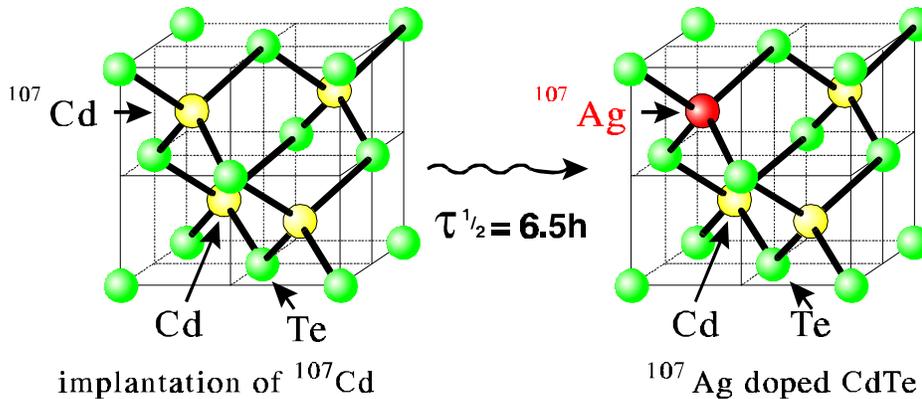
Fig. 28 Schematic representation of transmutation doping in which a radioactive ^{107}Cd atom is implanted in a CdTe lattice. After annealing the damage resulting from the implantation, the ^{107}Cd atom decays with a half life of 6.5 hours to a stable ^{107}Ag atom creating a p-type doped CdTe crystal.

obvious. Of course, the outer shell of carbon atoms dominates the chemistry of these complex molecules. For example, chemically inert rare gas atoms, such as Kr or Xe, can be attached to biological sites; or rare earth atoms, such as Ho, which when injected into the bloodstream, usually quickly concentrate in bones, remain in the blood. Recently, the first radioactive atom in a fullerene lattice, produced by irradiating Ho atoms inside fullerenes at the High Flux Reactor at ORNL, has been used for biomedical studies. However, the neutron flux of the reactor limits the irradiation times to only a few minutes, otherwise the fullerene structure is destroyed. Implantation of low energy radioactive ions produced by an ISOL facility in layers of fullerenes is perhaps a better technique for producing radioactive ions inside fullerenes. It is also possible to replace one of the carbons of the fullerene with other atoms. This can produce a selective bonding of the fullerene with specific chemicals. Such modifications are called receptors.

Applications to Tribological Studies — The decay of radioactive ions has been used in a variety of tribological studies. For example, a thin layer of the surface of internal combustion engine piston rings has been activated by direct bombardment with low energy proton beams creating radioactive ^{56}Co ($T_{1/2}$ =77.2 days) from the ^{56}Fe(p,n) reaction. The wear of the rings then can be monitored by the characteristic radiation of ^{56}Co collected as a function of time in the oil filter. Similar techniques have been demonstrated for tribological studies of plastics and ceramics by implanting long-lived radionuclides such as

^{7}Be ($T_{1/2}$ =53.3 days) and ^{22}Na ($T_{1/2}$ = 2.6 years) at a specific depth in the materials to be studied.

Again, the large assortment of beams from an advanced ISOL Facility allows such studies to be extended to a wide variety of other materials and applications. The half-lives and the energy of the extended variety of γ- and β-emitting radionuclides then could be selected to suit the application. In general, shorter half-lives are useful for R&D, and longer half-lives are applicable to field tests. Likewise, a wide range of radioactive beam energies allow the implantation depth and depth profile to be monitored. In contrast to activation studies, the same radionuclide can be implanted into an assortment of different materials to allow a critical comparison of the tribological properties of, for example, metals, plastics, and ceramics.

Facility Requirements for Applications — Most of the applications considered in this Section require a variety of intense, isotopically pure radioactive beams with energies from a few keV to about 10 MeV. Such energies are much less than most of the other applications of radioactive ions considered herein, which are based on using the radioactive beams to induce secondary nuclear reactions. Therefore, it would be desirable for the advanced ISOL facility to have the capability to provide low energy beams for applications simultaneously with high energy beams for nuclear physics studies. Of course, such a capability will also be useful for nuclear structure studies of stopped exotic nuclei (e.g., decay studies).

ORNL 97-12720.2/gel
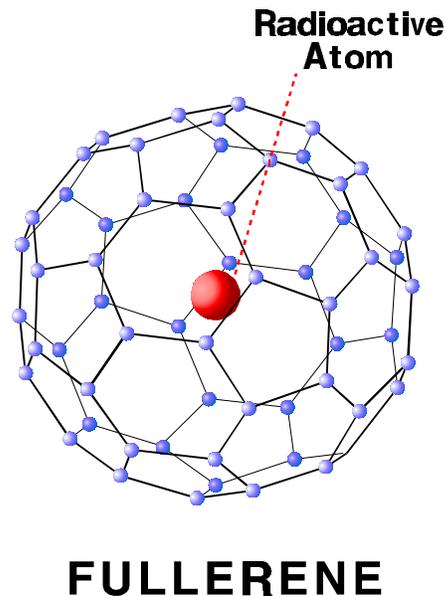
FULLERENE

Fig. 29 Illustration of a radioactive atom trapped at the center of a fullerene (buckyball). Trapping radioactive atoms in such giant molecules completely modifies their chemical properties. A myriad of medical and materials science applications can be imagined in which the fullerenes carry the radioactive ion to a specific biological or crystal site.

VI. Worldwide Perspective on Radioactive Beam Facilities

Introduction — Principles and Characteristics

The strong interest in the physics with accelerated short-lived nuclei is reflected in the many facilities that are in operation worldwide, under construction, or being proposed. These facilities are based on either in-flight Projectile Fragmentation (PF) or on Isotope Separation On-Line (ISOL) methods. The latter method is often also referred to as the two-accelerator method. Both methods have their respective advantages and complement each other in the type of physics that can be done.

Projectile Fragmentation was pioneered in the beginning of the eighties at the Berkeley Bevelac. In this method, as illustrated in Fig. 30, an energetic ion beam is fragmented while passing through a (thin) target, and the reaction products are subsequently transported to a secondary target after mass, charge and momentum selection in a fragment separator. Since the reaction products are produced in-flight, no post-acceleration is required. Fission in-flight of very heavy beams, but also charge exchange and transfer reactions, have been used as an alternative to Projectile Fragmentation.

In addition to the high energy that the fragments automatically carry over from the primary beam in this (thin target) production method, and that is key to certain classes of experiments, the in-flight production also means that the subsequent experiments with the radioactive fragments as a secondary beam can be done promptly. That is, they are only delayed by the flight time through the separator and beam line system to the reaction target, typically of the order of microseconds.

In an ISOL-type facility the radioactive nuclei are produced essentially at rest in a thick target by bombardment with particles from a primary source or driver accelerator (see Fig. 30). After ionization and selection of a specific mass by electromagnetic devices, these nuclei are accelerated in a post-accelerator. A wide range of primary beams including thermal neutrons, medium energy deuterons, GeV protons, and intermediate energy heavy ions are in use or have been proposed. Similarly a range of different types of post-accelerators are being considered including cyclotrons, linacs, and tandem accelerators.

The ISOL technique allows the radioactive beam to be prepared with the optimum characteristics needed for studies in nuclear structure and nuclear astrophysics. The post-accelerators, optimized for high quality beams, provide the easy energy variability, high energy precision and small emittances that are key to successful experiments. Another advantage of ISOL facilities is the high luminosity that can be achieved through the combination of a thick production target and a very intense primary beam. The time delay resulting from stopping, ionizing, and extracting the radioactive fragments from the production target and forming an ion beam out of them is a drawback of the ISOL

method. However, this drawback is partly alleviated by the fact that many nuclei of interest decay dominantly through the weak interaction which has a built-in time delay (typically milliseconds or longer).

The PF and ISOL approaches are truly complementary. Radioactive beams from a PF installation emerge immediately and at high energies, typically from 50 to several 100 MeV/nucleon. In contrast, ISOL beams are accelerated up essentially from zero energy to the region below, near and somewhat above the Coulomb barrier, that is, up to about 10-20 MeV/nucleon. As these beams have energies comparable to those of the nucleons in the nucleus they are ideally suited to the study of nuclear structure. Since they impact the target
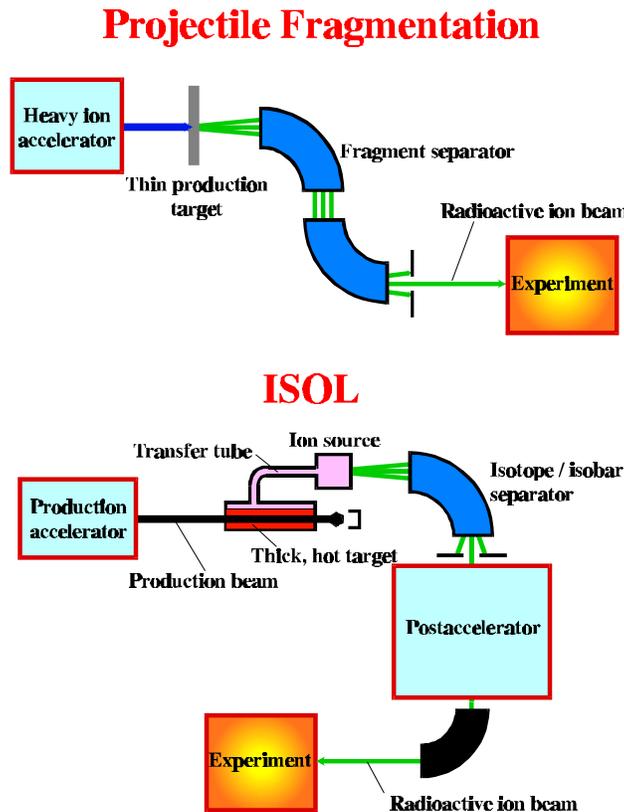
Fig. 30 Schematic representations of the two basic types of radioactive ion beam facilities. The lower part of the figure shows a facility based on the Isotope Separator On Line (ISOL) method. Radioactive atoms are produced essentially at rest by nuclear reactions induced by a driver beam in a thick, hot target. These atoms diffuse from the target into an ion source to be ionized and formed into a low energy beam, which is filtered to select ions of a single nuclear species, and subsequently accelerated (in the post-accelerator) to energies optimized to the science to be studied. The upper part of the figure shows a Projectile Fragmentation (PF) facility. The primary accelerator directs a beam of heavy ions on a thin production target where the primary beam particles are fragmented into a variety of nuclear species. The radioactive nuclei of interest to the experiment are collected and selected out of the other species produced in the target in the fragment separator.

nucleus rather gently, they do not obliterate the object whose structure is sought. Moreover, the temperatures of stellar environments correspond to low nuclear energies, of a couple of MeV/nucleon and lower. Finally, many nuclear physics tests of the Standard

Model and many applications of nuclear techniques require low energy, or even stopped beams of unstable nuclei. Of course, there do exist areas of overlap of the ISOL and PF approaches through decay studies of stopped short-lived nuclei, and at intermediate energies, where the two methods meet, allowing independent checks of important results with different experimental techniques.

In the remainder of this section, we present a brief technical overview of the enormous activity worldwide with respect to radioactive beam facilities, first discussing the situation outside the US, and then giving an assessment of the status within the US.

Radioactive Beam Facilities Outside the United States

Since the early Bevalac work PF has been extensively used outside the US at GANIL (France), RIKEN (Japan) and GSI (Germany). Whereas the first two of the foreign facilities make use of intermediate energy heavy ion accelerators to produce the primary beams, GSI utilizes relativistic heavy ion beams with energies up to 2 GeV/nucleon. At GSI a new dimension has been added with the Experimental Storage Ring (ESR) in which the radioactive nuclei can be stored and cooled.

Two new Projectile Fragmentation facilities utilizing cooler-storage rings have now been (partly) approved, one at RIKEN, Japan, the RIKEN RI Beam Factory (RIBF), and second, the AIRFLOW-CSR, at the Institute of Modern Physics at Lanzhou, China. The RIKEN proposal is presently the most ambitious project. The beams from the existing heavy ion accelerators will be boosted in two open-sector cyclotrons with superconducting coils to maximum energies of 400 MeV/nucleon for N=Z ions and 150 MeV/nucleon for the heaviest nuclei and there will be multiple fragment separators for parallel use. In the second phase of the project, called MUSES, a system of storage rings will be added, consisting of an accumulator cooler ring, a booster synchrotron ring, and double storage rings for experiments with merging and colliding beams. Beams of 2.5 GeV electrons will be available in one of the rings for the scattering of electrons from the radioactive nuclei stored in the other ring. The first phase of the project has started in 1997. The Lanzhou project foresees a system of two cooler-storage rings, of which one will be used to boost the energy of the primary beam, while the second will store the short-lived nuclei. At GSI there presently are also discussions going on with regard to an upgrade of their facility.

Although the suggestion to post-accelerate radioactive nuclei produced via the ISOL method is more than 25 years old, the first ISOL type RNB facility only came into operation at the end of the 1980s at Louvain-la-Neuve in Belgium. In this special purpose facility, called ARENAS, a high current, but low energy cyclotron is used as the primary accelerator, while the secondary beam is accelerated with the K=120 MeV Cyclone cyclotron. A new cyclotron that is designed to cover the very low energies of interest for astrophysical studies is presently being installed.

Until very recently, when the Oak Ridge cyclotron-tandem combination (HRIBF) started operation, ARENAS was the only operating ISOL-type RNB facility. Other facilities, however, are presently under construction. At GANIL in France the SPIRAL facility will use the present heavy ion accelerator complex with 95 MeV/nucleon heavy ions as the primary beams and the new K=256 MeV cyclotron CIME as post-accelerator. This facility, which should go into operation at the end of 1998, can be expected to provide a wide range of RNBs with energies well above the Coulomb barrier.

At the ISAC facility at the TRIUMF meson factory in Vancouver, Canada, a 500 MeV proton beam is being used as the production beam. In the first phase, beam currents up to 10 μA are being aimed for. Obviously, the accelerator will not be the limiting factor in going to even higher currents, but rather the high temperatures created in the target and the need to dissipate huge amounts of energy in the target. A RFQ-Linac combination will be used as post-accelerator for energies from 0.15 to 1.5 MeV/nucleon. Like the Louvain-la-Neuve facility, the research focus here is on nuclear astrophysics of the light elements.

A RFQ-Linac combination for energies up to 2 MeV/nucleon is presently under construction for the REX-ISOLDE project at CERN-ISOLDE at Geneve, Switzerland, in which 1 GeV protons (limited to 2.3 μA) from the CERN-PS are used as primary beams. At the EXCYT project in Catania, Italy, a scheme very similar to that of the Oak Ridge HRIBF is being adopted, wherein the Catania K=800 MeV cyclotron with superconducting coils is taken as the primary accelerator and the 15 MV tandem as the post-accelerator.

All of the ISOL facilities listed above must be seen as first-generation facilities, though some in the future would be upgradable into the kind of advanced second-generation ISOL facility that this Report focuses on.

In Japan, a new accelerator complex for very high current proton beams up to 50 GeV encompassing a 200 MeV linac, a 3 GeV Booster Synchrotron (200 μA) and a 50 GeV Synchrotron (10 μA) is likely to be funded in the near future at KEK (Tsukuba), primarily for hadron physics. However, part of this Japan Hadron Facility (JHF) project will be the E-Arena of the JHF ISOL facility. The aim will be to use the 3 GeV protons from the booster with maximum currents of 10 μA for the RNB production. The post-accelerator will involve an RFQ, followed by two linacs, a combination which will allow the RNBs to reach maximum energies of 6.5 MeV/nucleon. The RFQ and the first linac have already been built and tested in conjunction with the "R&D facility of E-Arena" at the KEK branch in Tokyo.

Other foreign sites with radioactive beam initiatives are Legnaro in Italy, the ISIS facility of the Rutherford Laboratory in the UK, and at the Tandem -- Linac facility in Sao Paolo, Brazil, which has just received funding.

An alternative to this two-accelerator type of ISOL facility -- an innovative approach using a high-flux reactor combined with a fission target for the production of the

unstable nuclei -- has been suggested in the PIAFE project in Grenoble, France and, more recently, in conjunction with the new Munich research reactor, presently under construction. The use of thermal neutron fission promises to produce high yields of certain neutron rich nuclei. However, the fate of these very intriguing projects still is somewhat uncertain.

Radioactive Beam Facilities in the US

In the US, the premier facility for early radioactive beam studies has been the Michigan State University facility which produces high energy beams of short-lived nuclei through in-flight Projectile Fragmentation of stable beam nuclei, the technique originally pioneered at the Bevalac at Berkeley. The MSU facility is presently being upgraded (supported by NSF) following the NSAC recommendation to enhance radioactive beam capabilities in the US to capitalize on the compelling new scientific opportunities that they provide. A Notre Dame University-Michigan University collaboration has developed a specialized in-flight approach to provide specific light mass radioactive beams at low energy. Their system is currently being upgraded. High-resolution, high quality beams obtained by the two-accelerator approach have been used in experiments at Argonne National Laboratory and Texas A&M University.

Recently, the first, and until now the only, ISOL-type facility in the US, the HRIBF at Oak Ridge National Laboratory has become operational and commenced its experimental program. This first-generation facility exploits an existing cyclotron-tandem combination and a newly developed ISOL-type production target and ion source for a variety of exotic beams.

The results of initial RNB studies have amplified the unique promise that radioactive beams carry but they have also made it very clear that to effectively capitalize on these new science opportunities, the greatly increased intensities and capabilities of next-generation facilities are needed as recommended with highest priority in the 1996 Long Range Plan of the Nuclear Science Advisory Committee to DOE and NSF.

Conclusions

The preceding overview demonstrates that there is an enormous worldwide activity in the construction of radioactive beam facilities that clearly reflects the strong scientific interest in the physics with such beams. The need for advanced ISOL facilities is clear and several countries are embarking on proposals that either constitute such facilities or are upgradable into them. At the present time, the US has no funded project for a next-generation ISOL facility, and is in danger of soon lagging in this frontier area of science. Yet, an opportunity to explore the exciting areas of physics we have discussed, which places the US at the forefront of this broad area of new science, is available if acted on expeditiously.

VII. Facility Requirements

The preceding Sections describe the new frontiers of science that will become accessible with intense, energetic beams of short-lived nuclei. While novel instrumentation, detectors, and techniques will need to be perfected to exploit these new beams, which often will have rather low intensity, we can nevertheless build on experience and employ the processes, procedures, reactions, and reaction models that have been developed to a high level of sophistication in the past decades in studies with beams of stable nuclei.

Utilizing inverse reaction geometry and kinematics, in which the roles of projectile and target are interchanged compared to traditional techniques, radioactive beam studies can focus on the key science questions through the use of well understood methods and reaction models. These include elastic and inelastic scattering reactions to obtain form factors, transition amplitudes and shape parameters of exotic nuclei; Coulomb excitation to explore rotational and vibrational excitations and the coupling of the collective and single particle degrees of freedom, in particular for nuclei near the drip lines; radiative capture and Coulomb dissociation to determine cross sections, resonance energies and strengths for astrophysical reactions; one and few nucleon transfer reactions to determine single particle energies, effective nucleon-nucleon interactions, strengths distributions, and particle correlations in doubly magic closed shell nuclei far from stability and in weakly bound nuclei near the drip lines; fusion - evaporation reactions with subsequent detection of γ rays to study the band structure of nuclei; fusion - fission reactions, in particular of nuclei near the limits of binding -- the drip lines, the borderline of the heaviest elements and nuclei with large neutron excess; strongly damped collisions to extend the range of neutron rich nuclei. These studies will also encompass the broad range of tools and methods developed for nuclear decay studies including the most modern methods to prepare nuclei for specific studies -- ion and atom traps.

This comprehensive approach to research with radioactive beams defines broadly the performance specifications expected from the next-generation full-powered ISOL facility that we are discussing in this Report. It is in this spirit that we give here an evaluation of the beam requirements for such a facility in terms of intensity and energy.

To do this, we group the science discussed in the previous sections into broad, somewhat schematic categories. Of course, we realize that we cannot be complete in this attempt, in particular in view of the likelihood -- as always with novel capabilities -- that interesting new developments might occur in directions that we cannot presently anticipate. Nevertheless, we hope that these specifications present a reasonably reliable assessment of the facility capabilities which are necessary in order to effectively pursue the science outlined in this Report.

The general scientific thrusts that we have discussed in this Report are schematically illustrated in Figure 31. This figure shows regions of interest in the proton

vs. neutron landscape that can be explored with a second-generation ISOL facility. Each topic is given a number which corresponds to an entry in Table 1 in which representative examples for each area of interest are given in order to quantify beam requirements and experimental approaches. These are just typical examples that characterize key areas of study; they are generally representative of a large class of similar (and as it might turn out, as often the case in science, more interesting) studies. The examples are given to broadly quantify the range of beam intensities and energies that will be expected from the ISOL facility, and thus to define its overall performance characteristics.

The relations between the science areas and the cross sections underlying the respective experiments, and thus the required beam intensities, are illustrated in the top part of Figure 32. The bottom part indicates the well-established reaction processes and methods that have been developed to a high level of sophistication in the past decades with stable beams, and that can now be effectively applied to the new science opportunities with unstable beams. The relationships between the science areas and the respective methods applied in each area can be seen from columns 1 and 2 in Table 1.

In our evaluation we have included considerations of realistic performance limitations based on the experience with first-generation facilities on the one hand, and, on the other, have made an attempt to define a facility performance that places the proposed ISOL facility at the forefront of this exciting new field of research.
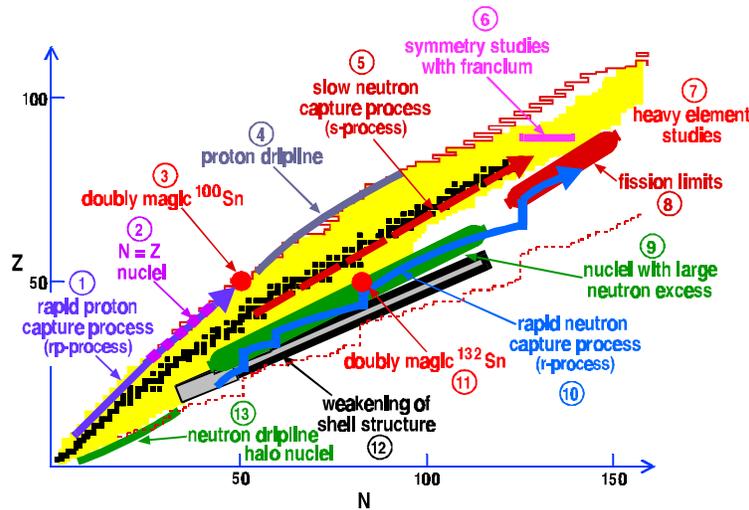
Fig. 31 Illustration of research opportunities with beams of short-lived nuclei as discussed in this Report. Regions of interest that can be explored with a second-generation ISOL facility are shown in the neutron vs. proton landscape. This is a schematic representation, characterizing the areas of research and exemplifying types of studies. The circled numbers correlate with the entries in Table 1 which gives representative examples of reactions and techniques, beams, desired intensities, and energy ranges for each area of interest. The desired beam intensities, while not available from present first-generation ISOL facilities, could be achievable with new technological developments as expected at an advanced ISOL facility. These examples are generally representative of a large class of similar studies. The examples are given to outline the overall performance characteristics needed for an exploration of the new science opportunities.

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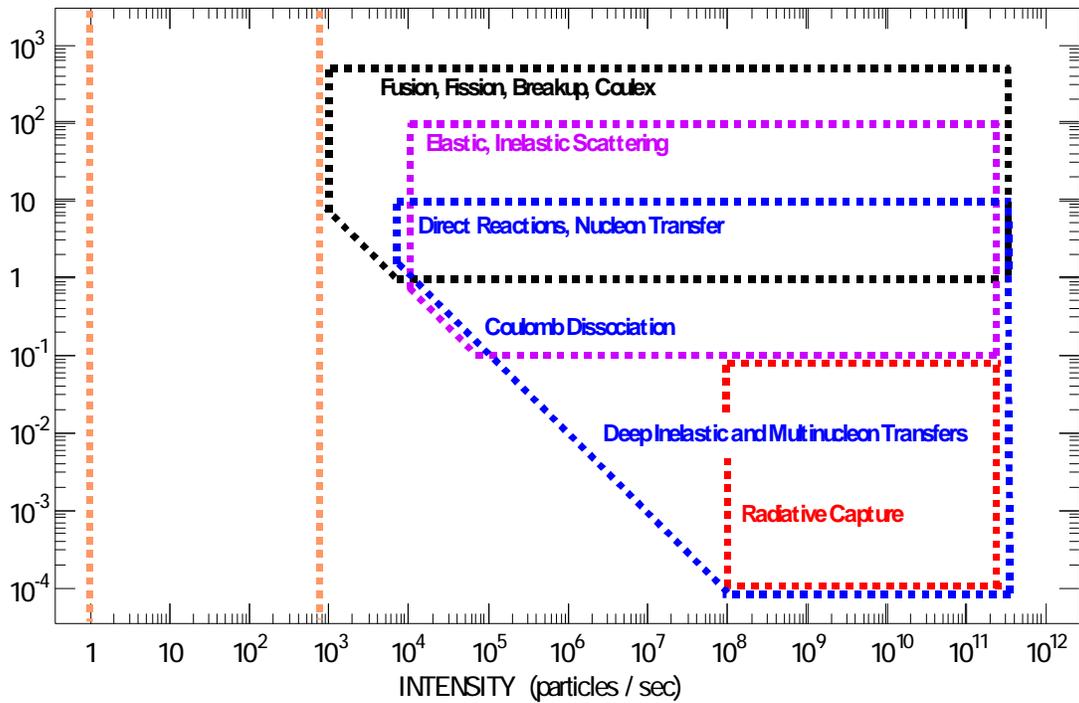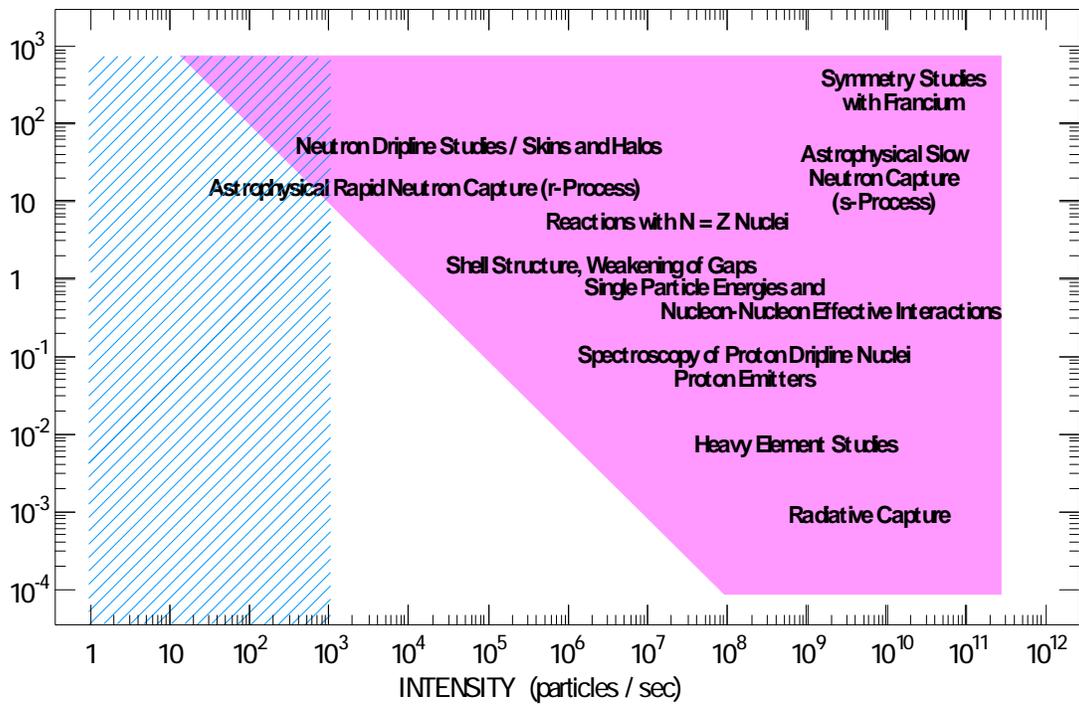
Fig. 32 Plot of cross section vs. required beam intensity for the areas of research illustrated in Figure 31. The top part shows very schematically the relation of these areas with typical cross sections and beam intensities associated with their study. The bottom part indicates the well-established reaction processes and methods that have been developed to a high level of sophistication in the past decades with stable beams, and which can now be effectively applied to the new science opportunities with unstable beams. The relation between the science areas and the respective methods applied in each area can be seen from columns 1 and 2 in Table 1.

Table I: Representative examples of beam requirements for the general research areas discussed in this Report and schematically illustrated in Fig. 31. Only a few typical ion species are shown for each entry to exemplify the intensity and energy ranges needed for performing experiments in these areas.

	Physics Topics*	Reactions and Techniques	Beams	Desired Intensities [particles/sec]	Energy Range [MeV/u]
1.	rapid proton capture (rp processes)	transfer, elastic, inelastic, radiative capture, Coulomb dissociation	^{14}O, ^{15}O, ^{26}Si, ^{34}Ar, ^{56}Ni	10^8-10^{11} 10^5-10^{11}	0.15-15
2.	reactions with and studies of N=Z nuclei, symmetry studies	transfer, fusion, decay studies	^{56}Ni, ^{62}Ga, ^{64}Ge, ^{68}Ge, ^{67}As, ^{72}Kr	10^4-10^9	0.1-15
3.	decay studies of ^{100}Sn	decay	^{100}Sn	1-10	low energy
4.	proton dripline studies	decay, fusion, transfer	^{56}Ni, ^{64,66}Ge, ^{72}Kr	10^6-10^9	5
5.	slow neutron capture (s-process)	capture	^{134,135}Cs, ^{155}Eu	10^8-10^{11}	0.1
6.	symmetry studies with francium	decays, traps	^{A}Fr	10^{11}	low energy
7.	heavy element studies	fusion, decay	$^{50-52}$Ca, ^{72}Ni, ^{84}Ge, ^{96}Kr	10^4-10^7 10^6-10^8	5-8
8.	fission limits	fusion-fission	$^{140-144}$Xe, $^{142-146}$Cs, ^{142}I, $^{145-148}$Xe, $^{147-150}$Cs	10^7-10^{11} 10^4-10^7	5
9.	rapid neutron capture (r-process)	capture, decay, mass measurement	^{130}Cd, ^{132}Sn, ^{142}I	10^4-10^9	0.1-5
10.	nuclei with large neutron excess	fusion, transfer, deep inelastic	$^{140-144}$Xe, $^{142-146}$Cs, ^{142}I, $^{145-148}$Xe, $^{147-150}$Cs	10^7-10^{11} 10^2-10^7	5-15
11.	single-particle states/ effective nucleon-nucleon interactions	direct reactions, nucleon transfer	^{132}Sn, ^{133}Sb	10^8-10^9	5-15
12.	shell structure, weakening of gaps, spin-orbit potential	mass measurement, Coulomb excitation, fusion, nucleon transfer, deep inelastic	^{A}Kr, ^{A}Sn, ^{A}Xe	10^2-10^9	0.1-10
13.	(near) neutron-dripline studies, halo nuclei	mass measurement, nucleon transfer	^{8}He, ^{11}Li, ^{29}Ne, ^{31}Na, ^{76}Cu	10^6-10^8 10^3-10^6	5-10

*The numbers 1-13 refer to the corresponding labeling in Fig. 31.

VIII. Summary And Outlook

This Report has summarized the exciting research opportunities that, in the Panel's and the community's view, are centered around a new facility for intense high resolution beams of short-lived (radioactive) nuclei for the areas of nuclear structure physics, of nucleosynthesis and nuclear astrophysics, and for important studies of fundamental symmetries.

In all of these areas, new studies of key importance will become possible: of our understanding of the nuclear many-body system, of the origins of the elements and their role in the reactions occurring in the cataclysmic events of the cosmos, and of aspects of the fundamental theory, the Standard Model, that best represents our current understanding of the physical laws and fundamental symmetries in Nature.

The prospects for this new area of research have matured over the last decade, starting from studies with short-lived nuclei of very low energy at isotope separators on the one hand, and from initial experiments using energetic beams at existing stable beam accelerators on the other. Subsequently, several dedicated first-generation facilities were built to begin an exploration of the physics made available by exotic beams. Studies of nuclei beyond those accessible with stable beams are beginning to provide fascinating insights. New phenomena such as halos and skins, growing evidence of the fragility of shell structure far from stability, and the possible existence of new phases of nucleonic matter such as proton-neutron pairing, are just examples.

There is growing evidence that our understanding of how structure evolves with N and Z may apply only to a limited set of nuclei. Moreover, we do not know, and cannot predict, where the drip lines are and thus, in a very real sense, do not even know the bounds of nuclear stability itself. We have studied only a part of a far richer perspective and need to expand our horizons. In these pages we have identified many new opportunities addressing these important physics questions. With the advent of radioactive ion beams we now have a tool to attack these questions with advanced technologies and to forge a new understanding.

There is very little doubt that we are on the verge of a most fascinating journey into new science. The availability of radioactive beams allows us to adopt the strategy of going to extreme values in the ratio of neutron-to-proton number in a nucleus, and to the heaviest nuclei to identify new phenomena, and then returning to experimentally more accessible regions near stability to improve our understanding of nuclei which comprise the world in which we live. In this process we will also gain new insights into the origins of the elements and the physical laws and fundamental symmetries in Nature.

To effectively capitalize on these new science opportunities, the greatly increased intensities and capabilities of next-generation facilities are needed. In concert with the 1996 Long Range Plan of the Nuclear Science Advisory Committee to DOE and NSF, we

strongly urge the design and construction of a next-generation ISOL facility with the intensities, beam energy range and variability, beam quality, and flexibility needed for the nuclear structure, nuclear astrophysics and fundamental symmetry studies that we have discussed.

We now have the background gained at on-line isotope separators and at first-generation ISOL and Projectile Fragmentation facilities, which provides the community with experience in both the production and utilization of radioactive beams. In addition, a vigorous program of R&D directed at the technical issues which must be met at a high intensity advanced facility is well under way. The technical tools for its construction are in hand. In fact, several concepts for facilities capable of producing the beams required to carry out the physics program outlined in this Report have already been presented.

The research and application opportunities offered by beams of exotic, short-lived nuclei are both timely and exciting and the construction of an advanced ISOL facility of the type needed and envisioned for the effective exploration of the science discussed in this Report would place the US program at the forefront of this new and exciting area of research.

Appendix - Glossary

In this Report we have tried to use as little technical jargon as possible but a certain minimum is unavoidable. We define some specific terms as we go along in the Report but here we give brief explanations of a few frequently used concepts.

A - Total number of nucleons in the nucleus, A=N+Z.

α–decay, α-particle - Some nuclei that are not stable decay by emitting an α-particle which is the nucleus ^{4}He consisting of two protons and two neutrons.

Beam intensities - These are given either as a number of particles per second (e.g., 10^7 particles/sec) or as a current (e.g., 1nA which equals 6×10^9 particles/sec).

β-decay, β-particle - Many nuclei that are not stable transform into another nucleus by changing a proton into a neutron or vice versa. This process is an effect of the weak interaction. In β-decay, A remains constant and Z and N change by one unit, in opposite directions. In this process a β-particle is usually emitted -- these particles are simply electrons or positrons (positively charged electrons).

Configuration - Refers to the set of orbits occupied by all the nucleons in the nucleus. A given nucleus can exist in several configurations, which, in general, will have different energies.

Cooper pairs - This refers to a concept in condensed matter physics in which two electrons that spin in opposite directions are paired off so that they have no net angular momentum. Cooper pairs are critical to understanding superconductivity and the concept has been taken over into nuclear physics to describe nucleon pairing as well.

Coulomb force - This is the force between electrically charged bodies. Bodies with like charges (e.g., the positively charged protons in the nucleus) repel each other, those with opposite charges (e.g., the protons of the nucleus and the orbiting electrons of the atom) attract each other.

Cross section - A measure of the probability of a reaction. This is expressed in terms of an area and can be thought of as the cross sectional area presented by a nucleus to an incident projectile. However, due to quantum physics, the nuclear cross section can actually differ, by many orders of magnitude, in either direction, from the geometrical area and it depends on the specific nuclear states involved, the nature of the projectile and the reaction, the beam energy, and so on. Cross sections are measured either in units of cm^2 or "barns" (one barn is 10^{-24}cm^2). Commonly used units are nanobarns (nb=10^{-9}b), microbarns (μb=10^{-6}b) and millibarns (mb=10^{-3}b).

Drip lines - The limits of nuclear existence. The neutron and proton drip lines specify the maximum number of neutrons that nuclei of a given element can contain and the maximum number of protons that nuclei with a given number of neutrons can contain, respectively. Nuclei within the drip lines can be either stable or unstable. Nuclei beyond the drip lines are called "unbound" (to nucleon emission) -- i.e., they decay by emitting a proton or neutron.

Element - One of the chemical elements such as nitrogen, oxygen, calcium, iron, tin, lead. Often denoted by their usual chemical symbol (N, O, Ca, Fe, Sn, Pb). The nucleus of an element has a characteristic number of protons, called the atomic number and denoted by Z. Thus, nitrogen, iron, tin, and lead have 7, 26, 50, and 82 protons, respectively.

Exotic, radioactive, or unstable nuclei - Nuclei which change into others. The time scale for these changes is specified by the "half-life" ($T_{1/2}$) which gives the time required for half of the original number of nuclei to decay. "Unstable" generally refers to instability with respect to the weak force: that is, such nuclei transform into another nucleus by changing a neutron into a proton (or vice versa) in the process called β-decay. "Unbound" refers to nuclei beyond the drip lines (see also "Drip lines").

Force - There are four forces in Nature -- the strong, weak, electromagnetic, and gravitational. The first three are important in nuclei. The words interaction and force are often used interchangeably in this Report.

γ-ray - electromagnetic radiation, similar to ordinary light but far more energetic, which is emitted when a nucleus deexcites from one state to a lower energy level.

Inverse reactions or inverse kinematics - A method of carrying out experiments particularly useful with unstable nuclei, which are too short-lived to survive as targets, in which the normal roles of target and beam are interchanged.

ISOL - The Isotope Separation On-Line technique for the production of beams of radioactive nuclei (see Fig. 30).

Isospin and isospin symmetry - A term reflecting the fact that protons and neutrons can be considered as two manifestations of the same particle, the nucleon, that the nuclear force is the same for each, and therefore that the properties of nuclei should be symmetric with respect to protons and neutrons (after correcting for the Coulomb force).

Isotopes - Nuclei of a given element may have different numbers of neutrons: oxygen nuclei with 8, 9 or 10 neutrons are all called isotopes of oxygen.

Level or energy level - A particular configuration of a nucleus and the energy required to put the nucleus in that configuration. The lowest energy configuration of a nucleus is called the ground state.

Magic numbers - Numbers of protons and neutrons leading to nuclei that have special stability. The most important of these are 2, 8, 20, 50, 82, and 126. Nuclei with N or Z equal to one of these numbers are themselves called magic or closed shell nuclei. The concept is similar to that of the closed electron shells in atoms that characterize the inert gases such as helium, neon, and xenon. Nucleons in the outermost, unfilled shell are often called valence nucleons, again in analogy with the terminology for electrons in atoms.

Mass of the nucleus - This can refer either to the actual mass of a nucleus or as a substitute for A: an "A=40 nucleus" and "a mass 40 nucleus" both refer to a nucleus with a total of 40 nucleons.

N - The number of neutrons in the nucleus.

Nucleon - Generic name referring to either a proton or a neutron.

Nucleosynthesis - The process (mostly occurring in violent stellar explosions) in which nuclei are formed.

Nucleus - The nucleus is the massive central part of the atom, measuring about 10^{-12} cm across. It consists of a grouping of protons and neutrons held together primarily by the strong, or nuclear, force. Nuclei with even numbers of protons and neutrons are often called simply even-even nuclei and similarly for odd-even and odd-odd nuclei. ^{A}X is the standard notation for a nucleus where X is the chemical symbol and corresponds to a specific atomic number Z, where A is the total number of nucleons in the nucleus, and where the number of neutrons, N, is just the difference between A and Z.

Orbit - Usually refers to the path taken by a nucleon in the nucleus. Different orbits are characterized by different radii, energies, and angular momenta. Orbit and orbital are often used interchangeably.

PF - The Projectile Fragmentation technique for the production of beams of radioactive nuclei (see Fig. 30).

Potential - A mathematical construct used to describe the force experienced by a particle -- usually it embodies the ideas of the strength of the force and the distance over which it acts.

Q-Value - The energy gain or loss in a nuclear reaction or decay process. Positive Q-values often lead to larger reaction probabilities and tend to populate a wider variety of levels in the final nucleus.

Quantum chromodynamics - Part of the Standard Model dealing with the strong interaction. This interaction holds the quarks together to form protons and neutrons. It is also responsible for binding these protons and neutrons together inside a nucleus.

Radioactive Nuclear Beams (RNB) facilities - Facilities that produce beams of unstable nuclei. (In this Report, the words radioactive, exotic, and unstable nuclei are often used interchangeably.) There are two generic methods of production, Projectile Fragmentation (PF) and Isotope Separation On-line (ISOL). In the former a high energy projectile usually bombards a thin light target and the unstable nuclei produced emerge directly as a beam of particles at nearly the same velocity as the incoming beam. In the ISOL technique, a thick target is used which stops the incoming projectile. The unstable nuclei produced come to rest, are ionized, and re-accelerated by a second accelerator. Both methods have advantages and limitations. Several PF facilities exist worldwide but there are no advanced ISOL facilities in existence.

Shell model - The standard theory of the nucleus which specifies a force or potential and results in predictions of the orbits and the energies of the nucleons in those orbits.

Spin and parity - These concepts characterize a given configuration in terms of its total angular momentum and its left-right symmetry. A typical notation is, for example, 0^+, meaning zero angular momentum and positive parity.

Stable nuclei - Nuclei which do not spontaneously change into other nuclei with different N, Z or A.

Standard Model of Particle Physics - Our existing theory of four forces of Nature: the strong, electrical, weak, and gravitational forces. This theory is deemed incomplete both because many of its basic building blocks are postulated, not derived, and because the four interactions are not described by a unified approach.

Units - The sizes of various quantities are often specified by a shorthand notation. Common units (and their abbreviations) are: milli = 10^{-3} or one thousandth (m), micro = 10^{-6} (μ), nano = 10^{-9} (n), kilo = 10^3 (k), and mega = 10^6 (M).

Valley of Stability - This refers to the locus of stable nuclei. It is usually depicted in a plot called a chart of the nuclides, as in Fig. 1, that shows the stable and unstable nuclei as a function of the number of protons (Z) and neutrons (N) in each nucleus.

Z - The number of protons in the nucleus.

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