OVERVIEW OF RESEARCH OPPORTUNITIES WITH RADIOACTIVE NUCLEAR BEAMS

An Update--1995

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ISL Steering Committee
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Dedication to Mike Nitschke

This updated ISL White Paper is dedicated to Mike Nitschke in order to recognize his insight into the potential of radioactive ion beam science and his pioneering efforts in bringing it to the fore. In particular, Mike was a strong advocate for the development of radioactive beams and the future research that a high-intensity radioactive beam facility of the ISL-type would make possible. As early as 1984, he organized the first Workshop to discuss radioactive beam research at the APS meeting in Washington, D.C. In 1989, during the last long-range planning exercise, he championed the idea of a broad-range RNB facility based on the ISOL approach that is known today as the IsoSpin Laboratory concept. This far-sighted idea caught the imagination of many scientists, and shortly thereafter the ISL community was formed. Also in 1989, with the help of other well-known scientists, he organized and hosted the First International Conference on Radioactive Nuclear Beams (the so-called Earthquake Conference) of which the fourth in this series will be in Japan in 1996. Mike was instrumental in preparing the ISL White Paper in 1990. As an active member of the ISL Steering Committee, he was one of our strongest technical leaders. He pioneered and refined many innovative ideas in producing and accelerating radioactive heavy ions. Mike was an inspiration to all of us working in the area of radioactive beams; we are indebted to him for his dedication and farsighted work. We, and all his colleagues and friends, will truly miss him.

The ISL Steering Committee

Preface

A central thrust of nuclear physics is the study of the interactions of nucleons in the nuclear many-body quantal environment. Until recently, manifestations of these interactions have largely been limited to nuclei near the valley of stability and to some proton rich nuclei. Access to unexplored extremes of N/Z promises to reveal qualitatively new phenomena likely to be radically different from anything we have observed to date. Even new forms of nuclear matter, and new nuclear topologies, can be expected. Shell structure as we know it near stability is likely to be altered substantially. Cherished ideas of nuclear structure and dynamics and of how they evolve are unlikely to survive intact in this expanded horizon.

The possibility to enter a completely new domain of our science has engendered, over the last few years, tremendous interest in the scientific research opportunities with Radioactive Nuclear Beams (RNBs). A broad international community of well over 600 active scientists is enthusiastically using existing RNB facilities and/or hoping and planning for future generation facilities. The recent Town Meeting on Nuclear Structure, Nuclear Reactions and Radioactive Beams held at TUNL January 19-21, 1995 as part of the 1995 NSF/DOE Long Range Plan process endorsed the immediate upgrade of the MSU RNB projectile fragmentation facility and the construction of an advanced ISOL-based facility with capabilities as envisaged in the ISL concept as its highest priority recommendation.

Research with RNBs to date has already demonstrated the potential for exciting new nuclear physics. Examples include the exotic structure of halo nuclei, which present us with new forms of nuclear matter, and the surprising impermanence of magic numbers, which hints at some of the marked changes in the underlying foundations of nuclear structure that await us. Indeed, as we shall see, the future potential of RNBs dwarfs even these examples.

In a sense, RNBs take us back to the historic roots of nuclear physics, but in the totally new environment far from the valley of stability. This is essentially virgin territory which promises an exploration as exciting as that which we have once before experienced in low-energy nuclear physics. Nuclear structure, and nuclear physics in a broader sense, will almost certainly be markedly different--recent experiments already virtually assure this--and will present both technical and conceptual challenges.

If our existing ideas and models need major renovation in newly explorable regions of the nuclear chart, if what we have thought to be the underpinnings of nuclear physics in a robust underlying shell structure turn out to be but a fragile reflection of how nuclear interactions manifest themselves near stability, then we cannot at all claim to have in hand an acceptable understanding of the atomic nucleus, of what happens when protons and neutrons come together, and of the diversity of quantal phenomena that clusters of nucleons can manifest. If, as seems likely, new structures, new excitation modes and new evolutionary trends appear in new regions away from stability, they will need to be understood in their own right and will hopefully lead to a more general and synoptic understanding of what really is going on at low energies in nuclei.

The purview of RNB science extends over the whole gamut of nuclear structure and reactions, nuclear astrophysics, fundamental physics, and many allied fields. Much of nuclear astrophysics including the study of nucleosynthesis and the evolution of the cosmos is inextricably linked to nuclei currently inaccessible to study. Simply put, to make progress in this broad and exciting field we need to have access to the nuclei of the stars. It is well recognized that the nucleus is also an excellent laboratory to test truly fundamental questions in modern physics. RNBs will give access to new nuclei with special properties and symmetries that will allow much more sensitive tests of the Standard Model and weak interactions in the nuclear medium. Not to be overlooked as well is the wide ranging exploitation of RNBs in atomic physics, materials science, and biophysics.

The advent of several RNB facilities worldwide (of both projectile fragmentation and ISOL types--see Section V) is a consequence of this rapidly growing momentum for RNB research and of the emerging consensus that it represents the future of low-energy nuclear physics. Indeed, existing projectile fragmentation facilities, such as MSU, and early generation ISOL ones, such as Louvain-la-Neuve or the HRIBF at Oak Ridge, have whetted the collective appetite of a large community of scientists. The scientific case for RNBs has been made in a number of forums, including, among others, the ISL White Paper, the NuPECC Report, the Oak Ridge HRIBF proposal, the ISAC proposal, the MSU NSCL coupled cyclotron proposal, and numerous conference overviews. Together, early RNB work has established the vitality of the field and these summaries have delineated many of the unique opportunities it presents. The importance of this new field has been recognized in a number of independent assessments, such as the recent USDOE review, the 1989 US Long Range Plan, and the 1993 Canadian NPPAP Report.

The present report has been prepared by the ISL Steering Committee as a brief synopsis of some of the excitement of RNB research. It will attempt to flesh out some of the ideas sketched above and to show how RNB nuclear physics promises to usher in a revolution in our understanding of nuclei as profound as anything in the history of our field. This report is both a summary of and an update to our previous White Paper. It attempts to focus on some of the newer ideas and discoveries that relate to RNB physics and which we feel make the scientific case even more compelling than heretofore realized. The emphasis is on a presentation of the conceptual underpinning that underlies expectations of truly novel nuclear physics far from stability.

In the last section, a synopsis is presented of the technological realizations of RNBs, of current efforts in North America, of the concept of the ISL, and of R&D efforts that will greatly aid its optimal realization. We stress here that the ISL is not an accelerator design effort but a conceptual goal focusing on the production of a wide variety of RNBs over a broad range of energies. The specific technical realization of a second-generation RNB facility, and the degree to which it achieves the ideal embodied in the ISL concept, will vary greatly depending on where it is sited, how it is designed, and the funds available for it.

In order to keep the overall length of this report to a reasonable minimum, accessible to broad segments of the nuclear science community, the discussions below are necessarily brief and many interesting topics are skipped. The interested reader is encouraged to read the earlier White Paper or other available summaries in which some specific topics are treated in greater detail.

In closing this Preface, perhaps the most important point to make is that this is a new, burgeoning, and still embryonic field. New ideas, new techniques, and new approaches to RNB physics and astrophysics are being developed at an extremely rapid pace. Indeed, much of the content of the pages to follow could not have been written a year ago. Hence, in all likelihood, the greatest discoveries to be made with RNBs cannot even be conceived or formulated at present.

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I. Nuclear Structure

Radioactive Nuclear Beams (RNBs) provide access to wholly unexplored realms of nuclei where there is every likelihood of discovering radically new types of structure unlike anything observed in the constrained environment of the valley of stability. Not only may new types of collectivity and new examples of double magic nuclei be encountered, but our traditional ideas of structure and its evolution with N, Z and A are apt to be challenged. The Pauli Principle and the short range and limited strength of the nuclear force assure that the outermost (or valence) nucleons primarily determine structure. The Pauli Principle also ensures that the addition of more nucleons leads to the occupation of new orbits. Hence it is inevitable that new manifestations of structure will emerge in new regions with large excesses of protons or neutrons relative to the valley of stability. Even the underlying shell structure and the nature of residual interactions that have given rise to nuclear structure as we know it are unlikely to survive near the proton and neutron drip lines. Near these drip lines, the unique combination of weak binding, the interaction of bound and continuum states, the large diffuseness of the nuclear surface, and extreme spatial dimensions characterizing the outermost nucleons, may render obsolete our traditional geometrical concepts of nuclear structure.

On the proton rich side, light N=Z nuclei exhibit sudden and huge spikes in certain binding energy relations. This sudden increase in manifestations of the integrated strength of the p-n pairing T=0 interaction by a factor of 2-5 for N=Z nuclei can be understood as a natural and intuitively simple outcome of Wigner SU(4) supermultiplet theory. In heavier N=Z nuclei, Coulomb and spin-orbit effects will tend to dilute these effects, and the study of the heaviest-bound N=Z nuclei will be a sensitive test of this competition. One intriguing recent speculation is that a pseudo-SU(4) symmetry might emerge, similar to the pseudo-SU(3) that is a useful framework in heavy nuclei. RNBs will access several new examples of N~Z nuclei up through ^{100}Sn. The unusual properties of such nuclei are also exemplified by the behavior of medium mass nuclei like ^{80}Zr which, with N=Z=40, was expected to be doubly magic or nearly doubly magic. Instead, it is deformed. Its N=Z neighbor ^{84}Mo is only slightly less so. This phenomenon is undoubtedly related to the crucial role of the p-n interaction in inducing configuration mixing. Assuming ^{100}Sn is doubly magic, the N=Z trajectory from ^{80}Zr to ^{100}Sn may comprise a unique example of a 1-dimensional (in the N-Z plane) shape/phase transition. Of course, if ^{100}Sn is not doubly magic, then the consequences are even more startling.

There is another very attractive aspect of proton-rich nuclei. On account of the Coulomb barrier, nuclei even beyond the limits of spontaneous proton emission will survive long enough to be studied. Radioactive decay by the emission of quasi-bound protons provides an excellent laboratory to study quantum mechanical tunnelling processes. Spectroscopy beyond the drip line will provide new opportunities to study the nuclear structure and interactions of unbound nucleons, as well as exotic forms of nucleon and multi-nucleon radioactivity. Two-proton radioactivity has long been proposed as an excellent way to study nucleon-nucleon correlations. The next generation RNB facilities should finally give access to examples of these types of decay.

On the neutron-rich side the possibilities are even more dramatic because of the larger "lever arm" separating the neutron drip line from the valley of β-stability and because the outer realms of these nuclei may constitute essentially a new form of many-body system, nearly-pure, low-density, diffuse, neutron matter. Of all the exotic facets of near-neutron drip-line nuclei, perhaps the most far reaching is that, in their diffuse, outer realms, even the historically ingrained form of the underlying shell model potential itself may change. Indeed, near the neutron-drip line, many benchmarks of nuclear structure, such as the magic numbers themselves, are at risk. In fact, this has already been observed in a region of deformation in supposedly singly magic N=20 nuclei and in the structure of N=8 nuclei. Moreover, the merging of some bound orbits into the continuum as the drip line is approached will unavoidably alter even the characteristic fermion symmetries associated with shell structure as it is presently conceived. The nuclear shell model will need to be reformulated and tested in terms of a continuum shell model.

Nuclei with extremely large N/Z ratios, in which protons and neutrons occupy very different orbits, will also experience substantially different effects of the p-n interaction which is central to the evolution of structure in known nuclei. Near the drip lines, the low binding of the outermost nucleons, which will bring into play the quantum mechanics of the interaction of bound and unbound levels, will doubtless modify the pairing interaction which scatters pairs of particles between nearby orbits. This force may even become stronger through coupling of particles in orbits whose wave functions are greatly extended in space and therefore exhibit enhanced overlap. The 2-neutron drip line ($S_{2n} \rightarrow 0$) may follow a locus quite different than suggested by traditional extrapolations. Indeed, recent calculations[1,2] suggest it may be substantially closer to stability (and accessibility) than previously thought.

Coupled with these likely changes in the pairing and p-n residual interaction, the modifications to the shell model itself throw into question virtually everything that we are accustomed to that determines structure and its evolution, and as a consequence a radically new kind of nuclear physics will surely emerge. If the scaffolding on which nuclear structure is erected is severely altered, so may be a number of long standing predictions based on it. One intriguing example is the existence and locus of superheavy nuclei and their stability and structure.

In the diffuse outer reaches of nearly unbound nuclei, the very notions of a nuclear surface and nuclear shapes (e.g., deformation) themselves may become meaningless. Even the vocabulary we will need to describe nuclei may need to be reinvented. Extremely neutron-rich nuclei are already known to exhibit neutron "halo" regions[3] that constitute virtually a new nuclear medium with densities of nucleons intermediate between typical nuclear densities and those of free nucleons. Such a medium allows novel studies of the nuclear equation of state. Other exotic topologies such as clumping of quasi-bound neutron matter or proton redistribution are not out of the question. Indeed, the possibility to study extremely neutron-rich nuclei reopens the question, never really answered, of whether bulk neutron matter may even be bound, or nearly so.

In the following pages, we will explore a few of the above ideas and their consequences.

To illustrate some of these ideas, we consider two drastic but plausible modifications of the nuclear potential in extremely neutron-rich nuclei. In their extreme forms as illustrated here, both are idealizations that may never be fully realized in actual nuclei, but they nevertheless illustrate the kinds of modifications to currently accepted ideas of structure that could occur. As we have just noted, the diffuse neutron-skin region near the drip line is likely to alter even the shell model potential itself. Nazarewicz and colleagues have recently mapped out an exciting scenario[1,2] in which the usual potential is replaced by one resembling a harmonic oscillator with $l \cdot s$ interaction. In terms of the Nilsson potential, this corresponds to curtailing the l^2 term. Such a scheme is illustrated on the right in Fig. 1. While theoretical estimates of shell effects such as these depend on details of the forces, a wide variety of short range interactions produce similar effects. The significance of this kind of change to the basic shell model is hard to overestimate. Magic numbers nearly universally applicable to known nuclei would disappear. For example, 20, 50, 82 and 126 would be replaced by 28, 40, 70 and 112. More striking still, the traditional pattern of single particle energies in normal shells, from high j at the bottom of a shell to lowest j at the top, is completely transformed into a "nested" pattern of outer high-j orbits, which surround pairs of medium-j orbits, which in turn enclose the lowest j pairs. Significant as the emergence of new magic numbers and altered single-particle energies is, this change in shell structure is of even deeper significance than perhaps at first appears. Medium and heavy nuclei are typically characterized (for normal parity orbits) by sequences of single-particle orbits in which the spin decreases more or less monotonically with energy in $\Delta j = 1$ fashion. Without an l^2 term, the sequence changes to $\Delta j = 2$ (at first $\Delta j = -2$, then $\Delta j = +2$). In this respect then, medium and heavy neutron-rich nuclei would resemble light nuclei near the valley of stability in which $\Delta j = 2$ sequences are characteristic.

Given that a quadrupole residual interaction tends to couple states with $\Delta j = \Delta l = 2$, configuration mixing in very neutron-rich nuclei may be substantially enhanced and the locus and evolution of collectivity are therefore likely to be quite different from our experience, and may increase very suddenly in selected cases. Whether or not this correlates with the familiar concept of deformation depends, of course, on the survivability of nuclear shape as a valid concept in diffuse nuclear matter. Nevertheless, new approximate symmetry schemes involving $\Delta j=2$ sequences may be forthcoming. Clearly, the existence, collectivity and systematics of vibrational phonon and multi-phonon states (a topic of high interest lately even near stability) is also almost certain to be unlike known patterns. Finally, a small l^2 term greatly affects the energy of the unique parity intruder orbit, which reverts towards its parent shell. The consequences will be particularly strong in octupole modes, which will be presented to higher energies, and at high spin.

Of course, the "weak l^2" scenario we have been discussing here is but one example, in extreme form, of the possibilities and may or may not be borne out by experiment. A provocative recent idea is that near the neutron drip line, the $l{\cdot}s$ term may also weaken. If both effects occur together, the Shell Model reverts to the high degeneracy of the harmonic oscillator and nuclear structure will be fundamentally altered. Another speculation is that, while the shell model potential for *neutrons* may lack an l^2 term (because of the diffuseness of the neutron surface), that for *protons* may have a much-reduced $l{\cdot}s$ term since the derivative of the nuclear density near the proton surface--enmeshed as it is in a neutron sea that extends to larger radii--may be rather small. The proton single-particle energies would resemble the pattern illustrated on the left in Fig. 1, with clusters of spin-orbit partner orbitals progressing from high-j to low-j within a major shell. The idea that *both* scenarios could occur in the *same* nucleus (one for neutrons, the other for protons) opens up still stranger structural possibilities. For example, contrary to the situation near stability, where both protons and neutrons have similar patterns of shell structure and hence often reinforce each other, they could drive the nucleus in opposing directions. What is important at the moment is not whether these particular scenarios survive but that substantial changes of *some* sort are almost inevitable and each will lead to new types of shell and collective structure, each with its own characteristic signatures and symmetries.

Another facet of the approach to the neutron drip lines is that some orbits will become embedded in the continuum. In either scenario illustrated in Fig. 1, or any other, the set of bound orbits will no longer comprise a complete sequence of j values (normal parity) from $j = \frac{1}{2}$ to j_{max}. In the examples of Fig. 1, this subset of bound orbits would lack either the lowest j values (left side) or the $j = l - \frac{1}{2}$ values (right side). The bound orbits that remain will mix, of course, with those in the continuum, but fundamental aspects of structure that result from either fermionic [Elliott] SU(3) or pseudo-SU(3) in nuclei nevertheless are likely to change in significant ways including the ordering and phenomenology of collective modes and their assignment to different representations. Moreover, one can expect different Coriolis coupling effects and rotational spectra, especially of low K orbits (e.g., decoupling parameters far different from unity). The symmetries associated with shell structure near the valley of stability may be replaced by entirely new ones associated with SU(3) in the continuum shell model.

If the fermion symmetries of the shell model change, it is also likely that the boson structure in the IBA model will be different. Recent studies have disclosed nearly universal properties of collective states in the IBA. These predictions reproduce global empirical properties of nuclei. This suggests that these empirical properties somehow result from very basic or generic aspects of shell structure and interactions, especially the interplay of pairing and quadrupole forces. If microscopic shell structure and interactions are substantially altered far from stability in ways currently unknown to us, evidence for it may first arise, ironically, in an inability of the macroscopic IBA to reproduce properties of specific nuclei when well established forms of its Hamiltonian are used. Moreover, the empirical manifestations of IBA symmetries may be quite unusual. For example, all known regions of O(6) nuclei have nearly the same energy scales for the O(6) and O(5) subgroups. This is in no way required by the model and could be different in new regions. The IBA symmetry triangle has been well explored and hence it could be rather easy to spot anomalous behavior empirically.

Testing all these ideas with RNBs is both an exciting prospect and a new challenge in nuclear spectroscopy. Of course, changes in shell structure can be probed by single nucleon transfer reactions with RNBs of moderate intensity in inverse kinematics. However, the quantity of data obtainable with RNBs is unlikely to be the same as that to which we are accustomed using stable beams, and it would therefore be advantageous if new, more efficient, signatures of structural phenomena could also be developed. The "no-l^2" scenario we have discussed provides an interesting illustration of such new signatures. The energy ratio $R_{4/2} = E(4_1^+)/E(2_1^+)$ in even-even nuclei, which is one of the simplest quantities to measure, is very sensitive to occupation of orbits with $\Delta j=2$ by odd numbers of nucleons. The reason is simple: in such a configuration the 2^+ state is formed by a co-planar alignment of orbits and hence is energetically lowered in the presence of the short-range, attractive nuclear interaction. This increases $E(4_1^+)/E(2_1^+)$ as is clearly seen in light singly-magic nuclei where $\Delta j=2$ pairs dominate (e.g., $d_{5/2}$-$s_{1/2}$) and $R_{4/2}\sim1.7$. In contrast, in medium and heavy singly-magic nuclei typical orbital sequences are $\Delta j=1$ (see Fig. 1, middle) and $R_{4/2}\sim1.2$-1.3 which is the value predicted by the shell model for configurations of the type $|j^nJ\rangle$. Hence, anomalously large $R_{4/2}$ values in heavy nuclei could initially signal changes in the underlying j-shell structure.

Another clue to radical changes in underlying structure may be deviations from an extraordinarily simple global phenomenology that has recently been found[4] to describe the evolution of structure over broad regions of the Nuclear Chart. This is illustrated, for all even-even nuclei with Z=50-82, in Fig. 2. The complete evolution of structure for all known nuclei in this region can be allocated to three structural regimes, based on their $R_{4/2}$ values, with extremely rapid, indeed phase transition-like, linking regions. These three regions are the rotor ($R_{4/2}\gtrsim3.15$) which has the expected slope of 3.33, an anharmonic vibrator region with slope 2.0 (remarkably, with *constant* anharmonicity) stretching over all vibrational and transitional structures, and a "pre-collective" or pair addition region with slope unity.

The tripartite classification has an enticing implication. If it applies in newly explored regions it *necessarily* implies that, in some new region, the identification of only one or two nuclei establishes the *entire* trajectory, determines the critical 2^+ energies at which the transitions to collective and, later, to rotational behavior result, and determines rotational and singly-magic energy scales simultaneously. Hence, measurement of these simple observables in only a few disparate nuclei allows one to project the entire structural evolution of major shell regions. Therefore, a critical question, with both practical and fundamental consequences, is whether this tri-partite classification of structure is characteristic only of nuclei near the valley of stability (and if so, what is special about such nuclei) or if it is truly general for all nuclei (and, if so, what very generic features of shell structure and interactions are responsible). Calculations of the "no l^2" scenario discussed above suggest that these correlations may indeed break down near the drip lines, at least for pre-collective nuclei. Such a breakdown would be, almost by definition, an indicator of major underlying structural changes.

Fortunately, such measurements should be easy, even with relatively weak RNB intensities. For example, extremely simple low-energy Coulomb excitation experiments in inverse kinematics have very large cross sections for the 2_1^+ state and will be a highly efficient way to map out basic structural manifestations across isotopic sequences extending toward the drip line. Experiments with only 10^5-10^6 particles/sec should be easily feasible in short runs. At somewhat higher RNB beam energies (but still well below the Coulomb barrier), the 4_1^+ state, and hence the ratio $R_{4/2}$, will be measurable.

These speculations about the scientific opportunities with of RNBs are not idle conjectures. RNBs exist today (albeit in restricted mass and energy ranges) and have already amply demonstrated their potential, bringing to light a number of exotic structures and effects like the ones we have been discussing. Perhaps the most dramatic example is the discovery of light neutron-rich *halo* nuclei, such as ^{11}Li, which consists of a relatively neutron-rich core and a pair of outer, halo, neutrons extending to very large radii (see Fig. 3, left). Halo nuclei, with up to 3 times normal neutron-to-proton ratios, are so far from our historic experience that we are just beginning to conceive some of the research possibilities they present. As an example of a topology heretofore unknown, they are a paradigm for the opportunities with RNBs. The halo region is a zone of weak binding in which quantum mechanical barrier penetration plays a critical role in distributing nuclear density in regions not classically allowed. Halo nuclei will clearly provide new challenges for the shell model. Since $\rho_n \sim 10^5 \rho_p$ in the halo region, halo nuclei provide our first experience with nearly-pure neutron matter. An example of calculated proton and neutron densities as a function of radius is shown in Fig. 4. Since ρ(n-halo)<<ρ(n-core) the discovery of neutron halos is tantamount to the discovery of a third form of nuclear matter, namely a quasi-bound medium in which the density of nucleons is intermediate between free nucleons and normal nuclear densities while, at the same time, the spatially extended wave functions of the halo nucleons themselves are diluted by orders of magnitude relative to free nucleons. Reactions with halo nuclei are discussed in greater detail in the next section.

Related to, but different from, halos are the neutron skins expected in heavier nuclei. The opportunity to study nuclear interactions in such halo and skin media is exciting indeed. New collective modes involving the halo (or skin) neutrons are likely. An example is a kind of pigmy E1 giant resonance in which the outermost neutrons oscillate against the core (see Fig. 3, middle). This excitation, which is clearly of interest in itself as a new collective mode, may also play an important role in modifying certain astrophysical mechanisms, in particular, the r-process for nucleosynthesis. Other exotic modes could arise if the protons and neutrons have very different average deformations. We have seen above that the concept of deformed shape in the outer realms of the neutron skin may become moot. Furthermore, if the shell model potentials for protons and neutrons are significantly different (as speculated above), differences in proton and neutron spatial distributions could be exacerbated. One possibility is a strongly quadrupole deformed inner proton density surrounded by a spherical neutron skin. Strong quadrupole isovector modes are plausible according to recent calculations[2] (see Fig. 3, right).

Also, nuclear reactions with halo nuclei may lead to new phenomena such as massive neutron flow processes. These are fascinating in themselves as well as for the insights they give into nuclear processes on an incredibly short time scale, and also as a means of preferentially forming nuclei that are even more neutron rich. Recent calculations[5] have in fact suggested that the use of the most neutron-rich RNBs to be available will enhance such production mechanisms and suggest that formation cross sections may be much larger than heretofore thought. For example, proton and neutron transfer cross section contours for Xe on ^{208}Pb at 700 MeV are illustrated in Fig. 5. For A (Xe) > 136, neutron flow goes *towards* the target. For an extreme example of a ^{154}Xe projectile, massive neutron flow can occur. Hg isotopes up to 10-15 reactions beyond stability can be produced with substantial cross sections. Even after neutron evaporation, very interesting neutron rich nuclei can be produced for study.

Of course, a critical realm for RNBs has always been in nuclear astrophysics. Incisive studies of key reactions at Louvain-la-Neuve, TRIUMF, Notre Dame, MSU and elsewhere have already had well publicized impact. [See Section IV for more details and for future prospects.] Note that astrophysical applications are not limited to light CNO nuclei. Key reactions involve Si and Cl nuclei. In the r-process region, the waiting point nuclei near ^{130}Cd are equally critical. Recent neutrino bubble scenarios in supernova explosions suggest that the r-process path itself may be much closer to stability in the A=60-100 mass region than heretofore thought. These ideas can only be tested with RNBs.

Besides these general issues of basic nuclear structure, it is worth outlining a few other specific areas in which RNBs will play a key role and greatly expand our knowledge of the nucleus. Despite our seemingly wide familiarity with doubly closed shell (DCS) nuclei, they are, in fact, a rare species. Beyond the lightest nuclei the only well studied examples are ^{16}O, ^{40}Ca, ^{48}Ca, perhaps ^{90}Zr, and ^{208}Pb. With RNBs, the number of these benchmark nuclei that will become accessible will increase significantly. New candidates could include, for example, ^{10}He, ^{28}O, ^{48}Ni, ^{78}Ni, ^{100}Sn, and ^{132}Sn (some of these have now begun to be studied), as well as numerous others if shell structure and magic numbers are no longer inviolate far from stability. Moreover, the spectroscopy of DCS $\pm$ 1 nuclei will be critical in disclosing single particle energies and hence the structure of the nuclear potential that we have been discussing. Transfer reactions will be pivotal in tracing the distribution of single-particle spectroscopic strength. Such reactions will also play a prominent role in providing access to nuclei still further from stability and will allow the basic characterization of a wealth of nuclei up to several neutrons closer to the drip line than possible with direct RNBs themselves.

Although weak RNB intensities will limit some experiments, a complementary aspect of RNB studies provides a compensating advantage. The high β-decay Q values far from stability will allow the population of daughter nuclei at high excitation energies and hence permit the study of a wide variety of excitations.

An extremely active area of current research with stable beams focuses on phenomena at high spin. This field should be equally rewarding in the RNB area. While fusion evaporation reactions may not easily reveal the full panoply of multi-band structure currently observable, nevertheless, with the help of present day and future γ-ray arrays, the spectroscopy of yrast and near-yrast states should present an ample slate of new phenomena. Coupled with recoil mass separators for particle identification, selectivity and sensitivity will be enhanced. A unique opportunity offered by high spin studies with RNBs occurs, ironically, in *stable* nuclei. To date, high spin nuclear physics has almost invariably been associated with neutron deficient nuclei since the precursor to observation of γ-ray cascades in high spin states is generally the evaporation of a number of neutrons. However, with neutron-rich targets and RNBs, it will be possible to study high spin states in *well-known* (at low spin) nuclei at or near stability and, for the first time, to link the study of low, medium and high spin phenomena in the *same* nucleus.

Another interest at high spin is the possibility of observing new collective modes, such as hyperdeformation or even $Y_{3,1}$ (banana) shapes, that are predicted in nuclei that will only be accessible with RNBs. Other interesting phenomena may result from the simultaneous population of high j-orbits for both protons and neutrons. If the orbits populated have low K, there will be a concentration of valence nucleons in a nuclear "waist". This quantal localization could be enhanced by Coriolis effects and lead to new types of p-n interactions and new collective modes involving the waist nucleons.

If high-spin states can be studied near the proton or neutron-drip lines, other possibilities arise. Owing to Coriolis coupling effects, the particle widths of quasi-bound levels may be angular momentum dependent. One may encounter deformed proton emitters. Tests of such ideas can be pursued through studies of the interplay between γ and particle decay widths.

Finally, some of the ideas discussed earlier can be tested at high spin. In the "no l^2" scenario, for example, the re-integration of the unique parity orbit in its own major shell will mitigate its effects and could delay band crossing and backbending to higher spins. Likewise, in N=Z nuclei, T=0 pairs will be less susceptible to Coriolis effects and, again, backbending could be delayed.

Other techniques worth exploiting with RNBs include studies of elastic scattering, of nucleonic momentum distributions with inverse reactions of (p,2p) type, and the measurement of interaction radii in nuclei with exotic N/Z ratios. These are possible even with very low beam intensities of a few particles/sec.

In these few pages we have barely touched on a few of the opportunities for new nuclear structure with RNBs, either from the viewpoint of structure itself or the reactions and techniques that will be used to access it. Some aspects of the discussion represent newly realized facets of RNB nuclear physics. Others have been discussed in much more detail in the ISL White Paper published in 1991. Our purpose here was to discuss some general ideas as to why and how RNBs will lead to exciting science, with emphasis on new concepts that are now emerging, as a broad community of scientists is enthusiastically cultivating the most innovative nuclear structure opportunities for RNBs.

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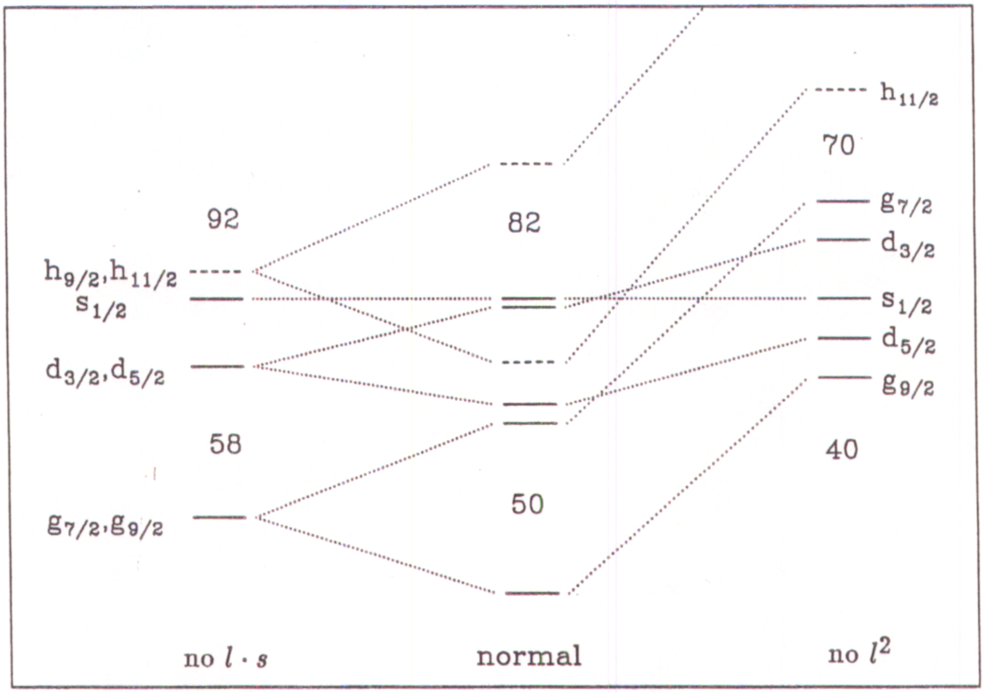

Fig. 1. Example of single-particle level sequences and magic numbers in the normal shell model (middle) and in idealized scenarios that could be reflected in neutron-rich nuclei far from stability.

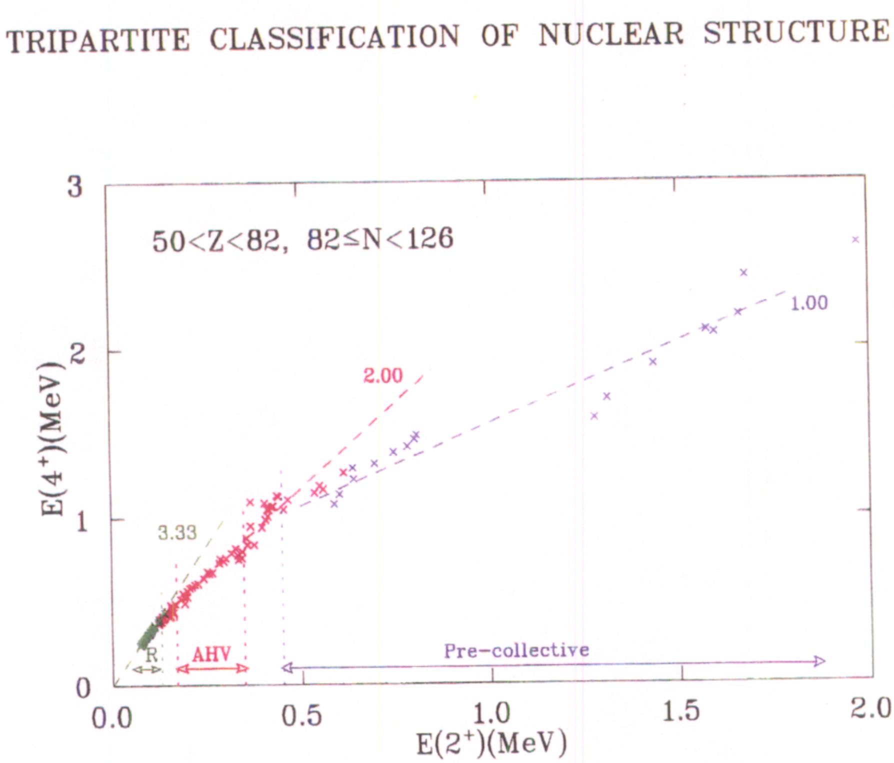

Fig. 2. A tripartite classification of the evolution of structure in the major shell 50<Z<82, 82<N<126. Deviations from this simple tri-linear scheme could signal radical changes in underlying shell structure.

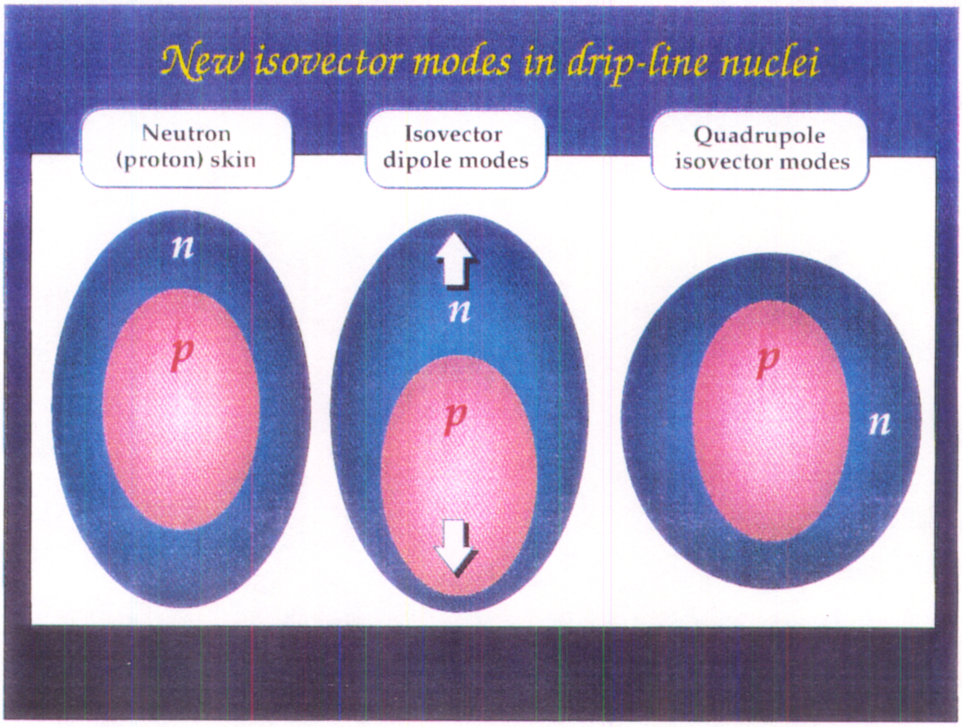

Fig. 3. Schematic illustration of three density distributions that could characterize new nuclei with significant neutron excesses. Left, a neutron skin. Middle, a dipole oscillation of skin-region neutrons against a core. Right, a prolate proton density eneshed in a spherical neutron distribution. From ref. 2.

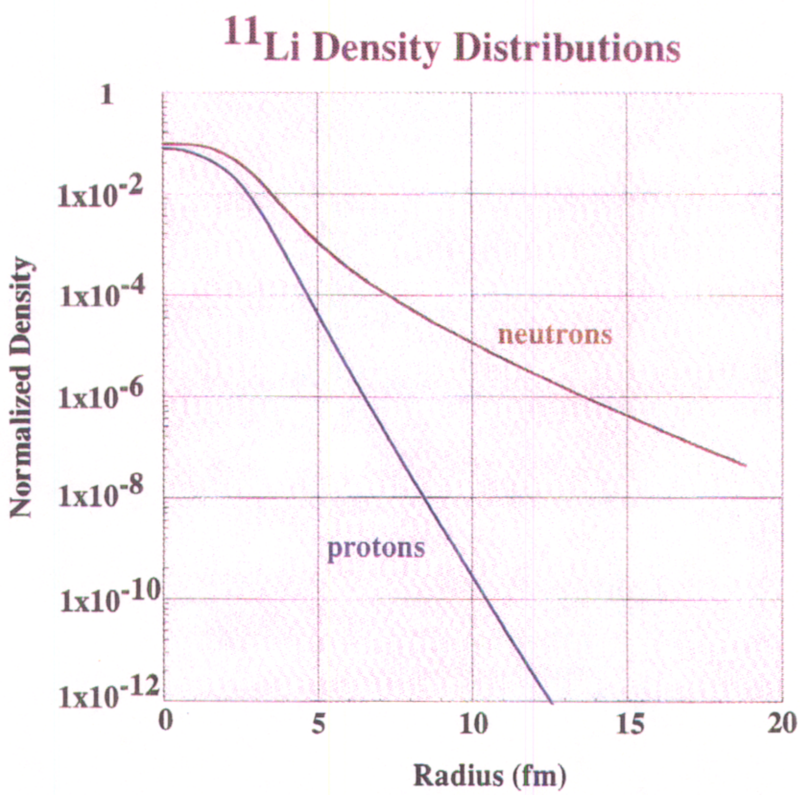

Fig. 4. A calculation of proton and neutron densities as a function of radius in the halo nucleus ^{11}Li. Note the nearly pure neutron nature of the outer regions. From ref. 6.

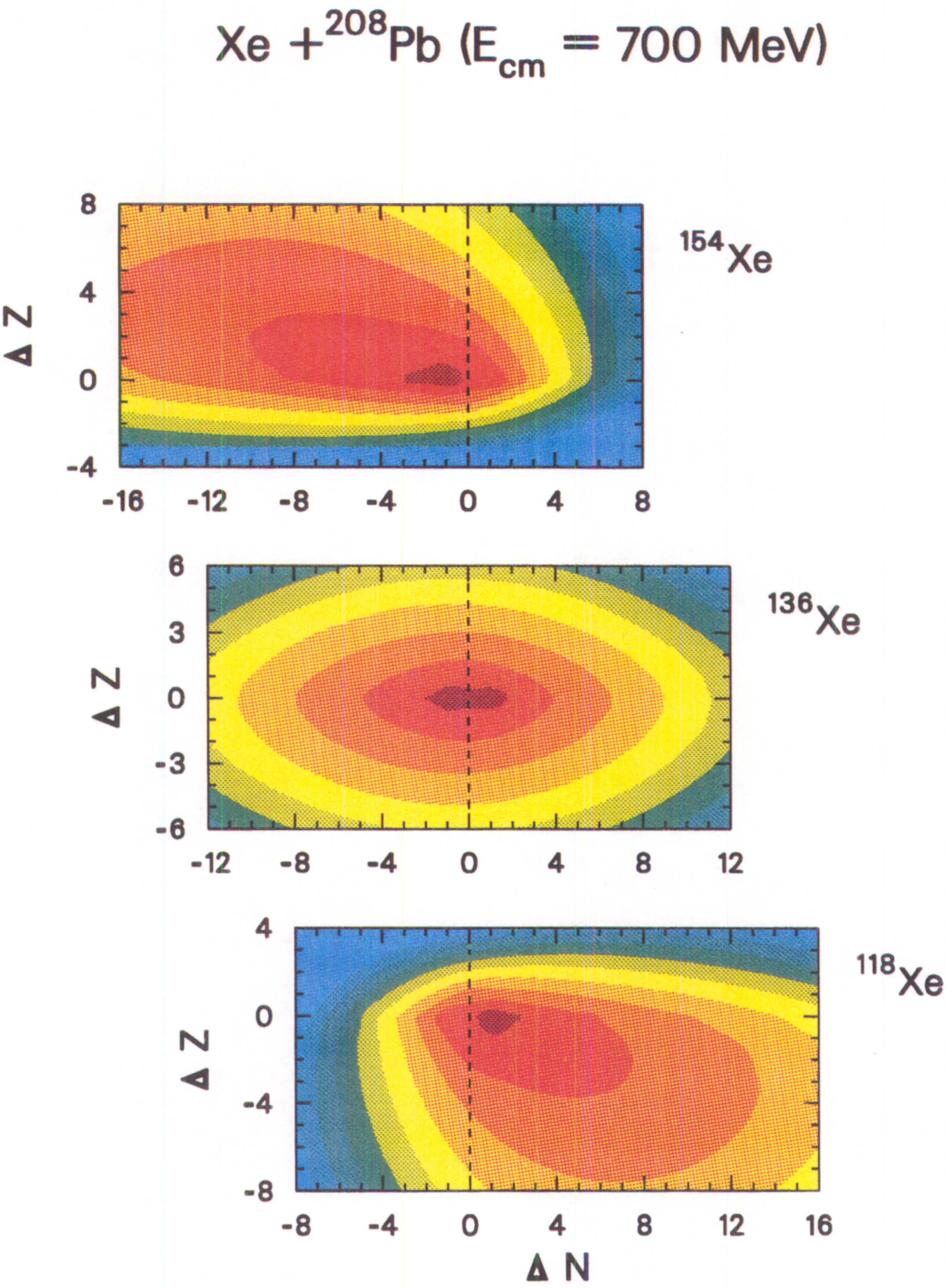

Fig. 5. Cross section contours as a function of proton transfer (ΔZ) and neutron transfer (ΔN) in the direction of the *target* for Xe isotopes on ^{208}Pb at 700 MeV. Each color change from dark red to blue represents an order of magnitude decrease in cross section. For very neutron-rich Xe projectiles substantial neutron transfer to final nuclei with Z~80 are predicted. Figure based on ref. 5, courtesy of G. Pollarolo.

II. Nuclear Reactions

Nuclei along the valley of stability have, in general, very similar properties, e.g., proton and neutron densities, binding energies, and single-particle energies. This is not true for nuclei far from stability. Weakly bound halo nuclei exhibit the qualitatively new features of low-density neutron matter and a large separation between the neutron and proton distributions. The qualitative features of halo nuclei are illustrated in Fig. 1 for the one-neutron halo nucleus ^{11}Be. The large spatial extent of such halo nuclei implies a correspondingly narrow momentum distribution for the valence neutrons. As their structure is unique their reactions should also provide new insights. For example, reactions which rely on Fermi momentum effects can finally be tested with beams which have significantly different Fermi momentum distributions.

The very different binding energies available in radioactive beams allow for Q-value differences, and hence reaction dynamics, which are not possible with stable beam/target combinations. Typically, neutron pickup or proton stripping reactions dominate, yet for very neutron-rich beams neutron stripping may dominate[1] and this may lead to a method for the production of very neutron-rich heavy nuclei. Moreover, well understood nuclear reaction mechanisms can be used to measure nuclear properties. For example, elastic scattering and Coulomb excitation have been used in the limited number of halo nuclei studied so far to deduce some of their properties and establish the picture of these nuclei as having an exotic topology, never before encountered, consisting of a central core surrounded by a diffuse neutron distribution with *rms*-radii of more than twice the central region.

The new tools offered by radioactive beams give hope of answering many long standing questions. Among these is the possibility of synthesis of superheavy elements. After a hiatus, the last year has witnessed great strides in the production and study of the heaviest nuclei. Recently, the nuclei ^{269}110, ^{271}110, ^{272}111 were produced in cold fusion reactions (A~60 on ^{208}Pb and ^{209}Bi targets) at GSI and ^{273}110 was synthesized at Dubna with the hot fission ^{34}S (^{244}Pu,5n) reaction. In spite of these advances, current attempts with stable beams and targets may be approaching the limit of their usefulness. While most of the known heavy elements have been produced with stable beams on ^{208}Pb targets, the remaining beam combinations lead to relatively unstable nuclei with low fission barriers. Neutron-rich beams could again open new possibilities and lead to compound systems with lower excitation energy and higher fission barriers. Indeed, plans for future heavy element production with stable beams anticipate the use of neutron-rich Zn isotopes. In reactions induced by RNBs, it is possible that the fusion barrier may be reduced by the presence of neutron skins. Hence the fusion cross sections may be several orders of magnitude higher than normally expected and offset the low intensity of secondary beams. Neutron-rich beams in the mass 50 to 100 region would be ideal for these studies and will be produced in acceptable quantities. The first step will be to study the systematics of heavy element production with neutron-rich beams. First generation RNB facilities may not have sufficient intensities to reach the superheavies but should provide the necessary information to evaluate the technique and refine our ideas of the dependence of fusion cross sections on neutron number, Q-value, neutron skin, and excitation energy. This will determine the feasibility of using radioactive beams for the production of superheavy nuclei. It is also important to note that we may not have far to go to reach long lived heavy elements. Current experiments on element 108 suggest that we are tantalizingly close to such a region.[2] Calculations on the structure of isotopes with only a few more neutrons predict that they may be extremely long lived.

Besides reviving the push for superheavy elements, RNBs will provide information on the fusion mechanism. Of recent interest is the enhancement of fusion in certain subbarrier reactions. It is thought that nuclear structure plays a large role in the excitation of low lying resonances or in the exchange of neutrons leading to neck formation and then fusion. Recent experiments show that careful excitation function measurements near the Bass barrier, plotted in the second derivative form, $d^2(E\sigma)/dE^2$, can give a "fingerprint" of complex barriers and disclose the effects, for example, of coupling to phonon excitations. This is illustrated in Fig. 2. The top part shows the simple fingerprint resulting from the collison of two magic spherical nuclei (^{40}Ca on ^{40}Ca) while the lower portion shows the effects of coupling to 2^+ and 3^- excitations in the fusion of ^{16}O on ^{144}Sm. Extension of these techniques to RNB studies could give valuable information on barrier structure and reaction processes in exotic nuclei. Of particular importance are halo and skin nuclei which offer a unique chance to study the mechanism of subbarrier fusion as these nuclei have extended neutron distributions and may have up to three orders of magnitude enhancement in the fusion cross section for very sub-barrier energies. These nuclei also may have unique low-lying resonance structures whose role can be studied. Moreover, many of these resonances are unbound (although not always) and offer the chance to study the effect of coupling to unbound states. These states can enhance or hinder the fusion cross section depending on their nature and spreading widths. Even secondary rates as low as 10^5 ions per second are sufficient to perform studies in the energy range below the barrier where these effects will be important. Several theoretical studies on this subject have been published, yet experiments have suffered from low intensities. Some of these questions could easily be answered by the next generation of RNB facilities.

Another reaction mechanism which has been debated is the nuclear charge equilibration process in deeply inelastic reactions. The mechanism of equilibration has not been determined and may proceed via neutron transfer or by the excitation of collective motion. Radioactive beams would allow the formation of nuclear systems at very different locations on the potential energy surface. The widths of the measured charge distribution as a function of the energy lost for stable versus radioactive beams are expected to show a large difference if collective degrees of freedom are important.[3] Hence radioactive beams may provide the first clear indication of the equilibration mechanism.

Elastic scattering can be used to study the structure and matter distribution of radioactive ions. For example, one might expect that weakly bound halo nuclei would show strong absorption and the elastic scattering angular distributions to be dominated by diffraction. Surprisingly, preliminary experiments have shown[4,5] instead that refractive effects dominate the scattering. The large halo acts like a lens to focus the scattering amplitudes to small angles. To study the details of the halo wave functions, higher energy scattering on light ions may be one of the ways to map the matter distributions of these nuclei, and can be performed with RNB intensities of only 100 ions per second, since the elastic scattering cross sections are large.

Besides improving our understanding of quantum phenomena, interesting new possibilities with RNBs also would be opened to study the optical model. The optical model parameters depend on a variety of details of the interacting nuclei, such as the density of final states, Q-values and transferred angular momenta.[6] As an example, radioactive beams would offer the possibility to study reactions with positive Q-values in which the polarization correction to the real potential may be positive and result in a reduction of the nuclear attraction, just opposite that of the usual effect for negative Q-value reactions.

Single nucleon exchange reactions can be used to study the evolution of shell structure away from stability, as they have been extensively used to study the shell structure of stable and near stable nuclei. As outlined in other places in this report, there are many reasons to expect new phenomena and structure in nuclei far from stability. It is already known that in the heavy Na isotopes and in the region around ^{11}Li an inversion in the single particle states occurs and the structure of these nuclei is strongly influenced by negative parity intruder states. One could study these inversions and examine whether this is a general feature of nuclei. Moreover, there have been recent predictions that, far from stability, shell effects should become less important.[7] Perhaps the height and width of r-process abundance peaks may already be evidence for this effect. Another interesting speculation, which has already been outlined, is that, for neutron-skin nuclei, the spin-orbit interaction would be reduced for protons (since it depends on the derivative of the nuclear potential with radius, and the protons are located in a bath of neutrons). Predictions indicate that nuclei in the ^{132}Sn and ^{44}S regions may have sufficient skins to allow this prediction to be studied. These nuclei will be produced in sufficient quantities to allow structure studies aimed at these questions to be performed.

Although the existence of a halo in weakly bound nuclei has been established, the exact nature of the halo wave function and the degree of core excitation are not well determined. Mean field and three body models give quite different predictions for the nature of these nuclei. Single and perhaps also double-nucleon exchange reactions may also be the best way to study the wave functions of the valence nucleons in halo nuclei. One of the predictions of three body models for ^{11}Li, for example, is that there should be a mixture of s and p components. This could be investigated in neutron or proton-stripping reactions. Spatial correlations in two-neutron systems could be studied with reactions such as (p,t). A high spatial correlation should lead to an enhanced cross section. The presently available beam intensities of 1000-10,000/s halo nuclei are not sufficient for these studies and require the next generation facilities where 10^5 to 10^6 ions/s should be available. Another open question is the goodness of the core of the halo nucleus (i.e., the nucleus ^{9}Li in the case of the halo nucleus ^{11}Li). In the limit of a very large halo, the valence nucleons are too far away to interact with the core which would have the properties of a free nucleus. One could study the core properties in (p,2p) or (p,np) reactions, or by Coulomb excitation and comparison to reactions using only the core nucleus itself. Core deexcitations in reactions where the valence neutrons are stripped in the sudden approximation may also be an indication of the modification of the core due to the presence of the halo.

Beams of nuclei at the driplines can also be used to study nuclei beyond the dripline and address such exotica as the possible stability of the tetra-neutron. Pickup or stripping reactions on near-dripline beams can be used for the production of nuclei beyond the dripline. This has already been applied in limited cases, such as ^{12}O where two-proton emission was studied, and ^{10}He where a very narrow resonance has been observed even at high excitation, i.e., 6.8 MeV.[8] The width and existence of these resonances is very difficult to understand within our standard nuclear structure models and it is essential to continue these studies in order to explore the nature of this phenomena.

The special symmetries of certain radioactive nuclei may also be useful in studying reaction mechanisms. Charge exchange reactions between mirror pairs below the Coulomb barrier may allow the possibility to search for exchange effects since 180 degree scattering will interfere with charge exchange. One would also be able to measure Gamow-Teller strength distributions via inverse kinematics (p,n) reactions, heavy-ion charge exchange and β-decay in nuclei where there is a large Q_β window allowing detailed comparisons to be made over a large energy range. At higher energies, E/A > 100 MeV, heavy-ion charge exchange reactions may provide a means for the measurement of the Gamow-Teller distribution in unstable nuclei, which is of interest for calculations of supernovae explosions and the r-process. At higher energy the very different Fermi momentum distributions of halo nuclei could be used to explore subthreshold particle production. The very different N/Z ratios of stable targets and radioactive beams could be used as a kind of labeling to identify target/beam contributions to the observed fragment production in heavy-ion collisions.

There are certainly many more areas in the reactions of nuclei where the special features of radioactive ions could be used to illuminate nuclear structure and nuclear reactions. The few cases listed here are meant to serve as an introduction to the possibilities. The key point is that the limits placed on reaction studies by the use of stable nuclei in reactions is severe due to the strong similarity among nuclei lying along the valley of stability. Even the first generation of radioactive beam facilities will remove a portion of these constraints. The possibilities outlined in this section have included a new push for superheavy elements, further understanding of nuclear reactions such as elastic, inelastic, and deeply inelastic scattering, and better understanding of near and subbarrier fusion reactions. In addition the established spectroscopic tools of nuclear physics can be used to probe the new structures found in nuclei far from stability. They also offer the chance to study in detail the new forms of nuclear matter represented in halo and skin nuclei.

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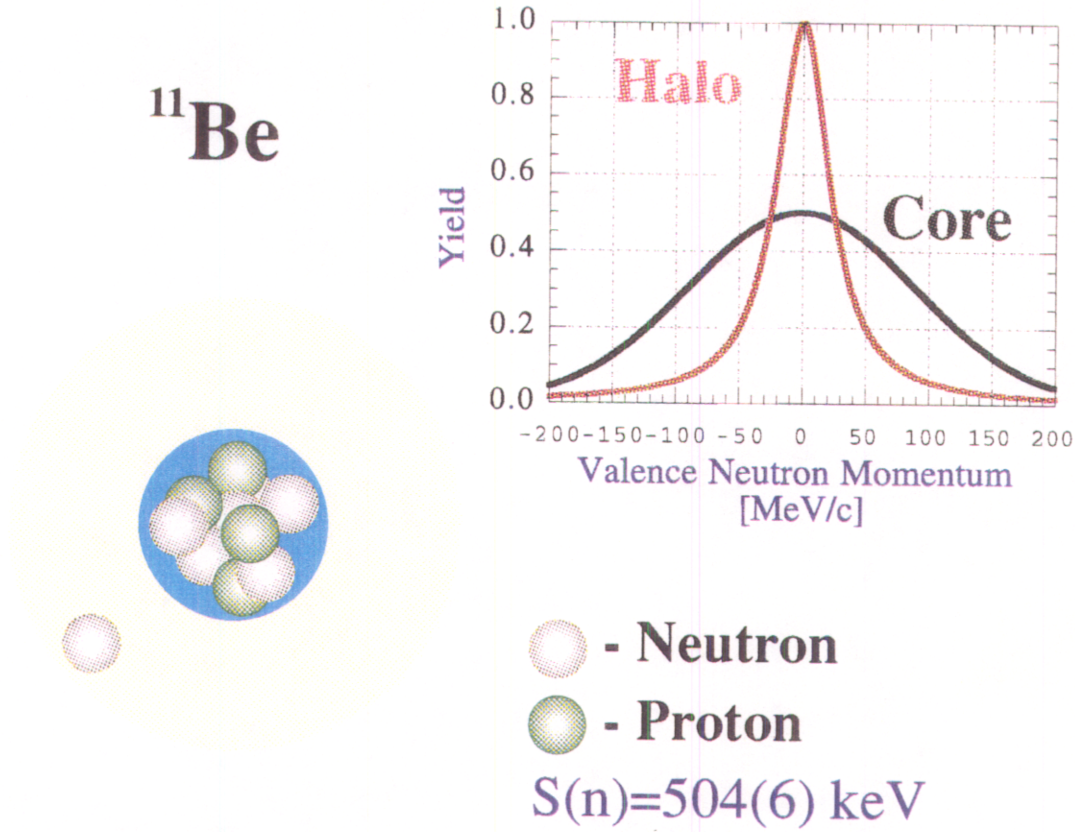

Fig. 1. The figure illustrates typical Fermi momenta for core and halo neutrons. The halo neutron with a larger spatial extent has a smaller corresponding momentum distribution. The core neutrons have a typical momentum distribution. These unique spatial and momentum distributions can be used for reaction studies.

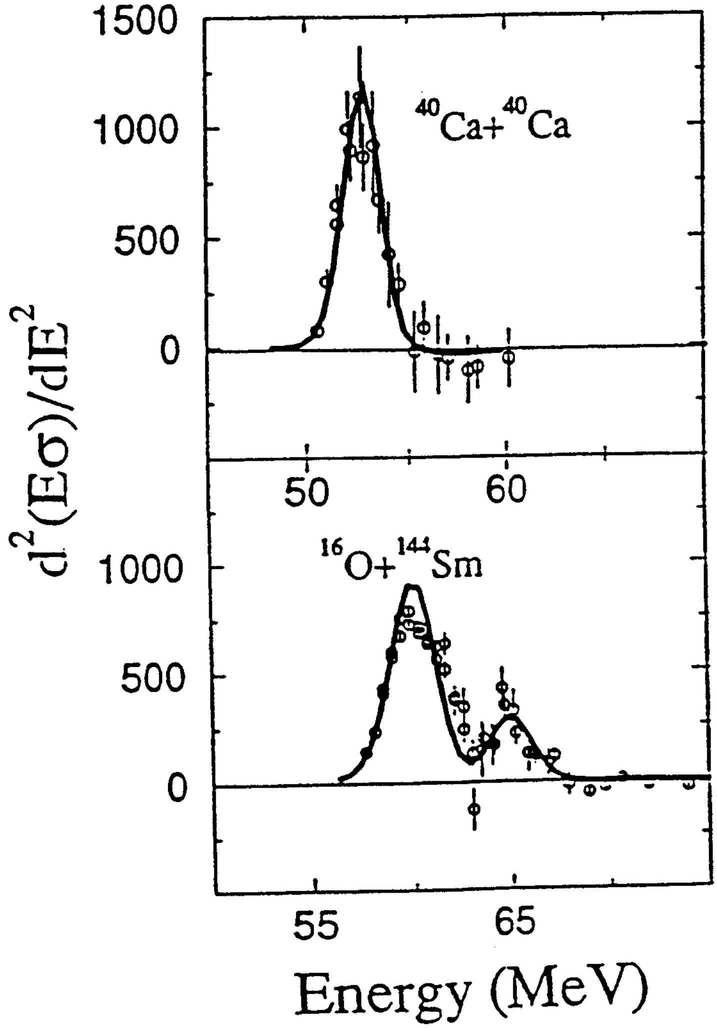

Fig. 2. Barrier "fingerprints" from the dependence of $d^2(E\sigma)/dE^2$ on bombarding energy. Top: ^{40}Ca on ^{40}Ca showing a simple barrier structure. Bottom: ^{16}O on ^{144}Sm showing the effects of coupling to 2^+ and 3^- excitations.

III. Fundamental Weak Interaction Studies

The measurement of electroweak interactions in nuclei has been of interest ever since the famous experiment of Wu that showed that β-decay violates parity. From this beginning to present day experiments that measure atomic parity nonconservation and a variety of beta decay correlations, the community has relied on increasingly more intense and varied sources of radioactive species. In this role, a high-intensity radioactive beam facility such as the ISL would be a major advancement towards executing higher precision tests of the standard model.

The basic process leading to parity nonconservation (PNC) in atoms comes about from the exchange of Z^0 bosons between the electrons and quarks during the small percentage of time that the atomic electrons spend within the nucleus. This weak neutral current process has the effect of introducing small parity admixtures into atomic states. Processes that are strictly forbidden by the Coulomb interaction can take place through these small parity admixtures. These PNC admixtures can be determined by using laser techniques to measure small changes in atomic transition rates when mirror symmetric reversals are made in specially arranged "handed" experiments. In particular, such experiments are especially sensitive to isospin-conserving radiative corrections and to certain types of new physics extensions beyond the minimal standard model such as the existence of extra Z bosons (Refs. 1 and 2). Moreover, since the electroweak interaction is momentum dependent, such atomic measurements test the standard model at low momentum in contrast to high-energy particle physics experiments. Finally, the characterization of a nuclear anapole moment, the leading parity nonconserving moment arising from nucleon-nucleon weak interaction effects (Ref. 3), and the determination of its spin dependence, are of high scientific importance. Both the spin-independent PNC amplitude and the nuclear anapole moment can be extracted from the same experiment.

PNC measurements using either the optical rotation method or Stark interference/fluorescence method have now achieved experimental precisions of 1 to 2% (Ref. 4). For comparison, the size of the radiative corrections through which new physics would be revealed are on the order of 6%. By combining the experimental measurements with atomic structure calculations that estimate the probability of the electron being within the nucleus, the results reported to date agree well with the predictions of the standard model. Scientists are now working on the next generation of experiments which promise accuracies of ~0.5%. However, a similar gain in accuracy must accompany the atomic structure calculations to translate these measurements into an improved test of electroweak interactions. Such relativistic many-body perturbation theory calculations are extremely challenging to undertake and even if significant improvements are made it will be very difficult (given limitations in the available data) to verify their accuracies to a fraction of a percent. To circumvent these calculational uncertainties it has been suggested that a series of cesium and francium radioisotopes (selected because of their simple atomic structure involving a single S electron outside a closed shell and because the PNC amplitude scales as Z^3) be studied. By taking a normalized difference ratio of their PNC amplitudes it will be possible to effectively eliminate the atomic structure uncertainties and perform a more sensitive test of the standard model approaching the 10^{-3} level.

These PNC ratio measurements have excited great interest within the community and several groups (Refs. 5-7) are currently in the early stages of undertaking experiments (see the example given in Fig. 1). To obtain the longest lever arm and consequently the most sensitive tests of the standard model, the measurements should span as large an isotopic range as possible. Such measurements require high intensities of radioactive species lying far from the valley of stability (e.g., $\geq 10^8$/sec/isotope for $^{125-139}$Cs and $^{209-227}$Fr for the initial experiments with even more exotic species desired thereafter) and an efficient method of collecting and introducing these species into the PNC measurement system. An ISL-type facility will go a long way towards solving the future high-intensity needs of these experiments, while recent advances involving magneto-optical traps (Refs. 8-10) have made great strides in fulfilling the high efficiency requirement. Clearly, such PNC measurements using radioactive species are just in their beginning stage and continuing technical breakthroughs will enable ever more precise tests of the standard model.

Turning to the investigation of the electroweak charged-current interactions in nuclei, several groups (Refs. 9, 11-12) are planning β-decay experiments that also employ the new radioactive atom optical trapping technology mentioned above. These experiments seek to measure the β-decay spin correlation terms (the β-asymmetry and the T-violating D term, see Ref. 13) of mixed Gamow-Teller/Fermi transitions in mirror nuclei such as ^{21}Na-^{21}Ne and ^{37}K-^{37}Ar. Even more involved β–ν correlations and nuclear polarization β-helicity measurements of the types outlined in Ref. 13 are being discussed. Such measurements are important in the search for right-handed currents, further tests of the conserved vector current (CVC) hypothesis, and in investigating time reversal invariance.

The ongoing precise β-decay measurements of $0^+ \rightarrow 0^+$ superallowed Fermi transitions provide another stringent test of the CVC hypothesis by determining the value of the weak vector-coupling constant and the V_{ud} quark mixing element of the Kobayashi-Maskawa (KM) matrix. By combining V_{ud} as determined from superallowed decay studies with the accepted values of the other matrix elements, V_{us} and V_{ub}, a powerful unitarity test of the KM matrix can be made (Ref. 14). The present value is two standard deviations shy of 1. However, the less accurate value of V_{ud} as extracted from the neutron lifetime and neutron β-decay angular correlation experiments gives a value that is significantly greater than 1. Clearly, more precise measurements of the neutron, and for even higher Z nuclei lying along the N=Z line, are needed to resolve this discrepancy and to determine the size of the small charge-dependent corrections required to interpret the superallowed β decay results.

All of these weak interaction investigations require excellent precision and high statistics. This points to the need for a high intensity and clean source of wide ranging radioactive species--exactly what an ISL-type facility would provide. To this end we feel that such a facility would enable a whole new class of high precision tests of electroweak interactions in nuclei to be carried out.

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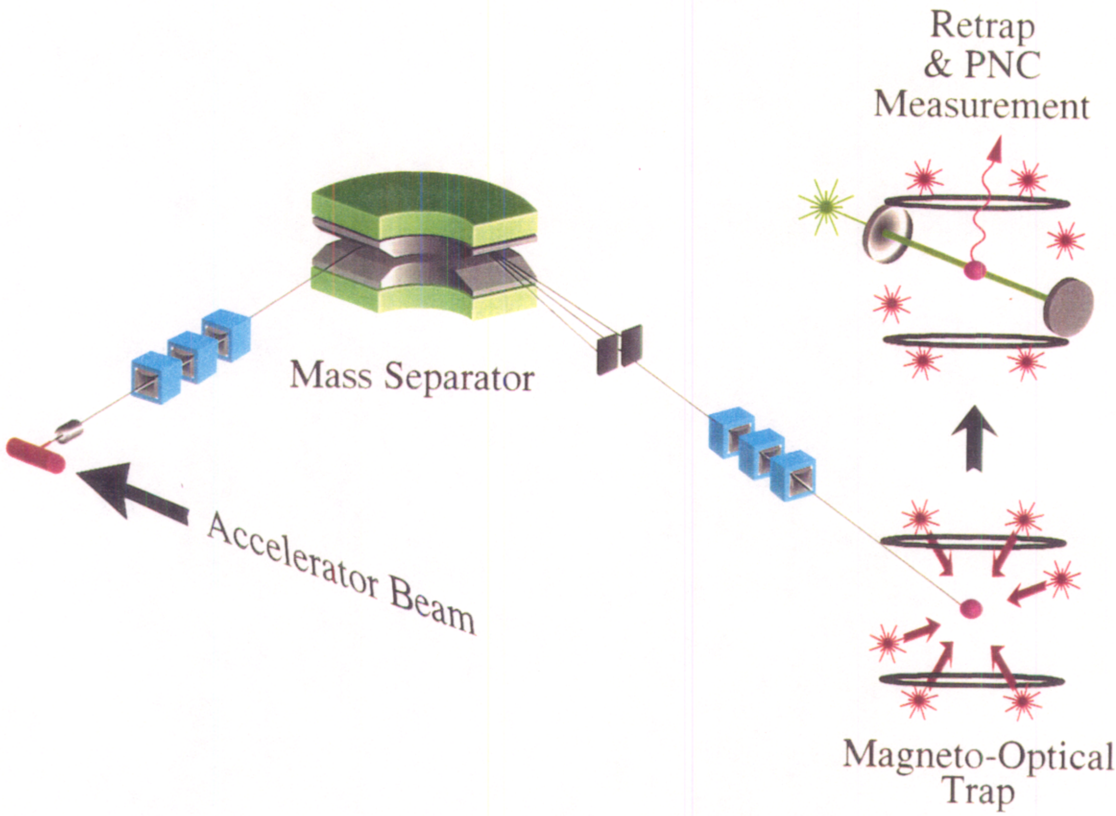

Fig. 1. Schematic layout of a high-precision PNC experiment involving radioactive atoms as provided by a high-intensity radioactive beam facility. After mass separation, the atoms are concentrated, cooled, and trapped in a magneto-optical trap (densities as high as 10^{11} atoms/cm^3 have been achieved). The trapped cloud of radioactive atoms is then transferred to another trap where the PNC transition rate is measured upon mirror symmetrical reversal of the coordinate system.

IV. Nuclear Astrophysics

A deep understanding of the energy generation and element formation processes in stars depends critically on the nuclear physics input parameters. New generations of satellite observatories from infrared to γ radiation are providing direct observations of nucleosynthesis products in explosive objects from nova to supernova. The observed abundance distributions from the ejecta sensitively probe our models of the hydrodynamics and nucleosynthesis in stellar explosions.

The explosive and mixing processes at high stellar temperature and density conditions are much faster than the time scales of nuclear β decay. Therefore nuclear processes under such conditions occur far off β-stability and require detailed studies of nuclear structure and nuclear reactions and decay mechanisms for unstable nuclei. Current stellar models of these scenarios are based only on crude predictions for the nuclear reaction rates and the nuclear decay properties.

Experiments with radioactive nuclear beams are essential to test the multitude of nuclear parameters used for modeling the explosive nucleosynthesis processes. The first measurements of nuclear reaction rates with radioactive beams, like $^{13}N(p,\gamma)^{14}O$, $^{8}Li(\alpha,n)^{11}B$ and $^{19}Ne(p,\gamma)^{20}Na$, have been successfully completed on small scale, university based radioactive beam facilities.[1-3] New detector systems have been developed in the course of these experiments to handle low event rates under high background conditions. This signals a promising future for such experiments. Higher intensity beams are required to push the measurements further away from the line of stability and to investigate, in particular, slow reactions which are expected to set the time scale in explosive stellar nucleosynthesis.

Cold hydrogen burning fuses hydrogen to helium in a slow process via the pp-chains and/or the classical CNO-cycles. This mode of hydrogen burning takes place in main-sequence stars. Hot hydrogen burning occurs under extreme temperature and density conditions that exist in collapsing pre-main sequence massive and supermassive stars, and in cataclysmic binary systems such as novae, x-ray bursters and type Ia supernovae. The hot mode of hydrogen burning is characterized by the hot pp-chains, the hot CNO-cycles, the rp-process and the αp-process. Simulations show that in these processes, the nuclear flow can go from light nuclei, ^{1}H, ^{4}He and ^{12}C to higher mass regions, and under extreme conditions even far beyond the Fe-Ni region.[4] In novae and type Ia supernovae, the products of this nucleosynthesis can be observed in the ejected material by infrared and γ-ray spectroscopy.

Large reaction network codes have been developed in recent years to predict, to understand, and to simulate the energy generation and nucleosynthesis in explosive events. The reliability of these calculations depends strongly on the nuclear input parameters, the decay and reaction rates. Although a multitude of reactions will occur under these conditions, it turns out that the reaction flow is almost entirely determined by a small number of steps. The flow is sensitive to slow processes along the reaction path. They determine the time scale, the end point, and the energy production of the process. These include slow β-decay processes as well as slow proton or α–capture reactions. The experimental verification of the predicted decay and reaction rates is thus vital to verify the present models for nucleosynthesis and energy generation in explosive stellar scenarios.

In novae, reactions like $^{14}O(\alpha,p)^{17}F$ and $^{15}O(\alpha,\gamma)^{19}Ne$ are the key reactions determining the break-out flow from the CNO region to the Ne, Na region. Such a break out may occur in high temperature novae above $300 \cdot 10^{6}$K. In this case, energy generation is not limited by the slow β decay of ^{14}O and ^{15}O, but mainly by the $^{15}O(\alpha,\gamma)^{19}Ne$ rate. This can increase by tenfold the energy production resulting in much higher peak temperatures than the ones presently thought. The study of these reactions with intense ^{14}O and ^{15}O beams using inverse kinematic techniques is one of the major goals in radioactive beam experiments.

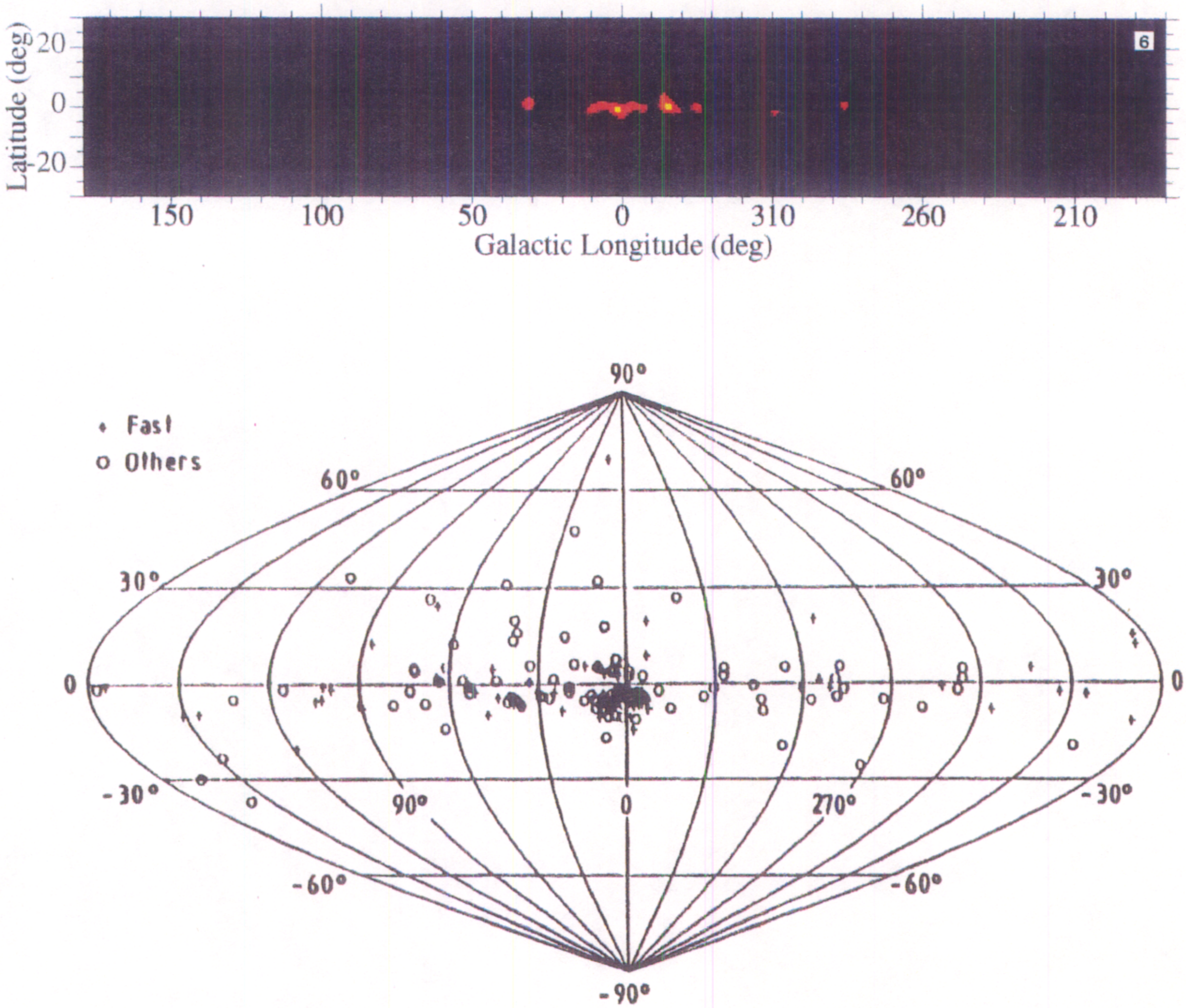

Fig. 1. The upper part shows the galactic intensity distribution of the $E_\gamma = 1.809$ MeV line as observed with the COMPTEL γ-ray observatory. This γ transition originates from the decay of long-lived ^{26}Al, the bright spots represent therefore a high abundance of ^{26}Al near the center of the galaxy along the galactic plane. The map, shown in the lower part of the figure, represents the galactic distribution of recently observed novae, which also seem to cluster around the galactic center. This comparison suggests that nucleosynthesis in novae is potentially a strong source for the production of ^{26}Al.

The slow proton capture reaction $^{26}Si(p,\gamma)^{27}P$ is of crucial interest for the interpretation of the distribution of radioactive ^{26}Al, in our galaxy, which has been observed with the Comptel Gamma-Ray Observatory[5] as shown in Fig. 1. This reaction may be a dominant depletion process for the ^{26}Si progenitor at high temperatures. Its study with radioactive ^{26}Si beams addresses the origin of ^{26}Al from nucleosynthesis in hot explosive events or deep convective massive stars.

A particular class of novae, the Ne-novae, show very enriched Si and S abundances, indicating that this mass range is the endpoint of the hydrogen burning nucleosynthesis. A few observations, however, also show enrichment in Fe. Its production is mainly limited by the weak bottleneck reaction, $^{39}Ca(p,\gamma)^{40}Sc$; its reaction rate determines the mass flow between the light sd-shell nuclei, $A \leq 40$, and the heavier pf-shell nuclei, $A \geq 40$, as indicated in Fig. 2. The experimental verification of this reaction rate is crucial for the temperature history of Fe-rich novae ejecta.

The rp- and αp-processes may occur at high temperature density conditions in x-ray bursters (accreting neutron stars) and in the neutrino heated hot bubble region in supernovae type II at high proton abundances (see below). Under these extreme conditions the reaction path runs along the drip line and nucleosynthesis and energy generation is mainly regulated by the weak interaction processes.

Recent simulations indicate that rapid processing of light elements up to the mass $A \approx 90$ region may occur under x-ray burst conditions. While only a small amount ($\leq 0.1\%$) of the ejected material may escape the gravitational potential of the neutron star, it may be sufficient to produce the as yet unexplained high abundances of the "p-process" nuclei ^{92}Mo, ^{94}Mo, ^{96}Ru and ^{102}Pd.

In the mass region $A \geq 56$ the rp-process path runs along the N=Z line, parallel to the proton drip line ($S_p \leq 0$). The uncertainty of the drip-line, based on various mass model predictions[6,7], introduces an enormous uncertainty in the time scale (10 s - 100 s), required for the nucleosynthesis of mass $A \approx 90$-100 nuclei from the initial A=4-16 abundances. Figure 3 shows schematically the reaction path calculated for two different mass models. The isotopes marked in red are predicted to be particle stable in the mass model by Hilf *et al.*[8] and particle unstable in the mass model by Möller.[6] In the second case the reaction path is closer to the line of stability and considerably more time is required to produce sufficiently high abundance of ^{92}Pd and ^{96}Cd because of the longer lifetimes of the β-unstable nuclei along the reaction path.

Most of the capture rates in the mass region $A \geq 60$ are calculated with statistical models. However, the large deformation of the N=Z isotopes in this mass range is critical for the calculations. Coulomb excitation experiments with these nuclei on light or heavy target materials determine the $B(E2{:}0_1^+ \rightarrow 2_1^+)$ values as a measure of the deformation. These experiments can be performed with low beam intensities of 10^5 part/s.

Reliable measurements of the masses, the lifetimes, and the β-delayed proton probabilities of the N=Z nuclei are also crucial in the mass range above ^{80}Zr. The isotopes ^{84}Mo, ^{92}Pd, and ^{96}Cd are of particular importance. These isotopes are difficult to produce with heavy-ion reactions using stable beams and stable targets. Crucial isotopes could be produced by fusion-evaporation reactions with beams such as ^{58}Cu or by projectile fragmentation

It has been recently suggested that the post-collapse phase in type II supernovae offers an ideal site for the r-process which is responsible for the formation of heavy elements $A \geq 100$ by rapid neutron capture in a neutron bath of 10^{20-30} neutrons/cm^3. The reaction path is mainly determined by the (n,γ)-(γ,n) equilibrium and runs far into the neutron rich side of stability.

After the collapse of the protostar and the rebounce of the outer envelope material on the neutron core, neutrino heating occurs in the wake of the shock front, causing a high photon to baryon ratio in the hot neutrino wind (hot-bubble). Baryonic matter, under these conditions of nuclear statistical equilibrium, is dominated by α particles, protons, and neutrons. In the subsequent expansion phase, the recombination of the α particles is limited by slow, three particle interactions like the triple α reaction, $^4He(2\alpha,\gamma)^{12}C$, and the reaction sequence

$^{4}He(\alpha n,\gamma)^{9}Be(\alpha,n)^{12}C$ that bridge the mass 5 and mass 8 gap. Once the α particles have recombined, higher mass nuclei quickly build up in the α-process[9]. Therefore, the α-process depends on the expansion and cooling rates as well as on the rates of the recombination processes of ^{4}He to ^{12}C.

The charged particle reactions are the first to fall out of the nuclear statistical equilibrium and the abundances freeze out due to the rapid expansion in the hot bubble. This leaves free neutrons and nuclei as seed material for a rapid neutron capture process, the r-process. The available seed material is limited by the small α recombination rate. While the r-process path is first determined by the (n,γ)-(γ,n) equilibrium, after further expansion the neutron capture processes decouple with rapidly decreasing density, and photodisintegration drives the reaction path closer to the line of stability.

To model this complex nucleosynthesis scenario requires an accurate knowledge of the α recombination processes as the determining factor in seed production. It also needs an understanding of the r-process, which is mainly hampered by the lack of experimental knowledge of masses, lifetimes, and decay properties of the very neutron rich isotopes. Also, the study of neutron capture rates on neutron rich radioactive nuclei is critical to the investigation of the late phases in this r-process scenario.

Radioactive beam experiments offer the ideal opportunity for studying nuclear structure effects that not only determine the α-recombination rates but also the r-process parameters. Besides the $^{4}He(2\alpha,\gamma)^{12}C$ and the $^{4}He(\alpha n,\gamma)^{9}Be$ reactions, recombination of α particles is also possible via an alternative process, triggered by the initial neutron flux. For the high neutron abundances, required in the r-process, sequences of two neutron capture reactions initiated by $^{4}He(2n,\gamma)^{6}He(2n,\gamma)^{8}He$, etc., offer an alternative bridge of the mass 5 and 8 gaps. The two-neutron capture cross section depends strongly on the pronounced halo structure of the ^{6}He and ^{8}He compound systems and of similar higher mass neutron-rich halo nuclei. The details of the halo structures are essential for determining the reaction rates and need to be studied with radioactive beam experiments. These measurements can be performed using elastic and inelastic scattering as well as Coulomb-excitation, and Couloumb-break up studies on the particular halo nuclei.

For the interpretation of r-process nucleosynthesis, measurements of nuclear masses, half-lives and decay properties of very neutron rich nuclei are crucial. These studies can be performed at the front end isotope separator in an ISOL system or also with stopped PF beams, using classical, but refined, spectroscopy techniques. The production of very neutron rich isotopes will be improved by increased primary beam intensity. Beam purity can be optimized by introducing isobar separators or using selective laser ion sources.

The p-process is thought to be responsible for the production of the stable neutron-deficient isotopes with charge numbers $Z \geq 34$ which cannot be produced by s-process and r-process nucleosynthesis. The abundances of these isotopes is typically small, approximately 0.01 - 0.1% of the elemental abundance, except for ^{92}Mo (14.85%) and ^{96}Ru (5.52%). The p-process nuclei are synthesized at temperatures of $\approx 2\text{-}3 \cdot 10^{9}K$ by photodisintegration [(γ,n)] of pre-existing s-process nuclei, driving the abundance distribution towards the neutron deficient side of the line of stability. In the higher mass regions these nuclei are possibly further photodisintegrated by subsequent (γ,α) and (γ,p) reactions.

The suggested sites for the p-process are either oxygen/neon zones of highly evolved massive stars during their pre-supernova phase or later during their explosion as supernovae type II.[10,11] The main uncertainties for modeling the process concern the photodisintegration rates (γ,n), (γ,p) and γ,α) of stable and unstable neutron-deficient nuclei. Some uncertainties are also connected with the reaction rates for neutron capture on the neutron deficient isotopes[12]. Essentially no experimental data are available. The present rates are based entirely on statistical model calculations. The various model results differ, however, in some cases.[12] In particular, near closed shell nuclei, the model predictions become unreliable and need to be verified experimentally. This can be performed by measuring proton-and alpha- capture reactions on neutron deficient isotopes in inverse kinematic using detailed balance to extract the information about the photodisintegration cross sections. For the study of (γ,n) reactions this approach is not feasible, and indirect methods need to be utilized to study the γ and neutron decay of high excited states in the compound nuclei of (γ,n) reactions.

Experimental Nuclear Astrophysics has proven to be a very powerful tool for understanding stellar processes. Besides the observational data, it is the only experimental way to verify our interpretation of the dramatic events observed throughout our universe. Its great success is the study of the slow reactions on stable nuclei which produce the long lifetimes of the stars. The key for understanding the cataclysmic explosions we observe in the Milky Way and in far distant galaxies is, however, the study of nuclear reactions far away from stability. A facility like the ISL will offer the unique opportunity to push our understanding to these very limits of stability. These limits set the conditions for the enormous eruptive processes, taking place light years away, in which all the elements have been created.

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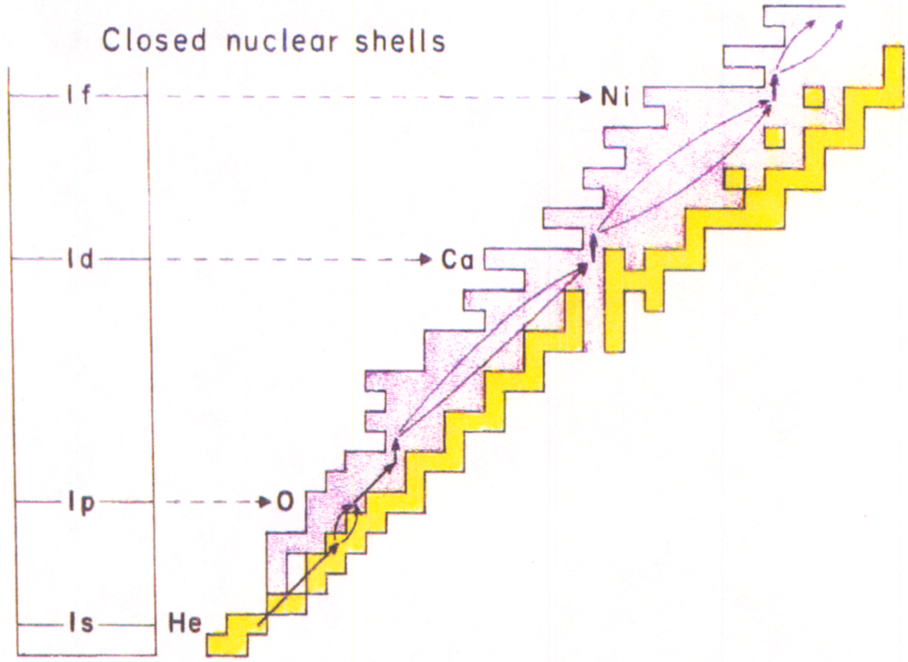

Fig. 2. Schematically shown in this picture is the reaction path of the rp-process below A=60. The reaction flow is controlled by the bottlenecks at shell closures where the proton-drip line is very close to the line of stability. Indicated are the bottleneck reactions for high temperature conditions, $^{15}O(\alpha,\gamma)^{19}Ne$, $^{39}Ca(p,\gamma)^{40}Sc$ and $^{55}Ni(p,\gamma)^{56}Cu$ which determine the reaction flow between the mass range of the 1s1p- and 2s1d-shell nuclei, the 2s1d- and 1f-shell nuclei, and between the 1f- and 2p-shell nuclei, respectively.

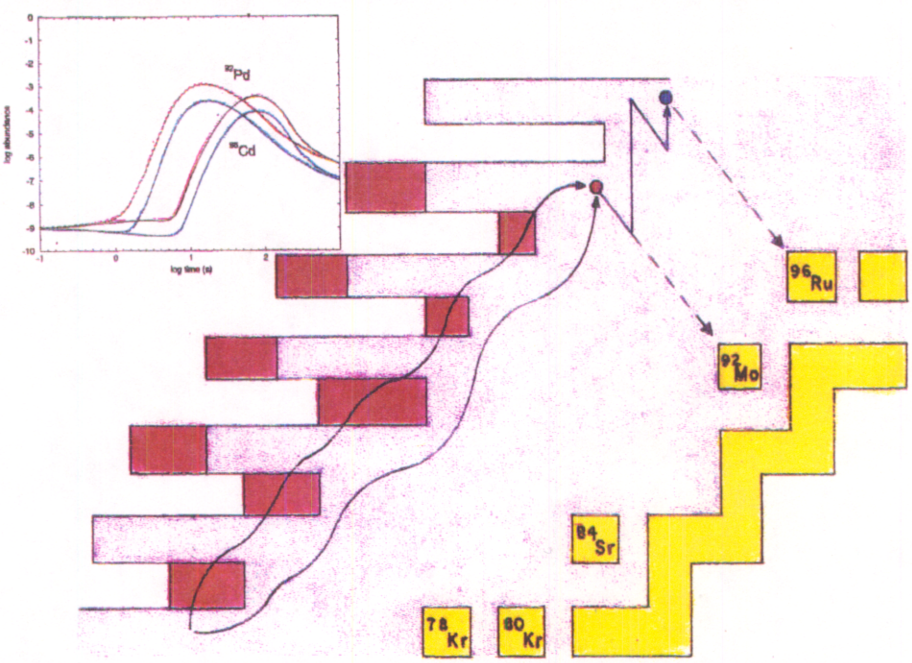

Fig. 3. The r-process reaction path above A=70 depends strongly on the nuclear masses. Schematically shown is the reaction path calculated for two different mass models, which predict different proton drip lines. The reaction path closer to the line of stability requires considerably more time to produce sufficient amounts of ^{92}Pd and ^{96}Cd, which are progenitors of the p-process isotopes ^{92}Mo and ^{96}Ru.

V. Facilities

THE FACILITY

The purpose of this section is to present some indication of the facilities that can be used to meet the challenge of the exciting physics opportunities presented above. To fully address this science, a wide range of radioactive species and beam energies is essential.

BACKGROUND

The use of isotope separators on-line to reactors and heavy ion accelerators to produce low energy beams of radioactive isotopes has been an on-going activity for the past 30 years. The objective in these cases was the separation of the reaction products in order to obtain a pure sample of the isotope under study. Additionally, reaction products emanating from a thin target following a heavy-ion reaction have been separated on-line using recoil mass separators, but again the primary objective was the separation of the reaction products, not the production of a secondary radioactive beam. Technological advances over the past 10 years, however, have made it possible to produce large quantities of specific radioactive-ion species at energies up to the GeV/u range. These beams of radioactive heavy ions can then be used to initiate reactions themselves and, in this way, enable scientists to produce and study nuclei even farther from stability. Not only has this advance revitalized the field of subatomic physics by providing a new tool for the study of the atomic nucleus, but it has revealed new opportunities in fundamental physics and other specific areas such as nuclear astrophysics and condensed matter physics.

At present there are two main approaches to the production of intense beams of energetic, radioactive, heavy ions. These are the projectile fragmentation method (PF) and the isotope separator on-line method (ISOL). In the PF method, an energetic (>50 MeV/u), stable heavy-ion beam is allowed to traverse a thin target, leading to the fragmentation of the projectile. The projectile of interest (A,Z) is selected on-line from the wide range of reaction products using electromagnetic devices coupled with wedge absorbers. Good selectivity is possible and the resultant radioactive heavy-ion beam has essentially the same velocity as that of the incident projectile. This leads to a wide range of very energetic and reasonably intense beams of very short-lived radioactive species that are especially well suited, among a variety of other uses, for reaction studies above the Coulomb barrier. The NSCL at Michigan State University is an example of one of the four major PF laboratories worldwide.

The second approach (ISOL) involves the coupling of a primary radioisotope production accelerator to an isotope separator that is itself coupled to a post-acceleration system. In this method, typically, a high-energy light-ion beam is directed onto a thick target that is maintained at an elevated temperature so that the reaction products diffuse out of the target into an ion source. At this stage the radioactive species are ionized, extracted, and mass separated prior to injection into a second accelerator. The ISOL approach is capable of producing higher intensity beams with better beam quality than the PF method, but at a lower beam energy. It is ideal for many nuclear structure studies, for low-energy astrophysics experiments, and for a wide variety of fundamental and condensed matter science.

These two methods of production are quite complementary and both are needed to cover the range of experimental objectives. Except for the low-energy astrophysics-oriented facility at Louvain-la-Neuve, there is no major facility in operation which uses the ISOL method, but there is considerable interest worldwide with about 10 known proposals in various stages of development. In this country, a first generation ISOL facility (HRIBF) is scheduled to come on-line at the Oak Ridge National Laboratory in 1996. Other first-generation facilities have been funded at the INS laboratory in Japan and at the GANIL laboratory in France.

A conceptual layout of a second generation radioactive ion-beam facility was presented in the IsoSpin Laboratory (ISL) report[1] in order to inform the community that technology was now available to consider the development of a facility to produce a wide range of radioactive projectiles with high intensity and with energies variable from about 0.2 to 10 MeV/u using the ISOL method. The facility outlined incorporates a high-intensity, intermediate energy proton accelerator as the production facility, a thick target on-line isotope separator as the separation facility, and a post-accelerator stage to achieve the desired energies of interest for the radioactive species extracted from the ISOL device. In that report,[1] calculated intensities of the available radioactive beams based upon experience gained at thick target ISOL facilities were provided to allow experimenters the opportunity to consider such beams in their individual projects. In addition, technical areas requiring further studies were identified in order to provide focus to future research and development work. A number of these R&D studies are being actively pursued at North American laboratories and through an international effort with the Rutherford Appleton Laboratory in England (the NACRIST collaboration).

Since the ISL report[1] appeared, there has been considerable interest expressed by the community in using such a facility. In addition, there have been several workshops held at ORNL[2], LBL[3] and TRIUMF[4] on technical issues related to the production of radioactive ion beams by the ISOL method. Concomitant with these activities, the NSCL at MSU has proposed an upgrade to increase the intensity of the radioactive ion beams it currently produces by the PF method. Finally, funding was provided for the development of a first generation ISOL radioactive ion-beam facility at ORNL, the Holifield Radioactive Ion Beam Facility (HRIBF). This facility[5] will use low energy (up to 60 MeV proton and higher energy deuteron, ^{3}He and α particle) beams to produce a range of mass separated, radioactive species which are then accelerated using the existing 25 MV tandem accelerator.

THE PRESENT

Over the past several years, the concept of an ISL facility has been developed, clarified and expanded. That process has now reached its natural completion as a concept circulating among the community of scientists. The next step in moving the concept to reality requires substantial technical and financial resources. Since the community has clearly expressed a need for an ISL facility, and since the budgets of the North American funding agencies are currently committed to other large projects, the logical approach during the interim involves the development of first generation facilities (such as HRIBF at ORNL or ISAC-1 at TRIUMF) where the initial experimental needs of the scientists can be met and where the technical developments needed for the ISL can proceed. At the same time, the active and exciting radioactive beam research program at MSU demonstrates the essential need for higher energy RNBs as well, and the proposed coupled cyclotron upgrade will meet many of these needs in the years ahead. In the longer term, in order to meet the clear need for low energy RNBs, it is the fervent hope of the North American (indeed, the world wide) radioactive ion beam community that a facility embodying the ISL vision be given the highest priority for next construction when the existing major construction projects are nearing completion. A brief description of developments related to a future ISL currently underway at a number of laboratories in North America is presented below:

MSU/NSCL. This facility produces a wide variety of energetic (<200 MeV/u) radioactive beams using the projectile fragmentation method (PF). Heavy ion beams, accelerated with a K=1200 superconducting cyclotron, fragment in a thin target and electromagnetic devices select specific fragments (A,Z) for subsequent use in secondary reactions. A successful program is in operation, and modest funding is being sought to increase the energy and beam intensity by coupling two of the existing MSU superconducting cyclotrons.[6] When this facility is upgraded, North American scientists will have a facility superior to those at GSI in Germany, GANIL in France and RIKEN in Japan.

NOTRE DAME. This facility was among the first to use radioactive beams to initiate secondary reactions. In these studies, a 3.5 T superconducting solenoid is used to collect the products of single-nucleon transfer reactions using ^{6}Li and ^{7}Li beams from the Notre Dame FN tandem accelerator. The superconducting solenoid acts both as a momentum analyzer and as a thick lens to focus the secondary beam. Current activity is centered on a survey of ^{6}He induced reactions in an attempt to see if standard transfer spectroscopy, but with radioactive beams, can elucidate the structure of halo nuclei. The development of an ^{8}B beam with an energy of 3-4 MeV/u is also underway. This beam will be used to study the breakup of ^{8}B into ^{7}Be+p at low energies. Recently, α- and d-capture reactions on ^{8}Li have also been a focus of activity.

HRIBF. Construction is underway on a low-energy radioactive ion-beam facility at ORNL. This facility will primarily use proton, deuteron, ^{3}He and alpha particle beams from the existing ORIC K=105 cyclotron to produce a range of low and medium-mass, neutron-deficient, radioactive isotopes which will be extracted and mass analyzed using a high resolution ISOL device.[5] These beams will be accelerated to energies between 0.2 and 20 MeV/u for A=10 and between about 0.2 and 5 MeV/u for A=90 using the existing 25 MV tandem accelerator. First beams are expected in 1995. Tentative plans exist for a later upgrade by using fission of heavy Z targets to generate a range of neutron-rich radioactive beams. HRIBF is an important facility on the path to the ISL as new and interesting science will emerge, but also because the feasibility to actually produce accelerated radioactive beams using the ISOL plus post-accelerator approach will be demonstrated in a more dramatic way than the more limited efforts underway elsewhere.

TRIUMF. Very low energy (12 keV/u) radioactive beams have been available for some years at this laboratory using a 500 MeV proton beam as the production source (spallation, fission, and fragmentation reactions) and a thick target ISOL device (TISOL) to extract and mass analyze the radioactive ion beam.[7] A wide range of beams have been available, but the primary proton beam intensity has been limited to 1 microamp due to the limited target handling capabilities and minimal shielding. Approval has essentially been obtained to upgrade the TISOL facility in two ways: First, to provide for the use of primary proton-beam intensities of at least 10 microamps and, second, to couple TISOL to a LINAC to produce both stopped and accelerated beams with energies between 0.2 and 1.5 MeV/u. The mass range of the accelerated beams will be limited to $A/q<30$, but a great deal of experience will be gained in understanding the coupling to and use of a LINAC as the post-accelerator. The intensity of the available beams will be greater than or at least comparable to those elsewhere, and will enable competitive studies with facilities in Europe and Japan. This facility, ISAC-1, could be upgraded to a full ISL type facility.

LAMPF. This facility has an intense 800 MeV proton accelerator which could provide the primary beam for an ISL facility. Recent R&D at Los Alamos has led to the successful demonstration of the high-intensity production of a wide variety of radioactive species using a thin uranium target/He-jet system operating with 700 μA of primary beam intensity. In particular, this method promises high yields of nonvolatile species that are not readily extracted from thick targets. As such, a thin-target, He-jet production system would greatly increase the variety of radioactive species available at a radioactive beam facility. LAMPF can support both the thick and thin target production methods and has an existing infrastructure to handle high levels of radioactivity. Addition of an ISL would therefore be relatively straightforward.

ANL. This laboratory has a LINAC, ATLAS, that can accelerate all ions up to uranium above the Coulomb barrier. A proposal is presently being prepared to use ATLAS as the post-accelerator of an ISOL-based RNB facility. Plans are being developed to install a 200 MV LINAC to accelerate 100kW of protons, deuterons, and heavier ions (1 mA protons, 0.5 mA deuterons, ~100 μA ^{4}He, ^{12}C). The deuterons will be used to generate a neutron beam (~100 particle μA) by stripping in a Be target. These neutrons will bombard a thick uranium target to produce large amounts of fission products which, after extraction with an ISOL system, will be accelerated in the ATLAS LINAC. Other primary beams can be used directly to make neutron-deficient products by a variety of reaction mechanisms. Given the presence of the ATLAS LINAC and the existing experimental systems, this facility could be easily upgraded to a full ISL system with the addition of an intense, high-energy proton accelerator.

LBL. This laboratory has been investigating several ISL areas of developments. A high voltage test stand utilizing electron-bombardment heating is used to thermodynamically test the design and viability of a He gas-cooled target. Currently, stainless-steel cylindrical targets can be tested with up to 10 kW of heating power. A finite-element heat transfer code is used to simulate target heating not only to compare with the present target, but also to determine modified target designs. ISL radiation safety challenges, such as Monte Carlo shielding calculations; target irradiation, storage, handling and disposal; and categorization of the facility have been studied. Radioactive beam intensities, for the first time including radioactive growth and decay, have been calculated for several targets using the Silberberg and Tsao semi-empirical program, and the LAHET and FLUKA Monte Carlo programs. This allows beam intensity predictions based on detailed target designs. Future tests include measurements of diffusion coefficients for a liquid-core Ta target by spiking with a known amount of an element and ion source efficiencies as a function of temperature for a coupled target/ion source.

THE FUTURE ISL LABORATORY

While first generation radioactive ion-beam facilities can be used for a wide variety of interesting and exciting research, their limitations will be felt quite early. It is critical that plans for a large scale, second generation facility such as the ISL be underway before these limitations are reached. A benchmark ISL facility was outlined in the ISL white paper.[1] Since then, the ideas have been refined and improved, and recent technological advances have been incorporated. It is important to recognize that the ISL is a *concept or vision defined by output specifications* rather than design choices. The goal is a wide variety of intense radioactive ion beams. There could be any number of schemes to achieve this or major portions of it. We do not wish to constrain or limit the options; nevertheless, it is useful to illustrate one possible realization in order to give the reader an idea of how the ISL goals could be achieved. One such scheme that incorporates the essential goals of the ISL benchmark facility discussed in the 1991 ISL White Paper is schematically outlined in Fig. 1. This facility would use a high-intensity (100 microamp), 1 GeV proton production facility to produce a wide range of radioactive species using spallation, fission, and fragmentation reactions. Using current and newly developing target and ion-source techniques, these products can be extracted in the form of ions. A very pure beam (A,Z) can be generated using a high-resolution mass analyzer. Using ideas being developed at LBL, it is even envisioned that the ISL facility could produce a wide range of extracted beams simultaneously. The latter possibility would significantly increase the usefulness of the ISL to service a wide community of users at the same time. Following mass analysis, one of the extracted beams will be injected into a

LINAC to produce an intense beam with energy variable from 0.2 to 10 MeV. [Interest has been expressed by some members of the community to move the upper energy range of the ISL into the lower energy range of the PF facilities, namely 30 MeV/u]. We stress that Fig. 1 is an illustration only. The RNB intensities given in the 1991 White Paper were based on a scheme similar to Fig. 1. They included losses due to ionization efficiency, transmission through the mass separator and accelerator, and stripping. Not included were radioactive growth and decay, release factors in the target material, and sticking prior to ionization.

AREAS REQUIRING TECHNICAL DEVELOPMENT

There are a number of research and development initiatives required before one can realize an optimized ISL facility. The community is beginning to work on these at various laboratories in North America and worldwide where the technical and financial resources are either already available or can be gathered. This continuing activity and the availability of first generation radioactive beam facilities will ensure the development of a broad community of scientists dedicated to research using radioactive ion beams. A short summary list of areas requiring R&D is presented below. There is no priority implied by the order in which they are presented.

1. Studies of the operation of a thick target ISOL device using production beams more intense than used at present (2 microamps) and as high as 100 microamps. This includes not only high-intensity production studies in the laboratory, but the development of a realistic scheme for the handling of the radioactively hot target and ion source front-end.

2. Studies of the use of LINACs to capture and accelerate the very low-velocity and low charge-to-mass radioactive ions from the ISOL device.

3. Studies of new ion sources to produce more efficiently the radioactive beams of interest. This includes the use of a laser ion source and other approaches to produce high quality, multiple charge ion beams (ECR, CUSP, and injected EBIS sources).

4. Studies of alternate methods of transferring radioactive products of interest (especially nonvolatile species) which would increase the variety of radioactive beams available. This includes the thin target, gas-jet approach which not only reduces radiation problems but also provides many more products not easily extracted with thick target technology. Additional ion source development directed at gas jet technology and the ionization of non-volatile species is needed.

5. Studies of the use of alternate methods of producing radioactive beams of interest, such as the use of intense beams of energetic neutrons leading to a range of beams of fission products which can complement the species produced by energetic proton beams.

6. Studies of possible methods to improve the quality, intensity, and variety of radioactive beams such as the so-called BRAMA facility and similar devices.

CONCLUDING REMARKS

The field of Radioactive Nuclear Beams is expanding around the world. A large, enthusiastic community of scientists eager to pursue RNB science already exists and believes this new technology represents the future of low-energy nuclear physics and astrophysics. First generation facilities in North America at MSU and Notre Dame are already in operation and have produced a wealth of exciting and unexpected new results. Facilities at Oak Ridge and TRIUMF are funded and eagerly awaited. These interim facilities, as well as others in operation worldwide, represent a crucial advance for our field. They will yield important new physics, they will help resolve many technical issues relating to RNBs, and they will certainly reveal many unexpected opportunities in the future. In short, they will lay the groundwork for a future ISL and are on a critical path towards its realization.

At the same time that these interim facilities are doing important research, it is equally clear that there are limits to the science they can achieve. The full potential of RNBs can only be realized with a broader range of beams, energies and intensities. In the projectile fragmentation field, the proposed MSU upgrade is highly recommended. It is cost-effective and will make the NSCL the premier facility of its type in the world. In the ISOL arena we need a facility with the capabilities embodied in the concept of the ISL. Only with such a facility or one that achieves major portions of the ISL goal can the full potential of the science outlined here, in the 1991 ISL White Paper, and in other reports, be realized and exploited. A unique and timely opportunity awaits to greatly expand the horizons of nuclear physics and to open new and yet unthought of vistas of our science.

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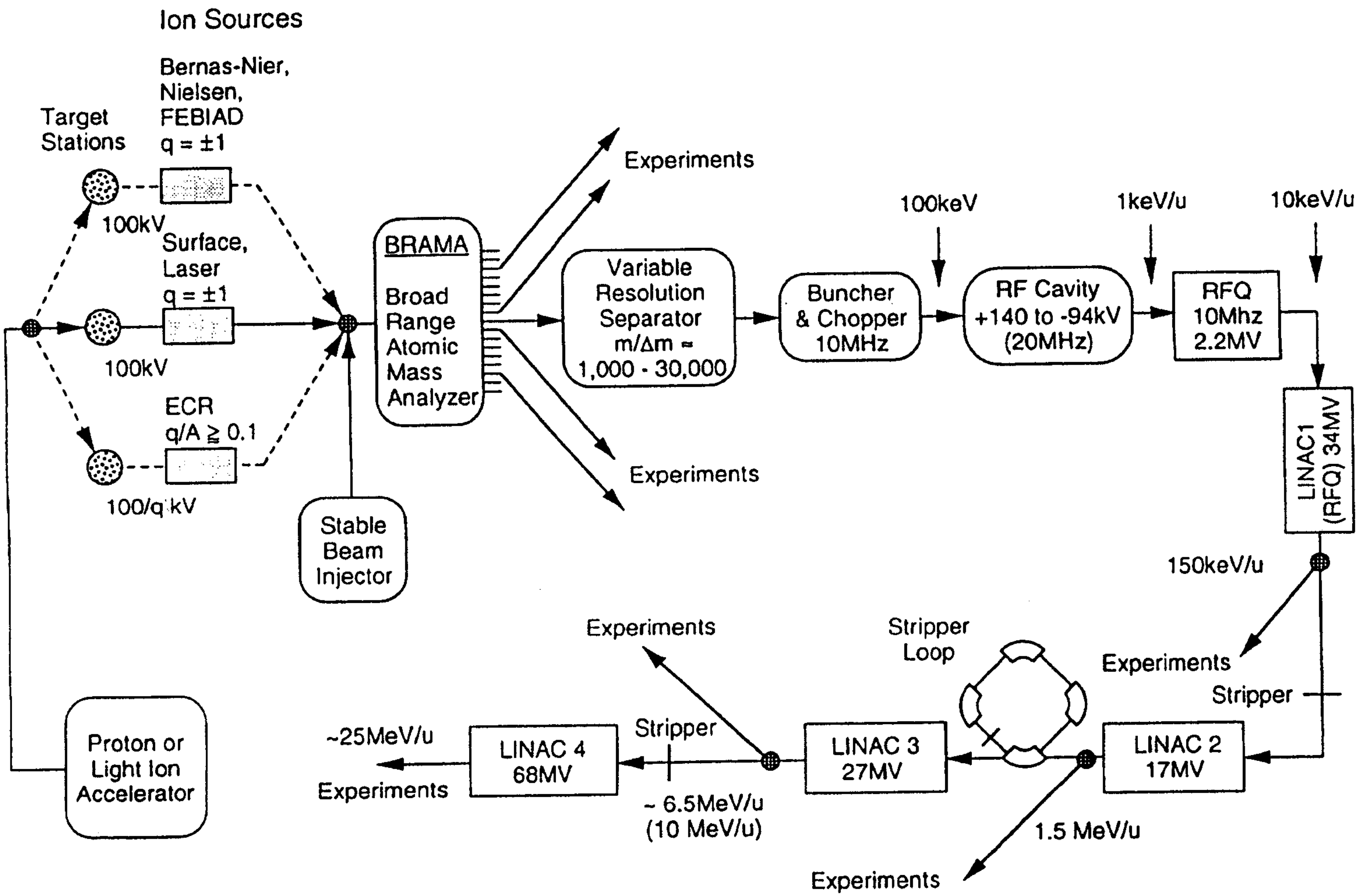

Fig. 1. A schematic representation of one concept of the ISL facility for the production of high-intensity radioactive beams. This facility would satisfy the requirements of the experimental program outlined here and incorporates a number of recent developments. This facility is considered technically feasible although some aspects do require thorough research and development studies to optimize their final design. The final facility specifications of the ISL facility should still be considered tentative to allow for a thorough review by the community of users and also to include up-to-date financial considerations when such a facility is built.