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NUCLEAR STRUCTURE AT EXTREMES OF STABILITY: PROSPECTS OF RADIOACTIVE Be EXPERIMENTS AND FACILITIES*

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In the last few years, our understanding of nuclei at extremes of stability has undergone substantial development and change. It is now thought that there is every likelihood for truly new manifestations of structure at extreme N/Z ratios, unlike anything observed to date. Changes in shell structure, residual interactions, symmetries, collective modes, and the evolution of structure are envisioned. These developing ideas expand the opportunities for nuclear structure studies with radioactive beams and focus attention on the need to develop efficient experimental techniques and improved signatures of structure. These developments are discussed along with an overview of current and future radioactive beam projects in North America.

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1. Introduction

Our perception of nuclear structure has undergone a major upheaval in the last few years. This emergence of new concepts and expanded horizons has been driven by new experimental capabilities, but is motivated by theoretical understanding. Heretofore, our images of nuclear structure and its evolution have been framed by standard approaches such as the Shell Model, viewed in terms of a characteristic Hamiltonian, and residual interactions that are universal in their perceived applicability to nuclei. Various collective models, embodying truncations and simplifications of the Shell Model, have given us the familiar predictions of vibrational and rotational motions, deformations, and the like.

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This view has been shattered by the advent of radioactive nuclear beams (RNBs) which give access to vast numbers of new nuclei far from stability, extending, in some cases, nearly to the proton and neutron drip lines. Theoretical attempts to model these exotic nuclei have highlighted the realization that the Shell Model framework is not at all an immutable edifice, applicable unchanged from drip line to drip line. Rather, the treatment of nuclei near the drip lines, especially on the neutron rich side, may require conceptual modifications to the basic Shell Model Hamiltonian itself, to the nature of residual interactions, and even to the framework in which to calculate these. It is especially appropriate to focus on some of these ideas here since many of the theoretical insights guiding these changing concepts have been put forth by Nazarewicz, Dobaczewski and their colleagues [1–4].

2. Structure near the drip lines

The standard Shell Model, that is, an independent particle model with more or less familiar single particle energies (s.p.e.'s) and residual interactions acting on a set of bound nucleons, applies in nuclei with roughly comparable numbers of protons and neutrons, standard nuclear densities, a reasonably well defined surface and a definite shape. However, near the drip lines, these concepts begin to break down.

Let us consider the neutron drip line since that side of stability brings into play all the key new elements. First of all, the extreme neutron excess leads to a neutron skin extending well beyond the proton density. (Well known examples of this in light nuclei are the halo nuclei such as ^{11}Li, but the concept applies to heavier nuclei too.) Thus, the outer realms of these nuclei consist of nearly-pure weakly-bound neutron matter. The outer neutron surface is extended spatially and extremely diffuse. Densities are orders of magnitude lower than normal nuclear densities. Indeed, this region of near-neutron drip line nuclei offers us, in effect, a third form of nuclear matter, intermediate between normal nuclei and free nucleons. Finally, with an extended, diffuse outer region, even the basic geometric concepts of surface and shape may lose meaning and utility as descriptive characteristics.

In such an environment, even the Shell Model Hamiltonian and residual interactions themselves can be radically different. A diffuse nuclear surface region cannot easily support a Shell Model potential with sharp contours. Hence, the Shell Model potential is likely to change from a Woods-Saxon to an harmonic oscillator (H.O.) (rounded bottom) shape. In the language of the Nilsson model, this is equivalent to the H.O. plus $l \cdot s$ spin orbit term but without the l^2 term. The spin orbit term itself may also change. (Some calculations [5] in light nuclei have addressed this issue.) Extreme "no-l^2" and no "$l \cdot s$" possibilities are illustrated for a set of single particle orbitals in Fig. 1.

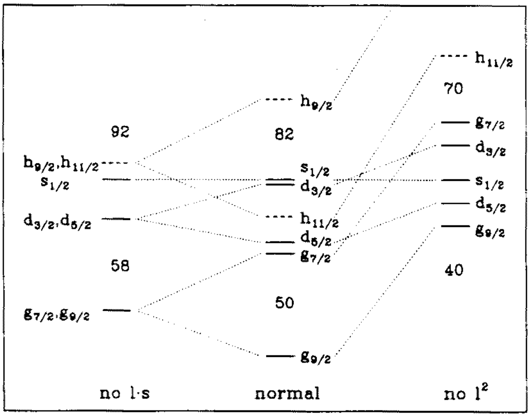

Fig. 1. Single particle energies in the standard Shell Model (middle), in a scenario with no $l \cdot s$ term (left), and with no "l^2" term (right).

Besides the basic potential itself, residual interactions are likely to change. Clearly, with protons and neutrons occupying very different orbits, the effects of the residual p-n interaction will be altered. The like-nucleon pairing interaction will scatter nucleon pairs in weakly-bound orbits into the continuum. The greater spatial extent of unbound orbits leads to greater overlap (the particles are "everywhere"), and hence the pairing fields will increase in the neutron surface region and be significant at very large radii.

To illustrate some of these ideas more concretely, let us consider some effects of the no-l^2 scenario for the shell model potential (Fig. 1, right) in comparison with the normal level sequence in the middle. Of course, without an l^2 term, the s.p.e.'s change. The largest shift occurs for the unique parity orbit (UPO) which reverts to its parent shell. Without the UPO, the magic numbers themselves change (in Fig. 1, from 50 and 82 to 40 and 70). A large number of high spin phenomena (backbending, superdeformation, *etc.*) as well as octupole collectivity involve the UPO. These phenomena will be significantly altered.

The changes to the sequencing of normal parity orbits are equally significant. In the normal Shell Model, these orbits decrease monotonically in spin with energy from j_{max} to $j = 1/2$, in steps of Δj = -1. In the no-l^2 case, the monotonous sequence is destroyed. Instead, a nested pattern emerges, with the highest j values surrounding the mid-j orbits and the lowest j orbit in the middle of the shell. Moreover, the sequence is purely $\Delta j = 2$: namely, in this example, 9/2, 5/2, 1/2, 3/2, 7/2 (recall $1/2 \rightarrow 3/2$ is $\Delta j = 2$). Since most collective effects in nuclei arise from the action of the quadrupole force which has large matrix elements connecting states with $\Delta j = \Delta l = 2$, it is certainly imaginable that collectivity and its evolution could be radically different in the no-l^2 scenario.

Though this scenario may be an exagerated limit, and though the neutron drip line in heavy nuclei may remain inaccessible, it is useful to ask how such changes in underlying single-particle structure might be observed. This is especially relevant since, with RNBs, beam intensities may be many orders of magnitude weaker than we are accustomed to. To re-phrase this question: are there any *simple* signatures of effects such as the no-l^2 scenario? We will illustrate two of these that have recently been discussed.

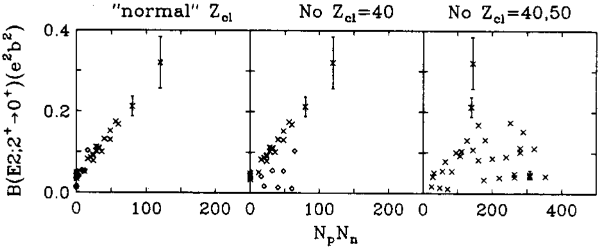

Fig. 2. $B(E2)$ values as a function of N_pN_n for the $A = 100$ region under three assumptions concerning magic numbers and shell gaps. (See text.)

Figure 2 illustrates the first with $B(E2)$ values plotted against N_pN_n for the $A = 100$ region. The three panels show, respectively, plots assuming the accepted proton shell closures in this region, namely $Z = 38, 50$ for $N < 60$ and $Z = 28, 50$ for $N \geq 60$ (left); assuming $Z = 28, 50$ throughout the region (middle); and assuming $Z = 28, 82$ throughout, that is, assuming $Z = 50$ is not a magic number (right). In the first panel the data lie along a compact linear trajectory. In the middle panel, a breakdown of this is seen and, on the right, the scatter of points destroys any semblance of simplicity. Hence, exploiting the N_pN_n scheme can give information on relevant magic numbers.

The use of such a simple observable as $R_{4/2}$ to deduce information on underlying shell structure may seem even more remarkable. However, the rationale is simple. Consider two like nucleons in a single-j configuration, $| j^2 J >$, under the influence of a short range interaction (surface δ force). Then, $R_{4/2} \sim 1.2$. The same $R_{4/2}$ value arises for $| j^n J >$, and for a multi-j configuration of the type $| j_1^{n_1} J_1, j_2^{n_2} J_2 \ldots J >$ where $n_1, n_2 \ldots$ are even. Consider, however, a two particle system with a particle in each of two orbits, that is, $| j_1 j_2 J >$. If $| j_1 - j_2 | \neq 2$, then the 2^+ state is formed by a non–co-planar alignment of angular momenta. Hence, with a short range interaction, the 2^+ state will not be lowered substantially and $R_{4/2}$ remains near 1.2. However, suppose $| j_1 - j_2 | = 2$. Then the 2^+ state requires *co-planar* alignment of the two angular momentum vectors and hence a large overlap and interaction, and thus the 2^+ state is strongly lowered. This gives larger $R_{4/2}$ values, which can even attain values of ~ 1.8 for a 2-particle system [6]. These simple ideas may account for the existing phenomenology of $R_{4/2}$ values in magic nuclei [6] and may provide a signature for "$\Delta j = 2$"

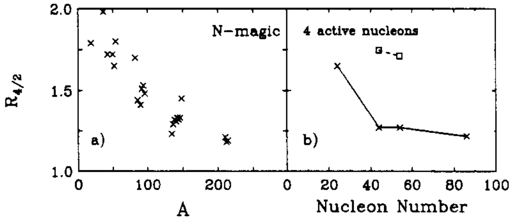

Fig. 3. (Left) Empirical $R_{4/2}$ values for neutron magic nuclei. (Right) Calculations of $R_{4/2}$ with a δ-function interaction using "normal" single particle energies and smoothly decreasing interaction strength (solid line) and for the "no-l^2" scenario of shell model s.p.e.'s in Fig. 1 (two upper points). Based on Refs. [6, 7].

j-shell structure near the neutron drip line [7]. Figure 3 shows that, in the $s - d$ and $p - f$ shells, where, in fact, $\Delta j = 2$, empirical $R_{4/2}$ values rise even above 1.5. Only in heavy nuclei, where the j_{max} state has descended to the next lower shell (where it is the UPO), and the remaining j-sequence is $\Delta j = 1$ (see Fig. 1, middle panel) does $R_{4/2}$ approach ~ 1.2. These empirical systematics are easily reproduced by schematic calculations with a surface δ-force as shown on the right (solid line) in Fig. 3. However, superposed in this figure are two calculations of $R_{4/2}$ using the $\Delta j = 2$ no-l^2 scenario of Fig. 1. Clearly, the $R_{4/2}$ values calculated with no l^2 term are anomalous, and such large $R_{4/2}$ values in new regions made accessible with RNBs could signal major changes in underlying j-structure [7].

3. Status of RNB facilities in North America

Worldwide interest in RNBs has grown enormously in the last five years. There are two principal approaches to the production and use of RNBs — projectile fragmentation (PF) and the ISOL (Isotope-Separator-On-Line) technique. These are illustrated in Fig. 4. The two approaches are complementary. In this section we summarize these production methods and the status of North American RNB activities. The reader is referred to the recent update of the ISL [IsoSpin Laboratory] White Paper [4] and to individual facility proposals [8–11].

In PF heavy ion projectiles impinge on a thin light target. The collisions lead to the production of a large variety of exotic species which exit the target at nearly the incident beam velocity. Downstream, the RNBs are

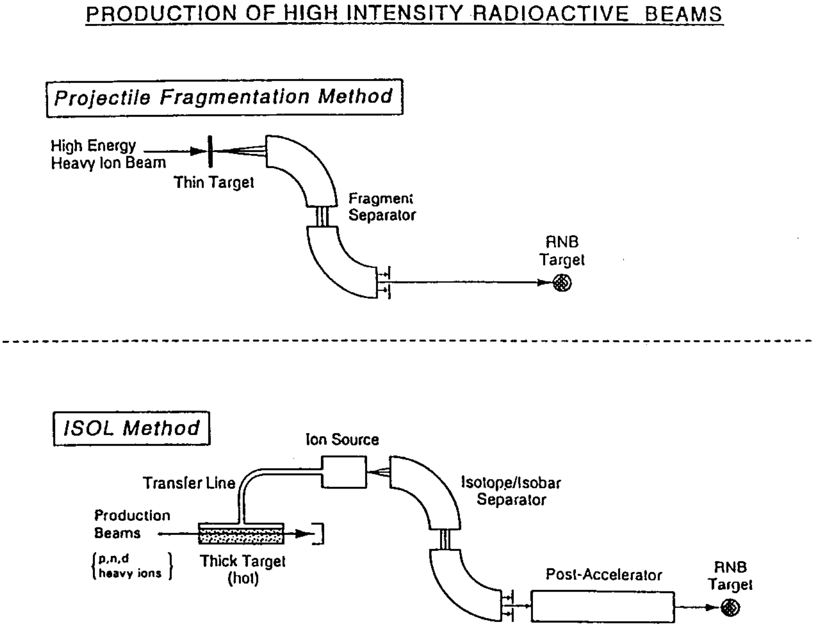

Fig. 4. Comparison of the Projectile Fragmentation and ISOL Methods for the Production of RNBs.

separated, and the desired species is focused onto a target for the study of secondary reactions, perhaps leading to even more exotic nuclei.

The PF approach produces RNBs virtually immediately and at high energies, typically 50-200 MeV/A. All reaction products are available but, of course, careful separation is necessary. With beam energies well above the Coulomb barrier, the technique is best suited to reaction studies, although a wealth of exciting structure studies (*e.g.*, of halo nuclei) have been performed at such facilities.

The ISOL technique is very nearly the inverse: light projectiles (p, n,He) or light heavy ions (*e.g.*, ^{12}C) bombard a heavy, thick target. The reaction products are produced at low velocity, diffuse to the surface, are ionized, and accelerated in a post-accelerator. The technique in chemically selective and inherently involves a delay—between production and ionization—which depends sensitively on diffusion, desorption and ionization rates. On one hand, this can be an advantage—a given element is selected before acceleration, but it is also a disadvantage in that some elements cannot be easily produced, and delay times for others are long enough that decay intensity losses are large. With final energies up to $\sim$ 10 MeV/A, this method is ideal for most nuclear structure and nuclear astrophysics experiments.

Most existing RNB facilities are of PF type. The principal ones worldwide are at RIKEN, GSI, MSU, and GANIL. They have been among the pioneers in developing the field of RNB physics and in revealing the exciting research opportunities it provides. For example, the study of halo nuclei has been carried out predominantly at PF facilities. In the ISOL approach, an existing facility at Louvain-la-Neuve, Belgium, is aimed primarily at the study of astrophysically important reactions.

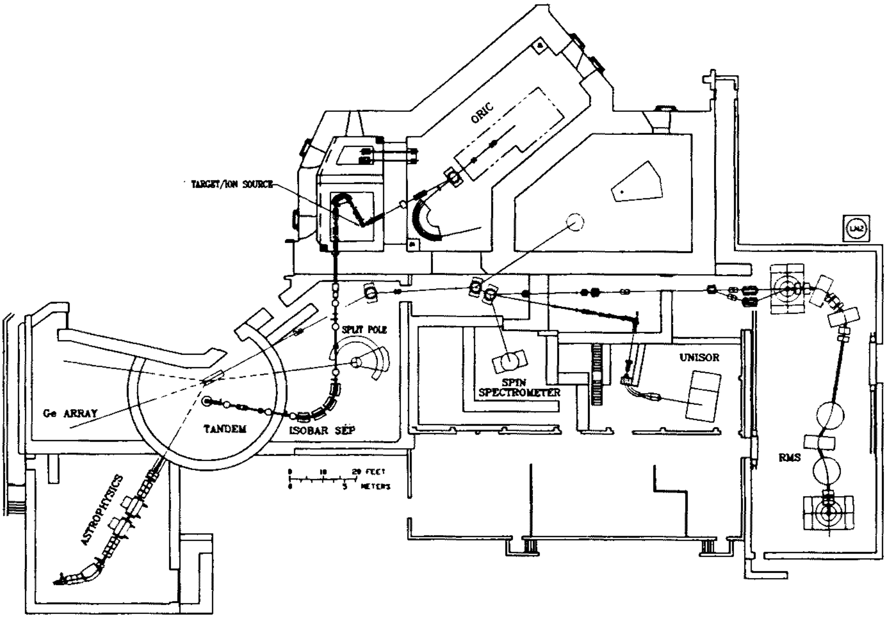

Fig. 5. Schematic diagram of the HRIBF based on the ORIC cyclotron as production accelerator and the Tandem Van de Graaf as post-accelerator. Two recoil separators, one for astrophysics and one for structure studies, are shown at left and right, respectively.

In North America, the ISOL HRIBF [8] at Oak Ridge is under construction (see Fig. 5). Protons, deuterons, ^{3}He and α particles from the ORIC K105 cyclotron will be used as production beams. The RNBs, mostly light and medium mass neutron deficient nuclei, are extracted from the ion source and mass analyzed in two stages prior to injection into the 25 MV Holifield tandem accelerator. Final energies will be between 0.2 and 20 MeV/A for $A \sim 10$ and 0.5 to 5 MeV/A for $A \sim 90$. This facility is nearing completion and initial beams such as ^{17}F and ^{63,64}Ga are expected in 1995.

A regular research program in both nuclear structure and astrophysics should start in 1996. The former work will exploit the new recoil separator (RMS) (Fig. 5, right) and an upgraded version of the Oak Ridge Ge array. The astrophysics program will use the (former) Daresbury recoil spectrometer (Fig. 5, lower left). Future plans entail the use of actinide targets to access neutron rich nuclei through the fission process, and, to approach ISL-like capabilities, a booster accelerator to give RNBs over the Coulomb barrier, and a higher energy primary accelerator to increase production.

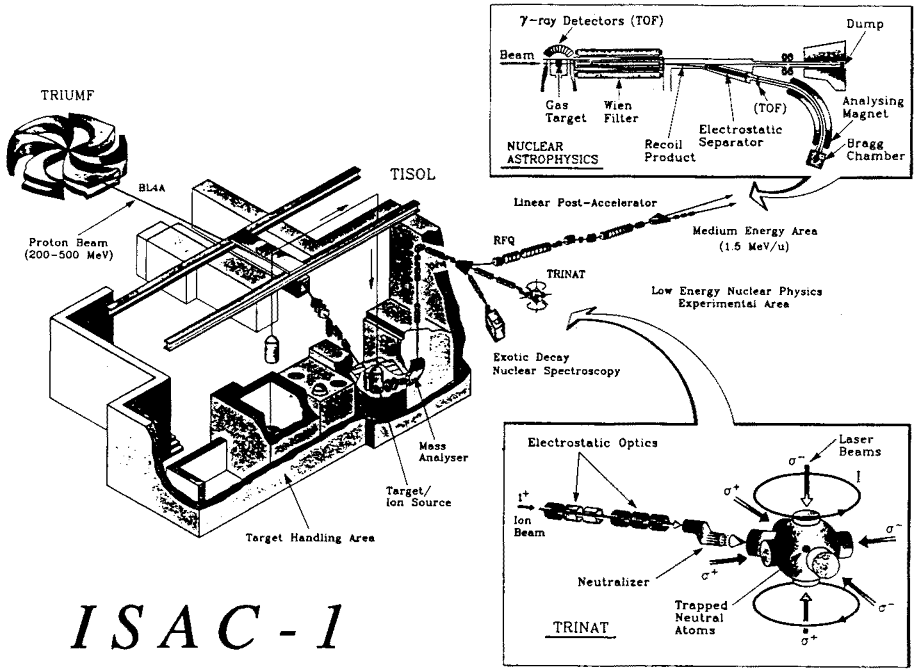

Fig. 6. Schematic diagram for the ISAC-1 facility based on the TRIUMF production accelerator and a linear post accelerator. Concepts for astrophysics and low-energy experimental areas are shown.

Another North American ISOL facility, ISAC-1, at TRIUMF [9] in Vancouver, Canada, has been funded for construction. A schematic design is shown in Fig. 6. ISAC-1 makes use of 200-500 MeV protons of up to 10 μA intensity (eventually up to $100 \mu A$) from the existing TRIUMF cyclotron driver accelerator and is aimed at both astrophysics studies and low-energy nuclear structure work with RNBs satisfying $A/q < 30$. Initially, an ISOL, thick target, device, similar to that at ISOLDE, will be built. Subsequently, an RFQ will be constructed to accelerate the RNBs to ~ 150 keV$/A$. Finally, a linear booster will complete the acceleration to ~ 1.5 MeV$/A$. Further upgrades to heavier ion species, multiple target stations, and higher energies are, of course, a future option and goal. In addition, the existing TISOL facility may continue to operate at TRIUMF. With the base provided by the powerful TRIUMF production accelerator and the experience gained at ISAC-1, the facility could be upgraded to one of ISL-type.

Projectile Fragmentation work in North America is centered at the NSCL at Michigan State University. This facility produces a wide variety of energetic (<200 MeV/A) RNBs. Heavy ion beams from the K1200 superconducting cyclotron fragment in a thin target and electromagnetic devices select specific fragments (A, Z) for subsequent use in secondary reactions. A very active program is underway. A proposed [10] upgrade (see Fig. 7) entails a coupling of the K500 and K1200 cyclotrons and the renovation of the separation system to produce significantly enhanced capabilities. As shown in Fig. 7, the upgrade will provide RNBs with higher energies and significantly higher intensities (often 3 orders of magnitude higher or more) than currently available.

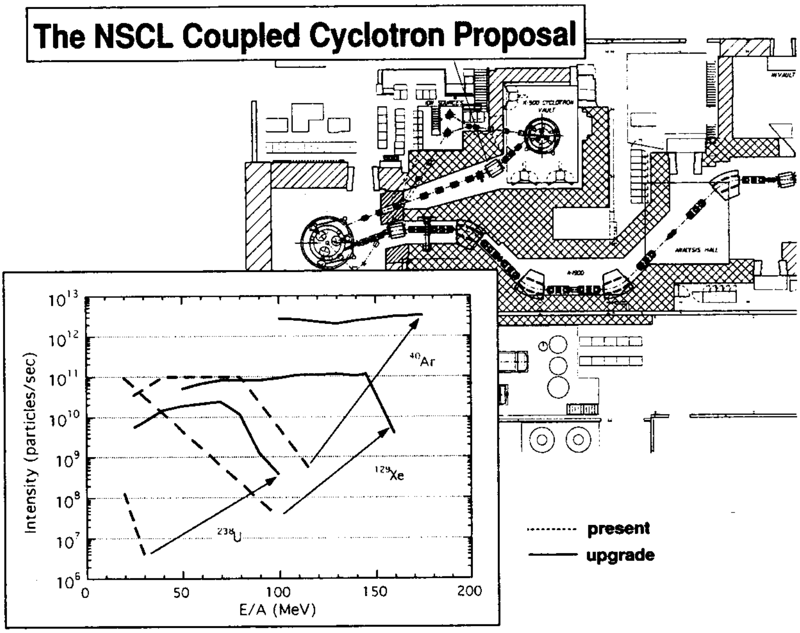

Fig. 7. Schematic layout of the Coupled Cyclotron Facility planned at MSU. The graph shows existing and upgraded intensities for selected ion species as a function of energy.

Argonne National Laboratory is developing a plan [11] for an ISL-like facility based on the existing ATLAS accelerator. A 215 MV primary linear accelerator can deliver beam currents of 1 mA(p), 0.5 mA (d), 0.25 pmA (^{4}He), and 0.08 pmA (^{12}C). A core idea involves the innovative concept of using the breakup of 200 MeV deuterons (for example, in a uranium target) to produce $\sim$ 0.1 pmA of 100 MeV neutrons which then bombard a second, thick ISOL target (*e.g.*, ^{238}U). This method has the advantage that energy loss and heat production in this second target is from the same nuclear collisions that can produce exotic nuclei. RNBs production rates for fission product nuclei should be comparable to those from higher energy proton beams. After ionization, extraction, and mass separation, these ions can be used directly in very low energy experiments (*e.g.*, with traps), accelerated in a system consisting of RFQ and superconducting cavities to $\sim$ 0.5–1 MeV/A for astrophysics or low-energy nuclear physics experiments, or can be directed to ATLAS for post-acceleration up to $\sim$ 15 MeV/A. The infrastructure of the ATLAS beam lines, the Fragment Mass Analyzer (FMA), and other experimental areas then provides an existing base for the experimental program.

RNB-related work is in progress at other North American laboratories as well. At Notre Dame, single nucleon transfer reactions, using Li beams from the FN tandem, have been used in a pioneering program that helped focus attention on the feasibility of using RNBs to initiate secondary reactions. A superconducting solenoid is used to collect the reaction products. At Los Alamos, R&D on a thin target — He jet production uses 800 MeV protons from LAMPF. At LBL, research on target design, safety, radioactivity handling, and RNB production rates, have provided much needed input into key technical issues for any future ISOL facility.

4. Conclusions

The field of RNBs offers exciting opportunities to study exotic nuclei exhibiting behavior unlike anything observed to date. Challenges to successful RNB science lie in the development of powerful accelerator facilities, highly efficient instruments, and simple new signatures of structure. In North America this research is poised at a critical juncture. In the recent US NSAC Long Range Plan (Interim Report) [12] the scientific merit of RNB research was described as “extremely compelling” and the main priority for new facility construction was given to RNB facilities, in particular to the immediate upgrade of the MSU facility and, when RHIC construction is substantially completed, to the design and construction of an advanced, cost-effective, broad-range ISOL facility.

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