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Radioactive Nuclear Beams and the North American IsoSpin Laboratory (ISL) Initiative

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Abstract

Radioactive nuclear beams (RNBs) offer exciting new research opportunities in fields as diverse as nuclear structure, nuclear reactions, astrophysics, atomic, materials, and applied science. Their realization in new accelerator complexes also offers important technical challenges. Some of the nuclear physics possibilities afforded by RNBs, with emphasis on low spin nuclear structure, are discussed, accompanied by an outline of the ISL initiative and its status.

1. INTRODUCTION

Nuclear physics research to date has of necessity focused primarily on nuclei along and near the valley of β stability. The principal exceptions to this are some moderately proton-rich nuclei which are accessible with heavy ion fusion evaporation reactions and some moderately neutron-rich nuclei obtained in the spontaneous or induced fission of actinide nuclei. While an impressive picture of nuclear structure has emerged from decades of study in this valley, the vistas provided are rather limited. The advent of RNBs, both as realized in current or nearly operational facilities, and as envisioned in more ambitious future efforts, promises to expand these vistas enormously, enlarging our horizons on the nuclear landscape and offering vast new opportunities for front-line research.

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2. RATIONALE FOR RNBs: UNIQUE ASPECTS AFFORDING UNIQUE OPPORTUNITIES

2.1. Astrophysics, Nuclear Reactions, and Atomic and Applied Science

There are many reasons why RNBs are an exciting new field. It is important to understand these both qualitatively and specifically so that the

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promise of this emerging field of study can be honestly evaluated and fully appreciated. Momentarily, we will address this issue as regards nuclear structure, but we first make brief comments on other research fields that will benefit from RNBs.

There are two critical issues in nuclear astrophysics, namely the energy producing mechanisms in stellar sources and the nucleosynthetic processes that lead to the observed elemental and isotopic abundances. Of course, these are not unrelated but at times focus somewhat differently. The former centers largely on light nuclei and involves issues as diverse as big bang cosmology in the initial period of our observed universe or the mechanisms of stellar energy production and evolution in main sequence stars. To understand these processes it is necessary to know a large number of reaction cross sections and their temperature (energy) dependence. Many of these are inaccessible, or largely so, in the laboratory of stable nuclides but can be studied directly with RNBs as stellar reactions take place on time scales and environments that enable unstable nuclei to play key roles. The nucleosynthesis, primarily of light nuclei, also takes place in such environments, lending critical importance to the study of a number of particular reactions, for example in the Li region and those involved in breakout paths from the CNO cycle. Nucleosynthesis, especially of heavy elements, takes place in explosive stellar events, presumably of supernova type. Here, the paths by which successively heavier species are produced largely occur off the valley of stability, as for example in the r-process which accounts for most of the production of nuclei above mass 80 and probably above iron. Nucleosynthesis is of interest for two reasons--the obvious one of understanding the origin of the elements but also because a quantitative knowledge of the process may help pin down the nature of the explosive stellar events in which it occurs. Interestingly, even though the nucleosynthetic process itself entails only a small fraction of the energy output of such events, it provides constraints on them (e.g., neutron flux, temperature, time duration). Nucleosynthesis calculations invariably involve both nuclear input and stellar input. Since this process occurs off stability, the former are usually based on partial data only, on extrapolations, and on phenomenological and microscopic models. All this lends considerable uncertainty. However, *if* the nuclear parameters could be determined in the laboratory with RNBs, then one major source of uncertainty is eliminated and it should be possible to better establish the stellar parameters. Therefore, it may eventually be that a relatively minor aspect (from the stellar point of view) of these explosive events when studied in the laboratory will be a leveraged tool to determine the origin, nature and evolution of the most spectacular stellar events we know of, events which can, over short time periods, produce in a single object, an energy output comparable to that of an entire galaxy.

The use of RNBs in nuclear reactions is another area of opportunity. First, as already mentioned, specific nuclear reaction studies (at low energy) are of critical importance in astrophysics. However, special features unique to nuclei

(especially neutron-rich nuclei) far from stability lead to new processes that make these reactions fascinating from their own point of view. The great neutron excess in some RNBs implies a large spatial extent to their wave functions, which extend far beyond the radii normally encountered in stable nuclei of the same mass. Moreover, these outermost nucleons are naturally rather weakly bound. Thus there emerges possibilities such as the study of reactions at extremely large impact parameters, unlike any heretofore available. At these distances the nuclear force is weak and the reaction mechanisms may well be different. In addition, the ratio of nuclear to Coulomb effects may be altered relative to reactions with stable species. Further, the outer reaches of these nuclei are dominated by neutrons and hence one has the intriguing possibility of studying reactions involving nearly pure neutron matter. Already reactions with "neutron halo" nuclei such as ${}^{11}\text{Li}$ have produced exciting results [1]. Of course, this particular subject need not be discussed by the present author as the pioneering work in this field is well known here. Another feature of the large radial extent of the nuclear wave functions and the weak binding of the outermost nucleons is the possibility to study nuclear (especially neutron) flow phenomena that will be a unique capability with RNBs. This same weak binding also often leads to exothermic reactions with large positive Q values that offer a number of interesting features [2]. This can facilitate detection of ejectile nuclei. It also enables transfer to be studied down to the Coulomb barrier or lower, where threshold effects can be investigated. Transfer reactions with inverse kinematics, that mimic the familiar reactions (d,p) , (p,d) , $(d,{}^3\text{He})$, and $({}^3\text{He},d)$, on nuclei near closed shells will be important probes of shell structure. Finally, high positive Q values also enhance the population of higher lying states and states of higher angular momentum. In this regard, isomeric beams have even higher Q values and, often having higher spin, further aid in populating higher spin final states. Of course, some nuclear reaction work with RNBs requires higher beam energies than likely to be available with the ISL and therefore falls in the province of facilities that produce these beams by projectile fragmentation.

The applications of RNBs in atomic and materials science are both deep and widespread as well as beyond the competence of this author to adequately describe. They involve such fascinating opportunities as the capability to selectively dope materials, at specific depths, with ions that have a pre-selected time dependence to their radiations and their chemical transformations. Such doping can be achieved at much lower fluxes than is common today, increasing the likelihood that a given dopant atom will traverse a previously "untainted" path and will come to occupy a previously undisturbed site. Chemical and lattice changes at specific sites can be studied. Moreover, since these unstable implanted nuclei signal their own decay by conversion electrons that are element specific they act as their own monitors of change. Diffusion processes in solids can be studied [3] by implanting RNBs and using their decay as a clock, using slicing and counting techniques, to probe diffusion rates to the

interior. Surface physics can be studied with low energy RNBs. Surface diffusion sites can be studied by "soft-landing" decelerated RNBs on various surfaces. Semiconductor devices can be fabricated, or modified, by the deposition of layers of specific materials at specified depths internal to the device. Mössbauer studies will find new applications as will hyperfine interaction research, polarization phenomena and many other, often exotic, applications of the ability to implant host environments with ions almost freely "tunable" as to half-life, decay energy, atomic binding energy and flux.

The above comments only touch on a few of the applications of RNBs in fields beyond nuclear structure. Some of these are discussed in more detail in the IsoSpin Laboratory Report [4] and in other surveys of RNB science, which the reader is urged to study. Here, our focus will be nuclear structure studies with RNBs, to which we now turn.

2.2. Nuclear Structure

The essence of why RNBs offer a significant opportunity for nuclear structure studies can perhaps be phrased simply as follows. The nucleus is a many-body system but, for reasons we shall see momentarily, it is one in which the structure is primarily determined by a very few nucleons--the outermost or valence nucleons--and their interactions--primarily the residual proton-neutron interaction. Largely, this is a consequence of the Pauli Principle, the relatively low angular momentum of nucleonic orbits, the primarily attractive, short-range nature of the nuclear force and its relative weakness compared to nucleonic binding energies.

The Pauli Principle limits the number of nucleons of given type (protons or neutrons) in a given orbit, of angular momentum j , to $2j+1$, which is therefore the "degeneracy" of the orbit. This, and the relatively low j values ($j \leq 15/2$ for virtually all orbits available to normally accessible nuclei) in turn forces additional nucleons to occupy successively new orbits, for relatively small changes in N or Z . These orbits have different shell model quantum numbers n, l, j , hence different radii and different radial and angular wave functions. Nucleons occupying the spherical filled closed shells provide the bulk of the potential in which all the nucleons orbit but play little role in the interactions that determine nuclear structure or lead to nucleon excitations, on account of the relative weakness of the nucleonic interactions which are generally unable to excite deeply bound nucleons. Therefore, the principal residual interactions that do determine structure are amongst the outermost, primarily valence, nucleons, and predominantly between valence protons and neutrons. (It is for this reason, for example, that the $N_p N_n$ scheme [5] is successful.) Since the residual interaction is predominantly short range, and attractive, these critical valence interactions that determine correlations, collectivity and structure are orbit dependent. The Pauli Principle (and low j values) then inevitably lead to important differences in residual interactions as N and Z change. Therefore, access to new realms of N and Z , with RNBs, and hence access to both new

orbits and new *combinations* of occupied (especially proton and neutron) orbits, is expected to lead to new shapes, new phenomenon, new types of nuclear structure, and new collective modes and phase transitions, in addition, of course, to new examples of familiar ones and a greatly expanded phenomenology or systematics of their occurrence and properties.

Thus we note an important point: the novelty of RNBs for nuclear structure lies very little in the fact that they will provide access to vast numbers of new nuclei per se but rather to the new *features* and *phenomenon* that these nuclei will undoubtedly exhibit. RNBs are not a "numbers game" but an avenue to observe new nuclear phenomena. Study of carefully selected nuclides with RNBs is likely a far better tack than a "shotgun" approach that seeks to study as many of these nuclei as possible. This is not meant to denigrate the interest attached to the discovery and study of many new nuclei but rather to focus attention on the opportunities that attend the study of specific nuclei and specific phenomena and to encourage the search for the most attractive of these and to plan experiments with these ideas, and the constraints they impose, in mind. "Survey" experiments will doubtless yield abundant benefits and surprises and are a necessary component of a research program that is entering new territory. But, careful theoretical work and experimental planning to focus on the physics issues that are likely to be most fruitful will pay enormous dividends.

Many of these specific items are outlined in the ISL report [4], and there is no need to repeat them here. However, it is perhaps useful to summarize them under a few key rubrics.

- Few-body quantal aspects

As noted, this is perhaps the key reason why RNBs offer new interest in nuclear structure. This facet has many particular specifics that could be cited. The access provided by RNBs to long iso-chains of nuclei will be invaluable in elucidating the evolution of nuclear structure and in isolating the dependence of that evolution on neutrons and protons separately.

A fortunate aspect of the study of such chains of nuclei is that the easiest-to-measure observables (e.g., in even-even nuclei, $E(2_1^+)$, $E(4_1^+)/E(2_1^+)$, $B(E2:0_1^+ \rightarrow 2_1^+)$ values and so on) are the most telling structural signatures. If additional data can be obtained, such as $E(2_2^+)$, $E(0_2^+)$, $E(3_1^+)$, $E(4_2^+)$, and $E2$ branching ratios from these states, rather subtle tests of phonon models and of Pauli blocking and fragmentation effects in multi-phonon states are possible in spherical nuclei. In deformed nuclei, the same information gives details on components of the shapes such as γ -asymmetry and its softness or rigidity.

One particular and little-known aspect of $B(E2:0_1^+ \rightarrow 2_1^+)$ values is interesting to note. In valence models of nuclear structure, $B(E2:0_1^+ \rightarrow 2_1^+)$ valences are proportional to $(e_p N_p + e_n N_n)$ where N_p and N_n are the numbers (or "effective" numbers in some models) of valence protons and neutrons and e_p and e_n are proton and neutron effective charges. We can thus write

Figure 1. Illustration of the application of eq. 2 to extract the effective charges e_p and e_n . Based on ref. 6.

$$M(E2) = \sqrt{B(E2:0_1^+ \rightarrow 2_1^+)} = f(N) (e_p N_p + e_n N_n) \quad (1)$$

The constant of proportionality, called $f(N)$, where $N = N_p + N_n$, of course is structure dependent. We can obtain e_p and e_n by rewriting this as

$$T = \frac{M(E2)}{f(N)N_n} = e_n + e_p N_p/N_n \quad (2)$$

If $M(E2)$ is measured for a series of isotopes or isotones--or indeed any other iso-chain such as iso- N or iso- $N_p N_n$ --and the left side of eq. 2 is plotted against N_p/N_n , a straight line should result, with slope e_p and intercept e_n . An example is shown in fig. 1 for a series of Pd nuclei, using, for purposes of illustration, the form of $f(N)$ appropriate to O(6) nuclei. (The particular form is not important in this case.).

The fascinating point arises when it is noted that the detailed expressions for $f(N)$ [e.g., $(2N+3)/5N$ for rotational or SU(3) nuclei in the IBA] are almost always slowly varying with N except very close to closed shells in vibrational nuclei. Thus we can approximate $f(N)$ as constant, and obtain [6] from eq. 1

$$\frac{\partial M(E2)}{\partial N_p} \propto e_p \quad \frac{\partial M(E2)}{\partial N_p} \propto e_n \quad (3)$$

Thus, effective charges take on a new meaning, as directly related (with known proportionality factors that are only omitted in eq. 3 for simplicity of presentation in this overview) to the derivatives of $M(E2)$ with proton and neutron numbers, that is, to a good measure, they are proportional to the *rates of change* of mean field *collectivity*. We have thus, by a simple valence space approach, isolated the *separate* proton and neutron contributions to collectivity. Analyses such as this confirm, for example, the role of neutrons in the $A = 100$ and 150 regions in polarizing proton shell structure.

This program can be carried out for many nuclei, but there are key gaps in the data, such as in the Pb region and, generally, far from stability. Fortunately, the measurement of $B(E2:0_1^+ \rightarrow 2_1^+)$ values with RNBs is very simple. They can be done in inverse kinematics by bombarding light mass targets with RNBs of the nucleus of interest. For modest RNB beam energies of, say 2-3 MeV/A, and 10^6 p/s, one could easily expect to measure one $B(E2)$ value per day. The forward focusing of the reaction has many advantages. One key problem in many RNB reactions is background from the radioactive decay of the beam. Here, however, with, say, RNBs of mass 100-200 on carbon targets, all the scattering is kinematically focussed into a cone subtending only a few degrees in the laboratory. Thus, a flared beam tube immediately after the target region can eliminate virtually all beam radioactivity induced by target scattering. (Upstream slit scattering and beam penumbra remain as concerns.) It might even be possible to do such experiments with Ge or NaI detectors in *singles* mode.

There are many other aspects of iso-chain studies that are beyond the scope of this report. One example concerns the $N_p N_n$ scheme in which it is often possible to predict the properties of unknown nuclei far from stability by a very reliable process of *interpolation* rather than *extrapolation*. This provides key tests for new measurements. Deviations from these predictions are directly related to the effective values of N_p and N_n and hence rather directly reflect shell structure and the existence and evolution of shell gaps. The role of neutrons in modulating proton shell structure, due to the p-n interaction, mentioned above for the $A = 100$ and 150 regions, can be probed in entirely new phase transitional portions of the nuclear chart.

Axial asymmetry is an important concept in nuclear structure. It can be deduced by standard data from $B(E2)$ ratios involving the γ band. But, at least qualitatively, a solid clue to axial asymmetry can be gleaned more simply from $B(E2:2_1^+ \rightarrow 0_1^+)$ values and $R_{4/2} = E(4_1^+)/E(2_1^+)$ values alone. This is seen in fig. 2 which plots these $B(E2)$ values (divided by A) against $R_{4/2}$. For $R_{4/2}$ values above 2.5 the plot is bi-valued. The $B(E2)$ values along the upper path correspond to nuclei in a spherical vibrational to symmetric quadrupole deformed transition region whereas those along the lower fork are nuclei with large γ values between 0° and 30° .

Recent studies [8] have shown that such asymmetry is virtually always of the γ -soft variety at low spin. Whether this is a peculiarity of nuclei near

Figure 2. Plot of measured $B(E2; 0_1^+ \rightarrow 2_1^+)$ values [7], in W.u., normalized by mass number, against experimental values of $R = E(4_1^+)/E(2_1^+)$.

stability or a fundamental feature of nuclear structure can be addressed by relatively simple experiments far from stability. The only information needed to test for γ -rigidity is the energy of the first 2^+ state (for normalization) and the energies, $E(2_\gamma^+)$, $E(3_\gamma^+)$, $E(4_\gamma^+)$ within the quasi- γ -band. In fact, absolute excitation energies are not needed, but rather only the transition energies $E(4_\gamma^+) - E(3_\gamma^+)$ and $E(3_\gamma^+) - E(2_\gamma^+)$.

Another aspect of this is the possibility that asymmetry at high spins may be rigid. If so, then there is presumably a γ -soft- γ -rigid phase transition at intermediate spins. One of the most appealing aspects of RNBs is the ability, using neutron-rich (stable) targets and neutron-rich RNBs, to study high spin states of nuclei at or near *stability* where the low spin structure is already established. In these nuclei, where the full nuclear range of angular momentum can be accessed, such spin dependent phase transitions can be studied for the first time.

Figure 3. Illustration of the concept of Quantal Localization for a $j = 17/2$ orbit. Shown are the semi-classical angles relative to the symmetry axis of the orbital planes of particles with different K quantum number.

Lastly, under this topic, it should be possible to map out the residual valence p-n interaction much more thoroughly by exploiting the low j values of typical nuclear orbits and the Pauli Principle to sequence through different single particle states of one type of nucleon for a given number of the other.

- Exotic orbits

Another opportunity for RNBs is the access they will provide to exotic nuclear orbits. Just to briefly mention a few appealing possibilities, there is hyperdeformation, which is predicted to occur in some relatively neutron-rich stable nuclei that will become accessible at high spin (see the point made just above); "banana" shapes corresponding to Y_3 modes; $\Delta l = 5$ nodes which, at least as collective excitations, are unavailable now since the relevant orbit combinations near stability, $s_{1/2} - h_{11/2}$ and $p_{3/2} - i_{13/2}$, do not have sufficient degeneracy in the low spin member to generate enough collectivity; and examples of quantal localization.

This latter is a special phenomenon which can perhaps be observed at both high and low spin. The idea is illustrated in fig. 3. The point is simply that, in a deformed field, a given single particle orbit splits into its substates, according to their Ω or K quantum number, and that the "classical" angle of the orbit plane relative to the nuclear equator is given by

$$\theta = \sin^{-1} \frac{K}{j} \quad (4)$$

From the properties of the sine, as illustrated in the figure, the spacing in angle of these orbits is K dependent. In particular, for high j and low K , the angles are very small and *close together*. Since the quantum mechanical wave function cloud for a given K must be largely contained within the angular region bordered by the adjacent K values, these high j , low K orbits are extremely localized in angular space. For $j = 17/2$, $K = 1/2$, the expected "range" of θ is on the order of $\pm 5^\circ$. This incredible localization should produce exotic correlations and collective manifestations when these orbits are populated with neutron-rich RNBs. Extremely large p-n interactions may ensue if protons and neutrons are placed simultaneously in high- j , low- K orbits since the overlap will be near unity. At high spin these effects, or at least the occupation of these orbits, should be enhanced by Coriolis effects.

- Exotic matter distribution

Currently, the most fascinating possibility here lies in the concept of "halo nuclei". As the subject is very well known, here the discussion can be very brief. The idea of (neutron) halo nuclei is that if species that having a sufficient neutron excess can be produced, then the outer reaches of the nucleonic density distribution may consist almost solely of pure neutron matter, forming a shell or halo about the "core" (which has a more equal distribution of protons and neutrons). The best studied, and most famous case [1], is of course ^{11}Li , which has caught the excitement of the worldwide RNB community through a series of fascinating experimental studies and complementary theoretical interpretations. This nucleus has been interpreted in terms of a ^9Li core surrounded by a halo of 2 neutrons extending to large radii. The nucleonic density distribution of ^{11}Li is illustrated in fig. 4 which shows that a) the matter distribution indeed extends to enormous radii, and b) that, in these outer reaches, it is nearly-pure, low-density neutron matter.

These nuclei provide an exotic and unique nuclear laboratory. We shall just mention a few possibilities that arise. Halo nuclei offer the opportunity to study if neutron matter (e.g., a di-neutron) is bound, or nearly so, and to study thereby certain aspects of the nuclear equation of state. One can study if there are correlations in the halo neutron distributions (already the subject of current study). One can ask whether the β decay of ^{11}Li is that of a di-neutron. Reactions induced by halo nuclei may occur at very large radii that are likely to proceed by neutron flow mechanisms that transfer "chunks" of isospin.

Figure 4. Calculated proton and neutron radial distributions for ^{11}Li . Based on ref. 9.

Coulomb dissociation of the weakly bound neutrons is another area of study. Finally, such nuclei may have low-lying mini-giant dipole resonances in which the halo neutrons oscillate against the core. If such modes are important they may modify astrophysical r -processes by changing (n,γ) cross sections. Another fascinating possibility is the study of medium effects on the strong force since the halo region provides a low density form of nuclear matter intermediate between the two known forms, bound nuclei and free nucleons. Lastly, and perhaps most importantly for the long term future, is the search for other, especially heavier, examples of halo nuclei or related structures.

- Special nuclear regions

RNBs, of course, provide entry to regions of the nuclear chart not otherwise accessible. Some of these are critical to nuclear structure studies. One of them is naturally ^{100}Sn and its neighbors with one more or less proton or neutron. This region will provide an initial test of the shell model and of

residual interactions. If ^{100}Sn is doubly magic, as expected, a major cornerstone of that model is confirmed. If it is not, then our understanding of the evolution of single particle states as a result of like and unlike nucleon-nucleon residual interactions (in particular the monopole component of the p-n interaction) is seriously shaken and a major challenge to microscopic theory is issued. In either case, study of single particle energies in the neighboring nuclei will be critical.

Related to the structure of ^{100}Sn is the extension of the $N = Z$ line beyond ^{84}Mo . $N = Z$ nuclei are of interest because (if the proton and neutron single-particle energies are similar) the Pauli Principle leads to special spatial symmetry aspects that enhance the short-range attractive p-n residual interaction, often dramatically. In light nuclei, this leads, in fact, to singularities [10] in p-n interaction strengths. Near ^{80}Zr , which could have been expected to be at least nearly doubly magic, it leads to a strongly deformed ground state. The evolution of this structure through ^{84}Mo to ^{88}Ru , ^{92}Pd , ^{96}Cd , and ultimately to ^{100}Sn , is perhaps one of the most enticing goals of a second-generation ISOL RNB facility such as the ISL. The most appropriate fusion evaporation reactions in this endeavor will be multi-nucleon evaporation. For the study of low spin final states, (RNB, pn) reactions may be useful. For higher spins, higher bombarding energies are needed. The preference for proton emission in the proton-rich intermediate nuclei suggests the use of reactions such as (RNB, 3pn).

Besides the $A = 80\text{-}100$ region, RNBs will give access to new phase transitional regions. It is in these regions that the few-body quantal aspect of the nucleus is displayed most graphically: as opposed to infinite body systems, nuclear phase transitions are not smooth. They show fluctuations due to finite number effects and are perhaps the only physical laboratory where such basic quantum mechanical issues can be studied extensively.

Of course, historically, the most sought after new region that may possibly be finally reached with RNBs is an island of superheavy nuclei in which the issues of their stability and properties provide critical tests of microscopic theories, of the shell model, and residual interaction theory. Conversely, the breakup of such nuclides might give enhanced access to very stable daughter nuclei such as ^{132}Sn .

- Special states

The high decay energies of unstable nuclei near the drip lines can give access to a wide range of special states and fundamental issues. There may be new opportunities to study cluster decay, in which medium-mass intact nuclei (such as ^{14}C , ^{24}Mg , etc.) are emitted. Of course, delayed multi-nucleon (n-proton or m-neutron) radioactivity can also be studied. Access to highly excited states, which then decay to low lying states, opens up the full panoply of level structure from truly chaotic to highly ordered and should allow one to probe

how chaos and order are related to the underlying structure, and which quantum numbers are most resistant to chaotic mixing.

3. THE ISL INITIATIVE

The above pages only touch on a few of the advantages and uses of RNBs but should serve to give a feeling for the opportunities proffered. Other aspects are discussed in a complementary article in these proceedings by J. Garrett [11], who focuses more pointedly on astrophysics issues, high spin states, and the proton rich nuclei that will be accessible with the Oak Ridge RIB facility. Here we briefly discuss the ISL initiative and its status.

Interest in RNBs in North America blossomed in the late 1980s and since then. As an outcome of the Los Alamos Workshop, a North American Steering Committee for the IsoSpin Laboratory was formed to develop and assess the physics case for an intense, dedicated RNB facility, to analyze the experimental needs of RNB experiments leading to a set of output specifications for such a facility, to discuss and assess possible designs, as well as to promote communication within the embryonic RNB community, to organize an ISL Users Group, foster R&D, and encourage the construction and use of first-generation RNB ISOL facilities such as RIB at Oak Ridge.

This charge led to the issuance of the ISL White Paper [4] (WP) "The IsoSpin Laboratory (ISL): Research Opportunities with Radioactive Nuclear Beams", which included a detailed discussion of many aspects of RNB science along with tentative specifications for the ISL and one possible solution to its design, labelled a "BenchMark Facility (BMF)". In developing the ISL concept, the following key characteristics were identified. The energy range should extend from virtually nil (for some atomic and astrophysics uses) to about 10 MeV/A and all masses up to $A = 240$ should be available. Of course, some studies, such as in inverse kinematics single nucleon transfer reactions, may benefit from higher energies. The facility should provide RNBs with intensities up to 10^{11} part/s. Beam resolution, timing characteristics, and emittances were also discussed and both "acceptable" and "desirable" criteria specified.

Though not at all intended to be the ultimate form of the ISL, the BMF gives a starting point and a well-defined design that can be used to calculate projected RNB intensities. The BMF envisions a production beam of 100 μ A of 500-1000 MeV protons (or possibly other light ions) impinging on a thick (or, perhaps, thin, in special applications) targets (roughly 1 mole), followed by an ion source, isobar separator, and low beta acceleration stages leading to a post accelerator producing beams up to 10 MeV/A.

The intensities resulting from this design were shown color-coded in fig. 1 of the ISL White Paper and are shown with graded shading in black and white in fig. 5 here. It is essential to refer to the full text of the WP to understand the assumptions and caveats involved in obtaining these intensities. Most important to note is that they do *not* include any losses due to decay. For many

Of course, the ISL White Paper is only a starting point for further discussion and a guide to some solutions to achieving the scientific aims. The latter themselves will evolve with time, and some science will require capabilities beyond those listed. The best ultimate choices, from a cost/benefit point of view, taking the scientific community's needs and interests into account, and the relation between scientific productivity and design, complexity and costs, are a topic of active current discussion and will hopefully be resolved in the near future.

A number of technical issues face the development of the ISL. Many of these center on the target/ion source complex where radiation hardening, beam heating, robotics and shielding, ionization schemes and efficiencies and many other topics need to be addressed. Others relate to the low energy acceleration stages (RFQs). The design of isobaric separators needs to be determined, although it is not expected that serious problems will arise here. Finally, the issues of experimental instrumentation and detection devices are complex and require much work since these devices will have to operate in an environment involving the decay of the RNBs themselves.

Much work has already been carried out on these topics. Some involves study of various existing options. Others will involve new studies and R&D efforts. Recently all these issues were aired in great detail by an international assembly of experts at the Workshop on the Production and Use of Intense Radioactive Beams at the ISL, held at Oak Ridge, October 7-10, 1992. One key outcome of this Workshop, whose Proceedings should be available early in 1993, is the establishment of four Working Groups (WG), which will maintain the initiatives and momentum begun with this Workshop. These four WGs are summarized in Table 1. The convenors listed there are members of the ISL Steering Committee who will act as initial organizers of these groups. Scientists interested in participating in this active R&D area, pointing toward the development of the optimal choices for the ISL, should contact the relevant Convenor as soon as possible.

Table 1
ISL Technical Working Groups

Working Group	Convenor
Targets	Dave Vieira (LAMPF)
Ion Sources	John D'Auria (TRIUMF)
Front-end RNB Acceleration Systems	Mike Nitschke (LBL)
Experimental Instrumentation & Detection Equipment	Cary Davids (ANL)

It is hoped that this brief overview of the scientific opportunities provided by RNBs, of the ISL concept and current specifications, possible design ideas, and recent developments will provide an up-to-date overview of the ISL initiative.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

- 1 I. Tanihata, Nucl. Phys. A520 (1990) 411c and refs. therein.
- 2 F. Becchetti, Workshop on the Production and Use of Intense Radioactive Beams at the ISL, Oak Ridge, Oct. 7-10, 1992, to be published.
- 3 H. Haas, Workshop on the Production and Use of Intense Radioactive Beams at the ISL, Oak Ridge, Oct. 7-10, 1992, to be published.
- 4 R.F. Casten *et al.*, The IsoSpin Laboratory (ISL): Research Opportunities with Radioactive Nuclear Beams, Los Alamos Report LALP 91-51.
- 5 R.F. Casten, Phys. Lett. 152B (1985) 145.
- 6 R.F. Casten and A. Wolf, Phys. Lett. 280B (1992) 1.
- 7 S. Raman, At. Data Nucl. Data Tables 36 (1987) 1.
- 8 N.V. Zamfir and R.F. Casten, Phys. Lett. 260B (1991) 265.
- 9 G.F. Bertsch, B.A. Brown, and H. Sagawa, Phys. Rev. C39 (1989) 1154.
- 10 D.S. Brenner *et al.*, Phys. Lett. 243B (1990) 1.
- 11 J.G. Garrett, these Proceedings.

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