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## Future Physics with a Proposed Radioactive Beam Facility in the U.S.

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# FUTURE PHYSICS WITH A PROPOSED RADIOACTIVE BEAM FACILITY IN THE UNITED STATES

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# FUTURE PHYSICS WITH A PROPOSED RADIOACTIVE BEAM FACILITY IN THE UNITED STATES

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A brief overview of the physics at a proposed radioactive beam facility or ISOSPIN LABORATORY is presented. Its impact on future directions in nuclear structure, nuclei far from stability, reaction physics, nuclear astrophysics, and several applied fields is pointed out. Of particular interest are neutron rich beams. Radioactive beams with energies on the order of ~10 MeV/nucleon or less are emphasized rather than the more energetic beams obtainable through projectile fragmentation. A concept of a high-intensity radioactive beam facility based on the post-acceleration of radioactive ions from an isotope-separator linked to a high-current, high-energy, light ion accelerator is discussed.

## 1. INTRODUCTION

It is a general observation that the depth of our understanding of physical phenomena can often be tested by applying our theories to extreme conditions. This is particularly true for the understanding of matter. While classical descriptions often suffice for the characterization of rarefied forms of matter, quantum mechanical rules have to be introduced on the molecular, nuclear, and subnuclear levels. Among the parameters employed for the description of matter are pressure, temperature, and density, supplemented on the microscopic scale by suitable quantum numbers. Sizable intellectual and economic effects are made to create nuclear matter at high density, pressure and temperature and to explore ideas that test the electro-weak, strong, and gravitational forces in a unified scheme.

Due to the fundamental nature of these questions they appeal to a wide scientific as well as the general community. It should, however, be pointed out that at high temperatures and densities many subtle phenomena are lost. While it is, for example, true that energies in the hundred GeV range are necessary to study the properties of the W boson, many complexities of the weak force can be examined at modest energies in β-decay processes. This underlines the complementary nature of

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high energy and nuclear physics to which in recent years one may want to add astrophysics and cosmology. A characteristic difference between high energy and nuclear physics is that in the latter an equilibration of the relevant degrees of freedom of the system (i.e., the nucleus) can be achieved while the former is dominated by transition phenomena (i.e., one has to find out what is happening while the nucleus is being blown apart). One of the parameters of nuclear matter that can be kept constant at modest temperatures and for sufficiently long time is the neutron to proton ratio, i.e., the isospin which, together with spin and temperature, constitutes three dimensions in which many nuclear phenomena can be characterized. At present the obtainable N/Z ratios are restricted to values that can be obtained through the combination of stable targets and projectiles in nuclear reactions. Considering that there are about 265 stable nuclei while the number of radioactive but particle-stable nuclei is estimated to be about 6000, a much larger isospin range could be explored if radioactive beams (and/or targets) of sufficient intensity were available. It was therefore proposed[1] to build an ISOSPIN LABORATORY in the U.S. specifically dedicated to the acceleration of radioactive beams and their use in nuclear and astrophysics and in the atomic and material sciences. A series of workshops has been held since 1981 in which Radioactive Nuclear Beams (RNBs) comprised the central topic. Most recently the "First International Conference on Radioactive Nuclear Beams" was convened in Berkeley[2] and a "Workshop on the Science of Intense Radioactive Ion Beams" was held at Los Alamos[3]. A large part of the physics reported here was discussed in these meetings, and only a brief summary will be attempted in this contribution. This summary is more general rather than specific and to some extent, biased by the personal interests of the author.

For a more objective account and the proper credits for many of the new ideas in isospin physics, the proceedings[2,3] should be consulted.

## 2. NUCLEAR STRUCTURE

One of the most fascinating aspects of isospin physics is the exploration of the boundaries of nuclear matter stability. In this endeavor RNBs may become similar in importance to the advent of heavy ion beams in the 1960's by enabling us to climb further out of the "valley of familiarity" toward the particle drip lines and the presumed (!) ultimate domain of fission instability. In the region of large isospin, which effectively means large neutron excess, one of the emerging consequences of increased isospin "pressure" will be a diffuse neutron skin or "halo" whose thickness will be determined by the relative stability of neutron matter. The closer neutron matter is to being stable, the thicker such a skin will be. The result could be two nearly distinct phases: a normal nuclear matter phase in the center, surrounded by a second phase of relatively pure neutron matter. One could also envision the existence of neutron-rich cores in heavier nuclei[4], resulting from a lower central density of protons, due to the Coulomb repulsion. Such a core would tend to reduce the bulk symmetry energy, as well as the Coulomb energy, and might occur instead of, or in addition to, the neutron skin. Even if this neutron-rich core is not stable, a low lying isovector monopole oscillation could occur (where the protons move out radially as the neutrons move in), which might be measured in the $\gamma$-ray spectrum following fusion reactions. Adding angular momentum to such a nucleus could produce some really exotic effects. Several of these speculations are based on effects that have already been seen in very neutron rich, light nuclei like $^{11}$Li, $^{11}$Be, and $^{14}$Be, where the enlargement of the nuclear matter radius beyond the $A^{1/3}$ parameterization has been clearly observed[5]. This effect is expected for the last member of an isotopic sequence due to the small neutron binding energy (on the proton-rich side, a corresponding proton "halo" is not anticipated because of the Coulomb barrier). Related to the large neutron excess, a lowering of the energy of the Giant Dipole Resonance has been observed for $^{11}$Li [Ref. 6], which can be understood as a reduction in the restoring force that comes predominantly from the surface. The most surprizing fact, however, is that, thus far, all shell model and Hartree-Fock calculations have failed to predict the properties of these nuclei. Calculations using the best shell model codes show an almost factor 3 discrepancy between the calculated and measured half-life of $^{11}$Li [Ref. 7]. Questions to be addressed in the future are related to the possible deformation of these nuclei (which seems to be ruled out for $^{11}$Li from magnetic moment measurements[8]), their electromagnetic dissociation cross sections, the momentum distribution of the neutrons, and "nuclear Rydberg states." A more fundamental questions is, however, to which extent can one infer the properties of neutron matter from studies of nuclei near the neutron drip line. In the case of $^{11}$Li, for example, a $^{9}$Li core may be surrounded by an extended "halo" or "neutron cloud" consisting of neutron matter of very low density. One could ask specifically if it is possible to deduce from the measurement of these nuclei by how much n-matter is unbound. Information about the halo neutrons could be obtained from 2n correlation experiments, electromagnetic dissociation, transverse momentum measurements in high-energy collisions, and stripping and transfer reactions. Finally, near the n-drip line new exotic decay modes, like ground state 2n emission, may be observable.

The physics of these lightest nuclei has evolved into a microcosm in which a combination of nuclear structure and reactions studies, together with theory promises to be particularly fruitful. This comprises, however, only a small segment of nuclear structure research with RNBs, and only a few highlights of other topics will be mentioned here, with details to be found in the workshop[3] and conference proceedings[2].

The nuclear shell model is founded on the independent-particle quantum structure, and constitutes a reference framework on which many manifestations of single-particle and collective behavior are built. The "anchor points" of this framework are the doubly closed shell nuclei. With RNBs it will be possible to add a new set of such nuclei: ${}^{78}_{28}Ni_{50}$, ${}^{100}_{50}Sn_{50}$, and ${}^{132}_{50}Sn_{82}$ with expected properties similar to ${}^{208}_{82}Pb_{126}$; and to explore their single particle/hole structure in neighboring odd-proton and odd-neutron nuclei. A more ambitious goal will be the exploration of the anticipated shell structure in the super-heavy region that would test our understanding and the predictive power of the current microscopic/ macroscopic nuclear models. In high-spin research new regions of prolate and oblate super deformation, and perhaps hyperdeformation (axis ratio 3:1), may become accessible with RNBs. It is ironic that the best candidates for the latter two forms of deformation are stable nuclei (${}^{148}Sm$ and ${}^{168}Er$, respectively) that can, however, not be produced in the necessary high-spin states using only stable beams and targets. These, and many other nuclear structure studies will become possible with RNBs, and much of nuclear structure will be learned from nuclear reactions.

## 3. NUCLEAR REACTION PHYSICS

The complementary nature of nuclear reaction physics and nuclear structure was already apparent in the case of ${}^{11}Li$, where the mapping of the outer-neutron wavefunctions facilitates the understanding of the structure of ${}^{11}Li$ as well as its behavior in nuclear interactions and vice versa. Extended neutron wavefunctions could lead to the enhancement of subbarrier fusion processes and to the formation of cold compound nuclei with obvious implications, for example, for the synthesis of heavy and super-heavy elements. The basic idea is that the transfer of a valence neutron proceeds via tunneling at large nuclear distances, which acts as a doorway mechanism, that upon closer approach, for sufficient overlap of the nuclear potentials, changes into a "free-flow" process[9]. Depending on the binding energy of the least bound neutron, the internuclear distance at which the neutron flow sets in can lie significantly outside the distance at which strong absorption becomes significant[10]. The next steps are the formation of a neck followed by fusion. Radioactive beams in which the last neutron is bound by less than ~1 MeV should be particularly suited to explore this process. A related phenomenon is a predicted large enhancement of subbarrier fusion for certain radioactive beam/target combinations that can arise in the case of large positive Q-values for n-transfer[11].

A future ISOSPIN LABORATORY will make it possible, for the first time, to carry out experiments with sets of mirror nuclei beyond the $^3H/^3He$ pair that could probe unique parts of both ground-state and excited-state wavefunctions via charge exchange reactions[12]. For mirror nuclei the reaction Q-value is ~0, which may lead to resonances between the unpaired neutron and proton via pion exchange. Another unique class of beams that would become available for reaction studies consists of projectiles in high-spin isomeric states that could even be polarized. Coulomb excitation of such beams would explore the rotational structure of nuclei built on these states, and excited state scattering studies could examine the question of spin-spin terms in the optical model potential[13]. In-beam studies of the giant-dipole resonance of high-spin isomeric states may reveal a new class of spectroscopic phenomena.

RNBs will have significant impact on research focused on the heaviest elements. Improvements in macroscopic-microscopic models[14] have provided new insight into the nature of the bi-modal fission process where the barrier to symmetric fission can be offset by the extra binding of the doubly magic fission fragment $^{132}_{50}Sn_{82}$. Such reactions should have enhanced cross sections and could serve to study problems that are specific to heavy element synthesis, i.e., fusion hindrance, "extra push," and $\Gamma_n/\Gamma_f$ competition. These reactions may also lead to the formation of relatively cold compound nuclei of the heaviest elements. More promising, because technically easier, may however be more asymmetric transfer reactions like $^{254}_{99}Es + ^{96}_{37}Rb$, which could lead to isotopes of $_{100}Fm$, $_{101}Md$, $_{102}No$, and $_{103}Lr$ near the N=162 deformed shell. Similarly $^{11}Li$ could be used as "neutron donor" in reactions like $^{254}_{99}Es$ ($^{11}_{3}Li$, $^{3}_{2}He$) $^{262}_{100}Fm_{162}$. The synthesis of super-heavy elements could receive a new impetus if sufficiently intense beams of $^{50}Ca$ or $^{52}Ca$ became available for compound nucleus reactions with neutron-rich actinide targets like $^{248}Cm$. Another class of RNBs reactions relevant to super-heavy elements is the transfer of a neutron to a heavy actinide target. This could provide information on the location of the $h_{11/2}$ or $k_{17/2}$ neutron orbitals and result in improved estimates of the half-lives of super-heavy elements. Such experiments would be similar to those carried out to locate the $i_{13/2}$ levels in the rare earth region[15]. A certain spin selectivity could be achieved by changing the mass of the RNBs projectile.

To further elucidate the fission process it has been suggested[13] to measure fission deexcitation channels using neutron-deficient pre-actinides in reverse kinematics. Such experiments would be particularly well suited for storage ring experiments where the circulating RNBs would interact with an internal light-gas target during multiple traversals.

## 4. NUCLEAR ASTROPHYSICS

This year two new windows to our universe are opening: the Hubble Space Telescope and the Gamma Ray Observatory. Nuclear astrophysicists will be challenged to interpret the signatures of the nuclear reactions in distance parts of the cosmos. On the cosmic time scale and under the extreme conditions in the interior of stars the conventional distinction between stable and unstable nuclei is not necessarily relevant. Contrary to earth-bound accelerator experiments the diverse cosmic acceleration mechanisms do not distinguish between stable and radioactive beams and targets, which — coupled with our desire to understand these processes — leads to the obvious challenge to try to duplicate some of these exotic reactions in the laboratory. A particular need exists for the understanding of the abundance distribution of the chemical elements that requires nuclear reaction rate and structure information for literally thousands of nuclei on both sides of beta-stability. It is unrealistic to assume that this information will be obtained in the foreseeable future or that it is even desirable to do so. More important is the investigation of certain key regions and a judicious selection of representative nuclei that can serve as test cases for model calculations used to make global predictions of, for example, β-strength functions, masses, half-lives, Q-values, nuclear partition rates, neutron capture rates, etc., including the effects of excited states.

A group of astrophysicists, meeting at the recent Workshops on the Science of Intense Radioactive Ion Beams, stated that "A radioactive ion beam facility . . . will play a key role in future astrophysical developments" and identified four major areas for this role[16]: (i) nuclear capture reactions involving stellar processes, (ii) production of exotic nuclei for r-process and rp-process modeling, (iii) nuclear transfer reaction cross sections for simulating specific neutron, proton, or alpha capture processes, and (iv) determination of Gamow-Teller strengths via (d,p) or (n,p) reactions on isotopes within the iron group. An example for the first class of experiments are "break-out reactions" like $^{19}Ne(p,\gamma)^{20}Na$ which are thought to govern the transition from the CNO cycle to intermediate nuclei that form part of the rp-process. This process may reach up to, or even go beyond, the iron peak via a sequence of $(p,\gamma)$ and $(\gamma,p)$ reactions and $\beta^+$/EC decays. On the neutron-rich side the location of the n-drip line and the nuclear properties near the r-process waiting points, i.e., near the neutron closed shells are of prime importance. Specific nuclei include the "waiting point nuclei" $^{80}_{30}Zn_{50}$ and $^{130}_{48}Cd_{82}$, and others on the r-process path. Both nuclei are two protons removed from the doubly magic nuclei $^{78}_{28}Ni_{50}$ and $^{132}_{50}Sn_{82}$ which were discussed earlier. An example of the third class of experiments is related to the Big-Bang nucleosynthesis that predicts the formation of, among other light nuclei, $^{7}Li$. Recently, a Big Bang model involving non-uniform neutron and proton distributions has been proposed that modifies the expected abundance of $^{7}Li$. To distinguish between these models and to compare the calculated abundances with those observed in "old" stars, the following reactions have to be considered[17]: $^{3}H(d,n)^{4}He$, $^{4}He(t,\gamma)^{7}Li$, $^{7}Li(t,n)^{9}Be$, $^{9}Be(t,n)^{11}B$, $^{8}Li(\alpha,n)^{11}B$, or $^{14}C(\alpha,\gamma)^{18}O$, several of which involve radioactive beams or targets.

Finally, it should be pointed out that astrophysical experiments are very demanding on a radioactive beam facility, requiring a wide range of energies and high intensities to study sub-Coulomb barrier cross sections and n-rich nuclei extremely far from stability.

## 5. APPLICATIONS OF RADIOACTIVE BEAMS

Only brief mention will be made of the applications of RNBs since the present author feels that he is even less of an expert on this subject than on the previous topics. A future ISOSPIN LABORATORY will provide low-energy (≤100 keV) RNBs with intensities about one order of magnitude higher than will be available after acceleration. It was pointed out by H. Ravn[18] that this, combined with the much more intense primary beam, will not only provide higher RNB intensities for experiments similar to those now being carried out, for example, at ISOLDE/CERN, but that beams of additional elements will become available that presently produce effects below the detection thresholds. It is expected that low-energy beam intensities, in favorable cases, may reach $\sim 10^{12}\ s^{-1}$. One of the applications for such beams are solid state studies. RNBs can be implanted in almost any materiel at various depths to study erosion, mechanical wear, diffusion, etc., or lattice locations. To study the structure of condensed matter, hyperfine interactions in solids, like Mössbauer effect, perturbed angular correlations, nuclear orientation, etc., in addition to channeling and blocking methods, positron life-time/annihilation, and conversion electron spectroscopy, have been used. Mössbauer, NMR, nuclear orientation, and laser spectroscopy are also the methods of choice to determine static properties of nuclei like E0, M1, and E2 moments. Collinear laser spectroscopy will be able to measure mean square charge radii over a wide range of neutron numbers and thus be capable of detecting subtle changes in nuclear structure. This technique would receive a tremendous boost in sensitivity if it were combined with a storage ring/cooler[19]. The recirculating RNBs would be equivalent to a factor $\sim 10^{6}$ increase in the effective beam intensity, and the cooled beams would allow measurements with very high optical resolution due to their small energy spread. If the cooling electron beam of the storage is included in the experimental setup a variety of photon (laser)-ion-electron studies can be carried out. Finally it should be mentioned that polarized RNBs can be obtained via tilted foils, spin exchange, and other techniques.

A unique application of high energy RNBs is their use in biomedical diagnostic studies,[20] where the precise location of implanted $\beta^+$ emitting ions, like $^{19}$Ne or $^{11}$C, in biological samples is determined by observing the two correlated 511-keV $\gamma$ rays from positron annihilation, with detectors similar to those employed in CT scanners.

## 6. PRODUCTION OF RADIOACTIVE BEAMS

There are two promising methods for the production of high intensity RNBs, the projectile fragmentation (PF) and the Isotope Separator On-Line (ISOL)/Post-Accelerator approach. They are in many ways complementary to each other.

In the first case high-energy heavy ions are fragmented on a light target, while in the second light high-energy projectiles fragment heavy targets. The velocity of the RNBs produced via PF is close to the beam velocity, while those produced via light-ion fragmentation (spallation) have, in general, energies below nuclear reaction thresholds. RNBs produced via PF can, therefore, be used directly to induce secondary reactions while the spallation products have to be accelerated. This leads to different production target requirements: to keep the momentum spread of the projectile fragments sufficiently small targets of ~1 g/cm$^2$ thickness have to be used. Conversely, in the ISOL method targets up to 300 g/cm$^2$ can be employed because of the large range of the primary beam. This, together with the larger primary beam intensity, gives the ISOL method an advantage of approximately three orders of magnitude over PF in the *primary* RNB production rate. Some of this advantage is, however, lost in the necessary subsequent acceleration process.

Several PF facilities are presently in operation: The BEVALAC, MSU, GANIL, and in the near future SIS18/ESR at GSI and RIPS in Japan. All facilities employ some form of RNB purification, and, except for the ESR, do not modify the RNB energy significantly. The ESR is unique in that it can, in principle, deliver cooled RNBs in the energy range of ~10 to 500 MeV/u. In recent discussions at the Los Alamos Workshop on the Science of Intense Radioactive Ion Beams and among the members of the newly formed steering committee for the planning of an RNB facility in the U.S., the majority of researchers felt that—considering the existence of the five mentioned PF facilities and the range of physics that can be addressed—it would be highly desirable to build an *ISOL*-based ISOSPIN LABORATORY in this country. Similar projects in various planning stages exist in Canada, Japan, Europe, and the USSR.

At the Los Alamos meeting preliminary ideas for an ISOSPIN LABORATORY were presented[21] (see Fig. 1). A light particle beam (p, d, $^{3}He$) of ~500–1000 MeV energy and 100–300 μA intensity traverses a 100–300 g/cm$^2$ thick target where it generates RNBs via spallation, fragmentation, and/or fission reactions. The radioactive species emanate from the hot target and undergo several chemical/physical purification steps that remove unwanted activities. This is followed by an ion source on ~100 kV potential and an isotope/isobar separator. A linac subsequently accelerates the RNBs to their final energy in the range of ~0.1 to 10 MeV/u.

This in itself constitutes a fully operational RNB facility; however, its experimental capabilities could be greatly enhanced through the addition of a storage ring. Beam cooling, for example, could reduce the beam energy spread by about two orders of magnitude compared to the linac, and a significant gain in luminosity could be achieved by using multiple beam traversals in a target internal to the ring. To make efficient use of the storage ring without loosing average beam current the radioactive ions will have to be stored in a "trap" and be "bunched" for injection into the ring. An expedient location for such a storage device (not shown in Fig. 1) would be between the isobar separator and the preaccelerator where radioactivity and space charge effects could be minimized. The trapping of the RNBs could be conveniently combined with a boost in their ionic charge thus reducing or eliminating the need for stripping and the concomitant intensity loss. The bunched nature of the beam leaving the trap would also greatly simplify the design (and reduce the cost!) of the linac, which could operate in a low duty factor (pulsed) rather than CW mode. Since for most in-beam experiments the duty factor of the direct beam from the linac would, in this case, be too small, it could be increased to nearly 100% by operating the storage ring as a "stretcher." At a later stage the linac beam could also be injected into a synchrotron for acceleration to higher energies.

Many questions regarding the individual components of the ISOSPIN LABORATORY remain to be studied before the optimal design is achieved. It seems however certain that, independent of future design modifications, intense high quality RNBs can be produced that will allow a wide range of new and exciting physics questions to be addressed.

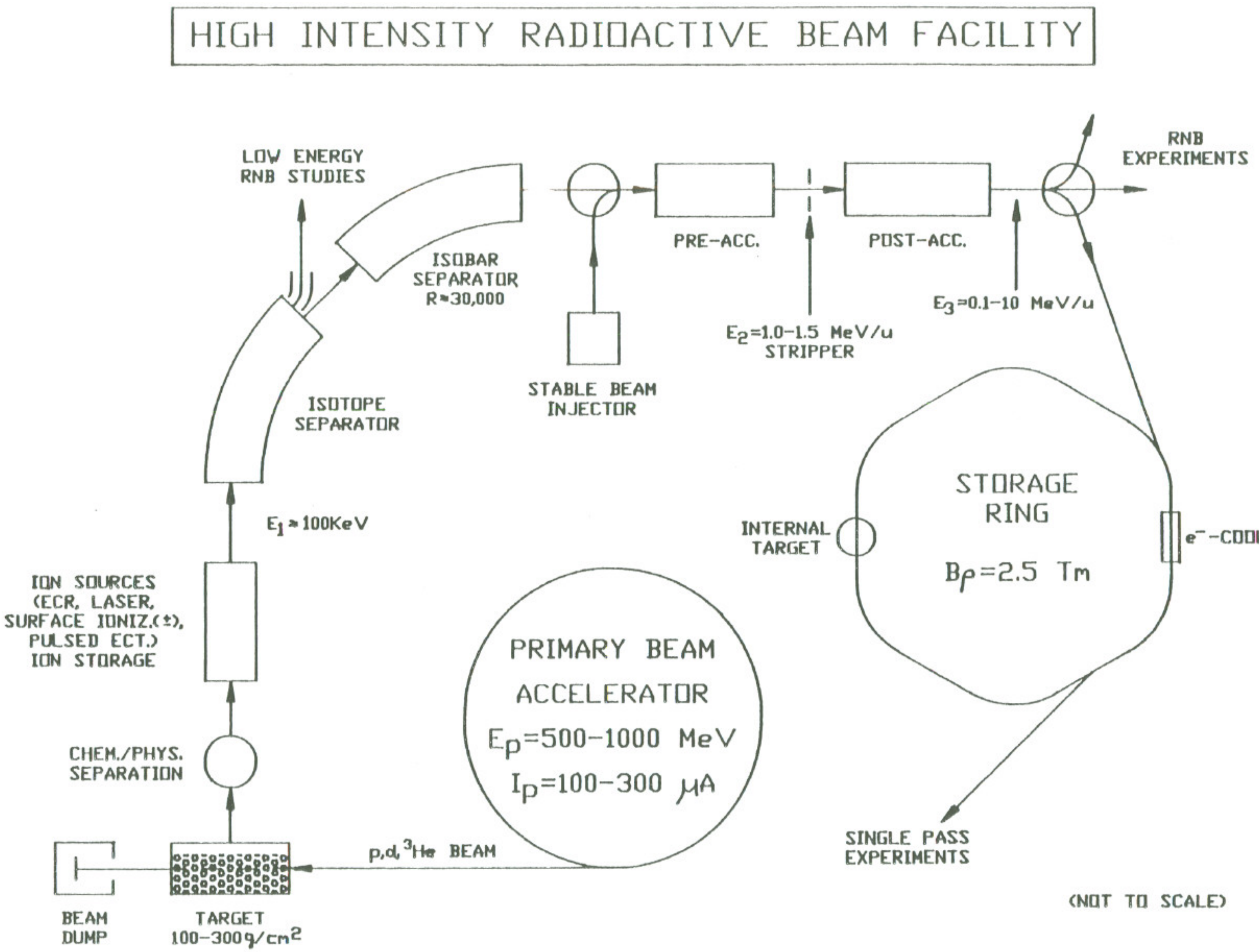


FIGURE 1.
Schematic representation of a proposed ISOSPIN LABORATORY based on the ISOL Post-Acceleration approach. (For details see text.)

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