Title

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Publication Date

1992-07-01

LBL-33072
UC-413

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the Thirteenth International Conference on Cyclotrons
and Their Applications, Vancouver, Canada, July 6–10, 1992,
and to be published in the Proceedings

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July 1992

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL - 33072

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This work was supported by the Director, Office of Energy Research Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098

Accelerated Radioactive Nuclear Beams: Existing and Planned Facilities

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ABSTRACT

An over-view of existing and planned radioactive nuclear beam facilities world-wide is given. Two types of production methods are distinguished: projectile fragmentation and the on-line isotope separator (ISOL) method. While most of the projectile fragmentation facilities are already in operation, almost all the ISOL-based facilities are in still the planning stage.

1. INTRODUCTION

The advent of intense Radioactive Nuclear Beams (RNB) in this decade may rival in importance the development of heavy ion beams in the 1960s. Radioactive beams were mentioned, for the first time, during the concluding discussion of the Symposium on Nuclides far of Stability in Lysekil in 1966 where J.P. Bondorf pointed out "the rich field of information that would be opened by a future use of unstable targets and projectiles in nuclear reaction studies".1) The first radioactive beams were produced in 1969 by a group from LRL (later LBL), Berkeley, that accelerated fission fragments from a ^{252}Cf source placed in the MIT MP Van De Graaff.2) The idea was kept alive in Europe mainly by members of the CERN/ISOLDE group. However, even as recently as 1977, a CERN Workshop on Intermediate Energy Physics concluded that there was not a sufficiently strong physics case to warrant a major RNB construction project.3) This has now changed profoundly, as a host of scientific questions has been raised that can only be addressed with radioactive beams. What is even more important, several crucial technological advances have occurred in the preceding years that allow the generation of *intense* RNBs for meaningful physics experiments.

The science of RNBs has been discussed at several workshops and conferences.4-11) The key new physics feature is that the neutron-to-proton ratio of radioactive projectiles can be varied over a wide range for experiments in the nuclear-, astrophysical-, atomic-, and material sciences. For example, in stellar processes at elevated temperatures the time for nuclei to β-decay toward more stable configurations may be long compared to the time it takes these nuclei to undergo nuclear reactions. This may lead to the synthesis of heavier elements from lighter precursors. An understanding of this process requires the measurement of a large number of nuclear reaction- and structure parameters, many of them involving radioactive beams or targets. RNBs may themselves have extreme nuclear matter distributions, if they are located near the neutron- or proton drip lines, and may produce even more exotic nuclei in compound nucleus or transfer reactions. This could provide access to new closed shells or regions of deformation, new nuclear shapes, and new forms of collectivity. Hyper deformed (axis ratio 3:1) and "banana" shaped nuclei have been predicted for nuclei that can only be studied with RNBs. The flexibility in the choice of the neutron to proton ratio offered by RNBs will allow the exploration of isospin dependent nuclear properties over a wide range of isotopes and isotones (and explains why the RNB facility proposed for North America has been given the name IsoSpin Laboratory). For details about these fascinating scientific questions the reader is referred to the above mentioned conference- and workshop proceedings.

2. PRODUCTION METHODS

There are two methods of producing high intensity RNBs: one is based on the fragmentation of high energy *heavy* ion projectiles on a light target and the second on the fragmentation, spallation, or fission of heavy targets by energetic *light* ion beams, followed by the post-acceleration of the radioactive species. The two methods are the kinematic inverses of each other and in many ways complementary. Projectile fragmentation has been used successfully in several laboratories while the second approach -- termed ISOL method -- is still in the development stage. The ISOL method derives its name from the fact that the central part of the RNB facility is similar to an Isotope Separator On-Line. A third method12-13) using peripheral reactions at low energies and a superconducting solenoid spectrometer has been used to produce RNBs of modest intensities; it will, however, not be discussed here in detail.

2.1 Projectile Fragmentation

Projectile fragmentation (PF) is a reaction process in which the heavy ion projectile reacts peripherally with the target nucleus, leaving the projectile with much of its initial momentum and a small angular spread. The cross section for PF becomes a significant fraction of the total reaction cross section for heavy ion beam energies of ~50MeV/u to several GeV/u. The projectile fragments are characterized by a wide distribution in A and Z and need to be purified in magnetic spectrometers to become useful for nuclear physics experiments. Due to overlapping charge-to-mass ratios a purely electro-magnetic separation is inadequate and a Z dependent ion-optical element in the form of a degrader has to be added. Many RNBs produced by PF in the past have been used at the full projectile energy. For other experiments, however, lower energies are needed and the RNBs have to be decelerated by passage through an absorber or -- after injection into a storage ring -- by an RF system. To avoid severe degradation of the beam quality during deceleration stochastic- and/or electron cooling has to be applied.

The advantages of using the PF method for RNB production are: short separation times (~μs) and therefore no losses due to radioactive decay, no chemical selectivity (the release of the radioactive species from the target is independent of Z), simple production targets (no large amounts of unwanted radioactivity are produced), high product collection efficiency (≳50%) due to forward kinematic focusing, and reliable operation. Some disadvantages are: low primary beam intensity compared to the ISOL method, target thickness limited by the acceptable momentum spread of the secondary beam, high projectile energies necessary for fully stripped ions in the separator (50-500MeV/u), poor secondary beam emittance (depending on the production mechanism and the target thickness), moderate beam purity, and difficult deceleration without intensity loss. The RNB production luminosity of a modern PF facility can reach 3×10^{35} $cm^{-2}s^{-1}$. A recent survey of the PF method has been given by Sherrill.[14)]

2.2. ISOL Method

Compared to PF, the ISOL method takes a complementary approach to RNB production. A high energy beam of light ions (typically protons) impinges on a thick target and creates radioactive species through target fragmentation, spallation or fission reactions. The products are produced with low kinetic energies and stop in the target. Target materials vary greatly, depending on the intended reaction mechanism, the chemical properties, and the half-life of the desired isotope: pure metals like Ta, La, Nb, V, and compounds like UC, ThO, and Hf_5Si_3 are used in solid-, liquid-, foil-, or powder form. To facilitate the removal of the activity from the target, transport to the ion source, and ionization, all parts with which the radioactive element comes into contact are kept elevated temperatures (up to ~2500C). If desired, a limited Z selection can be obtained by varying the temperature of the transport line to the ion source. The radioactivity is introduced into an ion source in gaseous form and singly or multiply charged ions are produced. They are accelerated to energies of a few tens of keV and mass-analyzed by an isotope separator. The function of the separator is to provide beams for post-acceleration that are free of unwanted isotopes, isobars, ionic charges, and molecular ions.

The most effective method for post-acceleration is a series of LINACs operating at ~100% duty factor, since they have excellent transmission and good beam quality. To make the acceleration process more economical the ions are, in general, stripped at intermediate energies. Most planned ISOL-based RNB facilities intend to provide beam energies of at least 1.2MeV/u and some may go as high as 30MeV/u. The RNB production luminosities are very high ($\lesssim10^{39}$ $cm^{-2}s^{-1}$) which is one of the main advantages over PF-based facilities. Other advantages are the high beam purity, ease of energy variation, and excellent beam quality characterized by small transverse and longitudinal emittances. Some disadvantages of the ISOL method are: RNB yields that are strongly dependent on the target/product chemistry, losses due to radioactive decay caused by delays associated with diffusion and effusion, the generation of large amounts of unwanted radioactivity, and the need for a post-accelerator. A recent survey of the ISOL method has been given by Ravn.[15)]

3. EXISTING AND PLANNED PROJECTILE FRAGMENTATION FACILITIES

3.1 Bevalac, Berkeley

The Bevalac has been considered the "grandfather" of the projectile fragmentation method. (For a detailed account of its capabilities see Ref. 16.) Using primary ion beams as heavy as ^{238}U with energies of up to 2.1GeV/u radioactive beam experiments have been carried out since the early 1970s.[17)] Primary intensities of 10^8/pulse can be routinely obtained at a pulse rate of one per 6s. The potential of the PF method was shown in a pioneering experiment in 1979 when over 64 isotopes formed in the fragmentation of ^{48}Ca were observed, many of them for the first time.[18)] Presently four beam lines are dedicated to RNB research: one for the radiotherapy treatment program, two for low- and medium mass nuclear science studies, and a fourth line for higher mass ($A \lesssim 100$) experiments. The latter is connected to the Bevalac's Heavy Ion Superconducting Spectrometer. All beam lines are operated in a dispersive mode that allows the separation of RNBs according to A/Z and Z. Additional selectivity can be obtained through time-of-flight selection. In favorable cases up to 1% of the primary beam can be converted to RNBs. Polarized- and low-energy beams have been produced for magnetic and life-time measurements.19)

3.2. RIKEN, Japan

The primary beam accelerator for the RIKEN RNB facility is a K=540 separated sector cyclotron injected by a heavy ion LINAC and an AVF cyclotron. High intensities of high charge state ions from ECR sources result in a variety of heavy ion primary beams with energies of ~100MeV/u. The facility has produced RNBs since 1990 and was recently described in Ref. 20. A second-generation projectile fragment separator for RNBs (RIPS) has been constructed as an achromatic spectrometer in which the projectile fragments are analyzed by a combination of magnetic and energy loss elements. The strong kinematic forward focusing characteristic of the PF process and large geometric- (5msr) and momentum (6%) acceptances of the spectrometer result in high intensity secondary beams. The maximum rigidity of RIPS is 65% larger than that of the cyclotron, which allows the analysis even of very neutron rich fragments at the highest primary beam energies. An example of typical conditions for the production of light, neutron-rich RNBs is: a primary beam of ^{18}O at 100 MeV/u with an intensity of 100 pnA and a converter target of Be with a thickness of 1.1 g/cm^2. Under these conditions the following RNB intensities were observed: 1.7×10^5 ^{8}He/s, 2.8×10^4 ^{11}Li/s, and 4.4×0^3 ^{14}Be/s. These beam intensities have allowed secondary reaction studies with cross sections as low as 1mb. Recently a spectrometer system has been added to RIPS for the exclusive measurement of secondary reaction products. Also, low energy RNBs to ~5MeV/u can be obtained with a degrader technique. An intermediate-energy PF reaction mechanism is used to obtain spin-polarized RNBs with $\lesssim$5% polarization.21) The polarized RNBs are emitted off the forward direction and are guided into RIPS by a beam swinger.

3.3. GSI, Germany

At GSI RNBs are produced through the fragmentation of heavy ion projectiles up to U from a synchrotron (SIS18), with typical energies of 0.5-1GeV/u. The secondary beams are analyzed in a large zero-degree achromatic spectrometer (FRS)22) and can either be studied directly in its focal plane or injected into a storage ring (ESR). Eventually, the ESR will be able to reinject beams into SIS18 for acceleration to higher energies. The FRS uses the energy-degrader technique and a combination of dipoles and quadrupoles to achieve A and Z resolution and to spatially separate individual isotopes. Its resolving power is 1.5×10^3 for 20π mm mrad beam emittance and its efficiency for projectile fragments is ~60%. Its luminosity for fragment production is $\lesssim 3\times10^{35}$ cm^{-2}s^{-1}.22) The feature of the GSI facility that is unique among the PF installations is the coupling of the FRS to the storage ring. It allows the direct observation of the decay of accumulated RNBs, measurements of their masses, and the study of their interaction with an internal gas target. Cooling the circulating beam with electrons results in a 10^7 fold improvement in the phase space density (a momentum spread of $\Delta p/p=2\times10^{-6}$ has been observed).23) Cooling is necessary for the successful deceleration of the beam due to the momentum dependence of the emittances. It is expected that beams can be decelerated from ~500MeV/u to <5MeV/u, and low energy RNBs thus would become available not only from ISOL- but also from PF- based facilities. There are, however, two effects that curtail the usefulness of this technique: one is the space charge forces in the ring that limit the number of circulating ions to ~10^6-10^7, and the other is the time it takes to cool the beam, which is on the order of several seconds, and rules out the deceleration of very short lived isotopes.

3.4. GANIL, France

The primary heavy ion beams at GANIL are produced with two K=400 cyclotrons that can be operated independently or in tandem. In the latter case stripping between the cyclotrons is employed to obtain higher charge states and final energies of 30-100 MeV/u. Beam intensities are well above 10^{12} ions/s and a one-order-of-magnitude upgrade is planned. A novel beam focusing- and reaction-product-collection device named SISSI has recently been installed at the target position. It increases the RNB intensities by a factor ~10.24)

The principal instrument for the production and study of secondary radioactive beams is LISE, a zero degree spectrometer consisting of two dipoles and several quadrupoles.25-26) The first dipole analyses the projectile fragments according to A/Z, a slit in the dispersion plane selects the desired momentum bite, and the second, symmetric dipole compensates the dispersion of the first one. Consequently, the spectrometer is doubly achromatic in angle and position, and the flight path between the target and the final focus is independent of the emission angle of the reaction products. By introducing an energy degrader of variable thickness in the dispersive plane, q/A ambiguities can be resolved and the spectrometer operates as an isotope separator. To improve further the isotopic selection a "Wien filter" has recently been added that separates the nuclei according to their velocity. Using the LISE spectrometer, all existing neutron-deficient nuclei up to Ti (Z=22) have been studied. Recent results from LISE3 are reported in Ref. 27. A second spectrometer at GANIL, SPEG, is particularly well suited for the measurement of masses of exotic nuclei. It combines high resolution time-of-flight with magnetic analysis and achieves a mass resolution of $m/\Delta m=1000$. Mass measurements have also been discussed using the two coupled K=400 cyclotrons.28)

3.5. NSCL, East Lansing

At the National Superconducting Cyclotron Laboratory (NSCL) primary ion beams in the energy range 50-200MeV/u are produced by a K=1200 superconducting cyclotron. A beam analysis device, A1200, connects the cyclotron to the experimental areas. With suitable targets installed at its "object" position the A1200 also can be used to collect and separate RNBs produced by PF and deliver them to several experimental devices. The A1200 was designed as an achromatic device with two intermediate images that allows for momentum measurements and the placement of degrader foils, as discussed for the other PF facilities.29) The A1200 has a resolving power that ranges from 0.7 to 1.5×10^3 depending on the chosen solid angle in the range from 4.3 to 0.8msr. Despite the good resolution very exotic nuclei can only be produced with modest purity. For example, for ^{65}As the expected RNB purity is $\sim5\times10^{-4}$. However, since the production rate is only ~10/s the flight time relative to the cyclotron RF cycle can be used to discriminate against unwanted nuclei. Currently, the construction of a large superconducting solenoid is underway that will allow the production of RNBs through transfer reactions with primary beams of $\lesssim$50MeV/u.30)

3.6. Planned PF Facilities

In Italy two laboratories have plans for radioactive beams. At the "Laboratorio Nazionale del Sud," Catania, a K=800 superconducting cyclotron will be injected by a 15MV MP-Tandem. RNBs can be produced from medium light ions at energies of 50-80MeV using the PF method.31) A fragment recoil separator is used to analyze the secondary beams and supply them to the experimental areas.

At the same laboratory low energy RNBs can be obtained by operating the cyclotron in a stand-alone mode, using an external ECR source, and transporting light ion beams with 50-80MeV/u energy to the Tandem area where they will be used to bombard a thick target. Target recoils will be attached to aerosols, transported to a negative-ion source and extracted by a 150kV potential. After isotope separation the ions are injected into the Tandem, which will provide RNBs with energies up to 8MeV/u and projected intensities of $\lesssim$10 pnA.

The second Italian project is at the Legnaro Laboratory associated with the ADRIA facility.32) It has two accelerator rings that have a maximum magnetic rigidity of 22.3Tm. The first synchrotron can deliver ion beams with intensities in excess of 10^{11} s^{-1} and energies of 1-2.5GeV/u to a production target for PF. The secondary beams are injected into the second ring and cooled stochastically or by electrons. After accumulation of a sufficient number of radioactive ions ($\sim10^7$) deceleration to the Coulomb barrier is planned. The extracted beams will be used for nuclear structure studies.

A large PF facility is under construction for the Dubna Laboratory, FSU, using two coupled cyclotrons that will provide beams from H to U with intensities of $\lesssim10^{13}$ s^{-1} and energies of 100-20 MeV/u.33-34) The RNBs will be analyzed and studied with several instruments: a projectile fragment separator (COMBAS), a time projection chamber, a He-filled neutron counter, and a 4π γ- and charged particle spectrometer. The separator is preceded by a beam swinger to allow the production of spin-aligned secondary fragments. Future expansion of the Dubna facility will include two storage rings (K4 and K10) with maximum rigidities of 4 and 10Tm, respectively.35) Both rings are equipped with electron coolers. RNBs produced by PF of the primary beam from the K4 ring can be injected into the K10 ring through a projectile fragment separator. The authors of the proposal (Ref. 35) "specify the main purpose of the project by dedicating it to the production of high precision RNBs."

At the Research Center for Nuclear Physics, Osaka University, Japan, a secondary beam channel is under construction.36) Its central instrument is a fragment separator employing the degrader technique described earlier. Calculations show that a mass resolution $m/\Delta m\approx330$ and a Z resolution $Z/\Delta Z\approx200$ can be expected. The separator receives its primary beam of medium heavy ions from a K=400 cyclotron.

4. EXISTING AND PLANNED ISOL-BASED RNB FACILITIES

In contrast to the PF situation, there is only one ISOL-based RNB facility in operation. Yet, as of this writing, (June 1992) there are twelve proposals for ISOL facilities in nine countries. The proposals are in various stages of development and no attempt will be made to judge their merits or chances of realization. Only very brief descriptions can be given here.

4.1. Louvain-la-Neuve, Belgium

The RNB facility at Louvain-la-Neuve has successfully produced pure RNBs of ^{13}N and ^{19}Ne for astrophysical experiments.[37-38] This was done by coupling together two cyclotrons: the first, using a beam of up to 500μA of 30MeV protons and suitable targets, produces large amounts of light radioactive isotopes near stability. The radioactive species emanate from the hot target and are ionized in an ECR source. The second cyclotron accelerates them to ~1MeV/u for astrophysical experiments. Measured intensities for ^{13}N and ^{19}Ne have exceeded 50 ppA. The high mass resolution of the second cyclotron was crucial for obtaining high RNB purities.

There are plans to expand the facility at Louvain-la-Neuve to produce other intense RNBs for nuclear-, astrophysical-, and solid-state studies (ARENAS^3).[39] The upgrade is mainly based on the development of efficient ECR sources for high charge states that will allow the production of RNBs near the Coulomb barrier. For astrophysical studies a post-acclerator with an energy range of 0.1-1.0MeV/u is under study.

4.2. PRIMA, ISOLDE/CERN, Switzerland

The ISOLDE facility is presently being reconstructed at a new experimental hall where it will make use of a 1GeV proton beam from the CERN PS Booster. In 1989 a detailed proposal (PRIMA) for the post-acceleration of radioactive ions from the ISOLDE facility was presented.[40] The physics motivation for PRIMA came predominantly from astrophysicists and has influenced the specifications: mass range 6-30u, energy $\leqq$1MeV/u, and intensities ~$10^9 s^{-1}$. Radioactive beams from ISOLDE3 would be accelerated in a pre-stripper RFQ accelerator, stripped at ~200keV/u, and further accelerated in a system of four LINACs of the interdigital H-type with magnetic focusing. To extend the mass and energy range in the future, higher charge states are needed and the use of an electron beam stripper combined with a superconducting booster LINAC is being investigated.

4.3. PSI, Switzerland

Plans are being discussed to construct an RNB facility at the Paul Sherrer Institut (PSI).[41] A primary production beam of 590MeV protons with a current of $\leqq$1mA is available. Contrary to most other ISOL-based projects, it is proposed to focus on the "thin target" approach. In this method the target thickness is kept thin enough (~0.2-10mg/cm^2) to let the proton-induced reaction products recoil into a stopping gas. Compared to the thick target method there is a loss in target thickness of ~10^4. To compensate partially for this, the PSI proposal envisions using up to 1000 targets of 0.2mg/cm^2 in a gas volume of 2ℓ (STP). Another approach uses a 1m long gas target at 10 bar with a volume of 20ℓ. In both cases the radioactive atoms are separated from the bulk of the gas by a skimmer technique and introduced into an ECR source. The post-acceleration could be accomplished with an existing K=120 cyclotron to give RNB energies of 1.0-30MeV/u. It is often assumed that the thin target approach is insensitive to chemical discrimination since the release from the target does not involve diffusion or desorption processes, and that it can, therefore, deliver elements that are usually inaccessible to the ISOL method. It should, however, be kept in mind that much of the chemical discrimination takes place in the *ion source* and depends strongly on its operating temperature. ECR sources, in particular, have, thus far, not been developed for high temperatures.

4.4. ISIS, Rutherford Laboratory, England

At the Rutherford Appleton Laboratory (RAL) a proton beam of 800Mev and 100μA (200μA after upgrade) is available for RNB production. It has been proposed to construct an RNB facility following the technologies developed at ISOLDE/CERN.[42] In a first option RNBs with masses up to A=80 and q=1 will be accelerated in a series of RFQs and LINACs to energies of 6.5 MeV/u. By going to q>1 and boosting the heavy ion LINAC, RNBs up to mass A=180 would become available. In a second option the RFQ injects directly into a fast-cycling synchrotron that would deliver light RNBs with energies up to 20MeV/u. In a future development the synchrotron could inject ions back into the ISIS ring and RNBs with 40.6 and 120 MeV/u energy could be obtained for light and heavy ions, respectively. It has been discussed to combine the ISOLDE/PRIMA proposal with the RAL plans to create a "European High Intensity Radioactive Nuclear Beam Facility."[43]

4.5. RNB, Moscow, Russia

An RNB facility at the Moscow Meson Factory is under discussion.[44] The proposal differs in several regards from other ISOL-based facilities. It is planned to use the full-intensity 600MeV-1mA proton beam on *thick* porous or liquid targets. To cope with the large amounts of radioactivity a purification step using gas-phase chemistry is interspersed between the target and the ion source. The chemical system also serves to transport the activities at the velocity of sound to a remotely located ion source that produces multiply charged ions. The post-acceleration proceeds in two steps: an isochronous injector cyclotron (K=208) coupled to a separated sector cyclotron (K=600). This accelerator complex will yield energies above the Coulomb barrier ($\geqq$5MeV/u) for masses A$\leqq$150. As an alternative, a system of CW LINACs for the acceleration of

RNBs from 1keV/u to 6.5MeV/u is being developed.[44)] Eventually a storage ring with cooling and acceleration may be added.

4.6. GANIL, France

GANIL has been at the forefront of radioactive beam research for several years using the PF method. There is now a proposal to add a unique ISOL-based facility using light ions as primary beams.[45-46)] This will be facilitated by an upgrade yielding beam intensities close to 5×10^{13} and 5×10^{12} for Ar and Kr, respectively. The arguments for using light ions as primary beams are that the cross sections for producing nuclei far from stability are larger, and that thinner targets can be used that will shorten the diffusion time and, therefore, reduce decay losses. (This will, however, not affect desorption-limited delays.) The basic features of the proposal are: the use of light C or Ar beams at energies of 100MeV/u with intensities of $\sim5\times10^{13}$ s^{-1} on thick targets, ionization of the radioactive species in an ECR source, and post-acceleration with a combination of RFQs and LINACs. The final beams will have energies >25MeV/u and can be injected into the main beam line at GANIL to make optimal use of the experimental areas. Another method of post-acceleration is to use the combination of an injector cyclotron and a separated-sector cyclotron similar to the "standard" GANIL design.[46)] The two cyclotrons also would serve as a powerful spectrometer.

4.7. PIAFFE, Grenoble, France

A second RNB facility in France (PIAFFE) is proposed for the high flux reactor at the Institut Laue Langevin in combination with the SARA accelerator complex at Grenoble.[47)] The goal is to produce beams of neutron-rich nuclei in the mass range of A=70-150u with energies of 2-10 MeV/u (≦20MeV/u for masses A≦85u). The expected beam intensities are 10^5-10^9 s^{-1} depending on the nuclear species. The production target consists of ~(1-3)g of ^{235}U immersed in a thermal neutron flux of $(1\text{-}3)\times10^{14}$ neutrons/cm^2/s. One of the advantages of using neutrons for RNB production is that target heating by the beam is negligible; the only heat source is the fission process. Two target arrangements are contemplated: A thick hot target where the release of the radioactive species is based on diffusion, and a series of thin targets where the activity recoils into a stopping gas (He). In the first case the ion source is ~1m from the target at the end of a transfer tube. For the He-jet system a skimmer arrangement is used to separate the transport gas from the activity that is then introduced into an ECR source outside the biological shield of the reactor. After mass separation q=+1 ions with 30 keV energy are transported (under vacuum) 450m(!) to the SARA accelerating complex, which consists of two coupled cyclotrons with K=88 and 160. With a new extraction system the 2-10MeV/u energy range of interest in nuclear physics could be covered. The over-all efficiency of the facility is estimated to be $\sim10^{-4}$. The projected intensities for certain neutron-rich isotopes compare favorably with those expected from some proton machines. The factor limiting the RNB intensities is, apparently, the safety of the reactor.

4.8. E-Arena, INS, Japan

An update of the Japanese plans for an RNB facility at the Japanese Hadron Project (JHP) was given recently by T. Nomura[48)] (see also Ref. 49). The primary beam is H^- with an energy of 1GeV and a maximum average current of 400μA. Standard ISOL techniques are used to generate the radioactive ions that are then accelerated to a maximum energy of 6.5 MeV/u by a series of RFQs and LINACs. The planned mass ranges are A≦60 for ions with q=+1, and A≦120 for q=+2. Substantial developments have been carried out to accelerate "slow" (1keV/u) ions to 45keV/u. For N_2^+ ions a transmission of 92% through a Split-Coax RFQ operating with a 30% duty factor has been obtained. In preparation for the E-Arena at the JHP a development project is underway that makes use of a 45 MeV primary proton beam from the INS K=68 cyclotron. RNBs of light isotopes of interest in astrophysics will be produced with energies ≦1MeV/u. A high resolution mass separator is an integral part of the project; it has achieved a resolution of m/Δm=5000.

4.9. ISAC, TRIUMF, Canada

One of the earliest proposals for a radioactive beam facility (ISAC) was made by Canadian researchers.[50)] Recent updates were given in Ref. 51 and 52. ISAC will make use of the variable energy proton beam (185-505MeV) at TRIUMF. Variable primary energy could be useful to enhance the production of desired nuclei while suppressing the "background" of unwanted ones. It is planned to couple the target/ion source via a high-resolution separator to an RFQ pre-accelerator, followed by a stripper and a drift-tube LINAC as post-accelerator. The final energy of ≦1.5MeV and the mass range of A≦60 were chosen mainly to study astrophysical problems. Presently, a Test Isotope Separator On-Line (TISOL) is in operation. One of its unique features is an on-line ECR source. This and other developments carried out at TISOL are intended not only to support a future ISAC proposal but also the plans for an IsoSpin Laboratory in North America discussed below.

The specifications of a TRIUMF-based RNB facility are in flux, depending on the fate of KAON. If KAON gets built, locating ISAC at a 3 or 30GeV beam line has been discussed.51) Higher primary beam energies would have the advantage of larger cross sections for nuclei far from stability and reduced energy deposition in the target.

4.10. OREB, Oak Ridge

At the Oak Ridge National Laboratory an RNB facility is under construction that could, in principle, provide 95 proton-rich isotopes between He and Rb with energies >5MeV/u.53) The facility is based on the ORIC cyclotron (K=105) as a light ion (LI) primary beam accelerator. The maximum energies for ^{1}H, ^{2}H, ^{3}He, and ^{4}He are 55, 52, 140, and 105 MeV, respectively, and the desired nuclei are typically formed in (LI; xn,yp) reactions. Negative(!) radioactive ions are generated by one of two methods: for elements with electron affinities greater than ~2eV direct surface ionization on hot LaB_6 can be used, for other elements a charge-exchange vapor cell may be employed. After extraction the ions are accelerated to 300keV and injected into the existing 25MV Tandem electrostatic accelerator. Ref. 53 gives details about expected RNB intensities and the planned physics program. As is true of the TISOL facility at TRIUMF, some of the work at OREB is undertaken to support plans for a future full-scale RNB facility in North America.

4.11. The IsoSpin Laboratory, North America

In 1989, as contribution to the Long Range Plan for Nuclear Science,54) the author proposed the construction of a High Intensity Radioactive Nuclear Beam Facility in North America, later named IsoSpin Laboratory (ISL). The scientific case for such a facility was discussed at several meetings.55) 8-9) A Steering Committee for the ISL has been formed that has published a report56) detailing the research opportunities at the ISL and showning its technical feasibility in the form of a "bench-mark facility" (BMF). The "design philosophy" for the ISL is to push the technologies for producing and accelerating radioactive species to their limits to obtain the highest RNB intensities feasible. Accordingly, the intensity of the primary 0.5-1GeV light ion beam (~100pμA) will be considerably above the ~2pμA that have traditionally been used, for example, at ISOLDE/CERN. The primary beam intensity is limited by the power density in the target to $\lesssim$1kW/cm^2 for many materials (total power ~40kW). Besides the conventional surface- and plasma sources ECR- and Laser sources will play a major role in the ISL. The characteristics of the target matrix and the ion source must be matched to the chemical nature and the half-life of the radioactive isotope to maximize its yield. To cope with the large amounts of unwanted radioactivity a chemical/physical purification step is interspersed between the target and the ion source, and a high resolution isotope separator will reduce isobaric contamination of the desired RNBs. The post-acceleration, as proposed for the BMF, starts with a low-β RFQ, stripping at ~100keV, followed by a drift-tube LINAC, stripping at ~1.2MeV/u, and final acceleration to ~10MeV/u with a superconducting LINAC. Acceleration to higher energies and the addition of a storage ring are being discussed. To minimize beam losses, the goal is to obtain close to 100% transmission for all ion-optical elements and accelerating structures. It may be possible to eliminate stripping losses with a device proposed by Cramer.57) Expected RNB intensities and further technical and scientific details are given in Ref. 56.

It is hoped that funding for several planned RNB facilities will become available in this decade, allowing us to open new and exciting chapters in nuclear- and astrophysics, atomic physics, and material science.

This work was performed under DoE contract DE-AC03-76SF00098.

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