RADIOACTIVE BEAMS WITH THE HHIRF ACCELERATORS

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INTRODUCTION

There is an increasing interest in radioactive ion beams (RIBs) for astrophysics, nuclear physics, and applied programs. This interest has led to an International Conference on Radioactive Nuclear Beams[1] and a Workshop on the Science of Intense Radioactive Ion Beams.[2] In addition, a steering committee has been formed to consider the development of a very large and intense RIB facility in North America.

The two accelerators of the Holifield Heavy Ion Research Facility (HHIRF) provide a unique opportunity to quickly and economically develop an interim proton-rich, medium-intensity, ISOL-type,[3] RIB facility. This extension of the HHIRF would provide for research and development until the much larger facility can be realized in the late 1990s. Presently, the Oak Ridge Isochronous Cyclotron (ORIC) serves as an energy booster for heavy ions from the 25-MV tandem accelerator. To produce RIBs, this process could simply be reversed. The tandem accelerator would be injected with heavy ions produced by ORIC. In this case, the two accelerators will be coupled by a thick target, ion source, mass separator, and charge exchange canal, all mounted on a 300-kV high-voltage platform in an existing shielded room. Light ions from ORIC, with an internal ion source, would produce radioactive heavy ions for tandem injection. Moreover, the UNISOR on-line isotope separator allows the timely development of the target-ion source hardware and chemistry. A central feature of this plan[4] is that most of the main components already exist. The new hardware required for RIBs is shown in Fig. 1. The existing components include:

UNISOR. This on-line isotope separator has been operating since 1971, is managed and used by a consortium of university physicists, and provides intensive in-house experience. UNISOR, with its high-efficiency FEBIAD ion source, allows the immediate investigation and development of the thick-target and ion-source materials, geometry, chemistry, and procedures required to produce RIBs for subsequent acceleration. In particular, experiments have started in which elements for future RIBs are implanted in ISOL target material of interest. The chemistry and physics of the subsequent thermal diffusion, desorption, and ionization are being studied independently of producing RIBs.

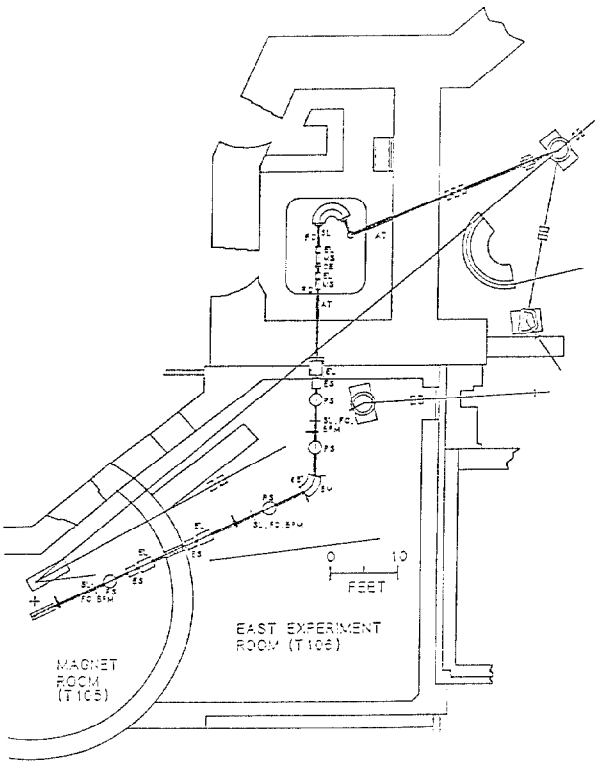

Fig. 1. Additional hardware required to produce RIBs from the HHIRF accelerator system.

Tandem accelerator. The tandem terminal presently operates at 25 MV, the highest voltage in the world. The charge state fractions and transmission efficiencies through the tandem have been extensively measured. With gas stripping, beams of mass 52 can be accelerated above 5 MeV/amu with a

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total efficiency of 20%. With foil stripping, beams of mass 80 can be accelerated above 5 MeV/amu with a total efficiency of over 8%. Beams of lower masses can be accelerated to higher energies with total efficiencies approaching 50%.

The tandem has some very important advantages for RIBs. No modifications would be required for service as a RIB accelerator. Since it is inherently a dc machine, no bunching is required for the injected beam, maximizing the dc beam available from an ISOL source. In addition, other inherent advantages, such as simplicity, reliability, flexibility, and excellent beam quality, are also available. One of the main difficulties with RIBs is the separation of analogue and isobaric beams. The folded configuration of the tandem allows the separation of analogue beams. More importantly, the excellent emittance (1-2 π mm mrad) and low energy spread ($< 1 \times 10^{-4}$) of tandem beams will allow convenient use of the existing energy analyzing magnet for separation of isobaric beams. This potential is illustrated with Fig. 2 which shows a BPM scan of the energy analyzer magnet focal plane

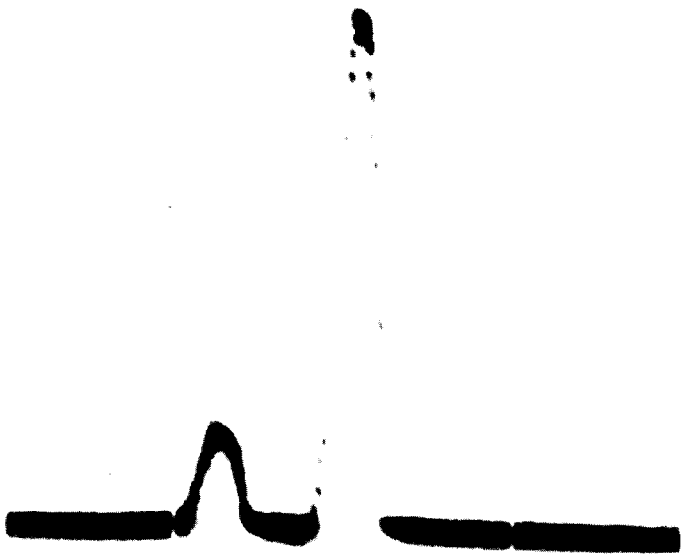

Fig. 2. BPM scan of analogue beams in the focal plane of the tandem energy analyzer magnet. The right peak is a 120.15-MeV $^{48}Ti^{6+}$ beam and the left peak is a 40.05-MeV $^{16}O^{2+}$ beam. The two beams have the same magnetic rigidity, except for a mass difference of 1/1300. Mass resolutions of 1/10,000 should be possible with the addition of quadrupole elements.

with 120.15-MeV $^{48}Ti^{6+}$ and 40.05-MeV $^{16}O^{2+}$ analogue beams following $(^{48}Ti\ ^{16}O)^{-}$ injection. These beams have the same magnetic rigidity, except for a 1/1302 difference in mass. The theoretical mass resolving power (MRP) in the present configuration is 1/3350. Fig. 2 shows that this mass resolution should be attainable. With the addition of entrance and exit quadrupoles, a MRP of the order of 10,000 should be attainable, which would allow separation of many troublesome isobars.

ORIC accelerator. The k = 105 ORIC was designed for the acceleration of both light and heavy ions and was used extensively for intense light-ion beams in the first years after its completion in the early 1960s. ORIC was originally designed to accelerate 1 mA of 75-MeV protons. Thus, ORIC is an ideal driver for the intense light-ion primary beams needed to produce secondary RIBs. Since the continued use of the ORIC as an energy booster is planned, the modifications required for internal-ion-source light-ion operation are designed not to interfere with this operation. For this study, H and He beams were limited to 2 kW of extracted beam power and Li and B beams were limited to 10 pμA of extracted beam current.

Shielded space. The shielding for the original ORIC vault and target rooms was designed for 75-MeV, 1-mA proton beams. These rooms are also equipped with single-pass HVAC systems appropriate for high-radiation areas. In this plan, room C111, shown in Fig. 1, will house the ISOL target-ion source and mass separator on the high-voltage platform, as well as the associated storage caves and remote handling equipment which may be required. No new civil construction is required.

ADDITIONAL EQUIPMENT

The additional equipment required to produce RIBs at the HHIRF is shown in Fig. 1. Except for a necessary change in elevation, the high-voltage platform could be fed by an existing 43-ft-long beam line from ORIC. The high-voltage platform would be operated at potentials up to 280 kV and with the ISOL source potential of 20 to 80 kV with respect to platform ground, would provide the nominal 300-keV energy which is presently used for tandem injection. The ORIC beams would be transported from ground potential to the platform and the ISOL source through acceleration tubes. Depending on the RIB, either positive or negative ions would be formed in the ISOL source. These ions would be accelerated to platform potential and mass analyzed through a 165^{o} n=1/2 double focusing magnet. This mass-analyzed beam would be charge exchanged, if required, and accelerated to ground potential, ready for tandem injection. The north end of room C111 could be configured as an ion source service area with appropriate shielding and remote-handling equipment. A 75-foot-long beam line at an elevation of 7 1/2 feet will be built to transport the negative ion beam through room T106 from the high-voltage platform to the tandem accelerator. Injection would be accomplished by merging the beam through the existing, de-energized, mass-analyzing tandem injector magnet.

EXPECTED ENERGY AND INTENSITY

The maximum energy for RIBs from the HHIRF for some of the most interesting beams is listed in Table 1. With single

Table 1. Estimated maximum accelerated beam intensity and energy for selected RIBs, excluding decay and target release losses.

Isotope	Beam Intensity (Ions/s)	Maximum Beam Energy (MeV/Amu)	Isotope	Beam Intensity (Ions/s)	Maximum Beam Energy (MeV/Amu)
^{10}C	1.7 x 10^{8}	13.0	^{68}As	4.3 x 10^{9}	5.9
^{11}C	2.0 x 10^{8}	13.0	^{69}As	5.1 x 10^{9}	5.9
^{14}O	5.7 x 10^{8}	13.0	^{70}As	4.1 x 10^{9}	5.8
^{15}O	1.3 x 10^{9}	13.0	^{71}As	4.7 x 10^{9}	5.7
^{17}F	4.5 x 10^{10}	12.7	^{72}As	3.2 x 10^{9}	5.6
^{18}F	2.3 x 10^{10}	12.3	^{73}As	4.6 x 10^{9}	5.5
^{21}Na	1.7 x 10^{8}	11.2	^{74}As	3.8 x 10^{9}	5.5
^{22}Na	1.7 x 10^{8}	10.7	^{76}As	1.1 x 10^{9}	5.3
^{26}Si	4.8 x 10^{9}	8.8	^{70}Se	7.8 x 10^{8}	5.8
^{27}Si	4.1 x 10^{9}	8.8	^{71}Se	3.7 x 10^{8}	5.7
^{29}P	8.6 x 10^{9}	8.6	^{72}Se	7.8 x 10^{8}	5.6
^{30}P	5.8 x 10^{9}	8.4	^{74}Br	1.3 x 10^{8}	5.5
^{30}S	1.3 x 10^{9}	8.4	^{76}Br	6.6 x 10^{7}	5.3
^{31}S	1.2 x 10^{9}	8.2	^{77}Br	2.7 x 10^{7}	5.3
^{33}Cl	1.0 x 10^{11}	7.8	^{78}Br	1.5 x 10^{8}	5.2
^{34}Cl	8.6 x 10^{10}	7.5	^{77}Rb	5.6 x 10^{5}	5.3
^{37}K	2.6 x 10^{7}	7.0	^{78}Rb	4.8 x 10^{5}	5.2
^{38}K	1.3 x 10^{8}	6.8	^{79}Rb	5.4 x 10^{5}	5.2
^{58}Cu	4.1 x 10^{9}	6.3	^{80}Rb	4.4 x10^{5}	5.1
^{63}Ga	7.3 x 10^{5}	6.1	^{81}Rb	3.6 x 10^{6}	5.0
^{64}Ge	7.2 x 10^{8}	6.0	^{82}Rb	4.2 x 10^{5}	4.9

stripping masses up to about 80 can be accelerated to energies above 5 MeV/nucleon. The maximum beam currents for these energies are much more difficult to estimate, and depend on the product of a number of factors. These factors can be divided into a thick target production rate for radioactive atoms and the conversion efficiency of these atoms to beam on target. The thick target production rates were estimated using fusion cross sections based on measured nuclear systematics and stopping powers. Production rates for C, O, F, Na, Si, P, S, Cl, K, Cu, Ga, Ge, As, Se, Br, and Rb RIBs were calculated using (H, xn) (He, xn), (Li, xn), (B, xn), and (p, αxn) reactions on Be, C, N, O, Mg Al, Si, S, Ca, Zn, Ni, Ge, and Sr target atoms contained in BeO, BN, C, MgO, AlB_2, SiO_2, Zr_5Si_3, ThS, CaO, ZnO, NiO, Zr_5Ge_3, and SrO refractory target materials.

The overall efficiency of converting extracted atoms to accelerated beam on target is listed in Table 2 and is a simple measure of the system merit. Two methods are considered for negative ion formation: direct surface ionization and charge exchange. Direct surface ionization is applicable to elements with large electron affinities and conversion efficiencies were estimated from the Langmuir-Saha relation for a LaB_6 surface ionizer operated at 1370°K. Conversion efficiencies using charge-exchange are the product of two factors: the efficiency for positive ionization and the efficiency for conversion of positive to negative ions. The positive ion efficiencies were estimated by scaling the probability for electron impact ionization of the element in question to that of calcium which has a 30% measured efficiency. The efficiencies for sequential charge exchange are based on measured results. In addition, a 50% loss factor has been included to account for transport losses. Table 2 shows that 23 of the 35 elements considered have an estimated efficiency of the order of 10^{-3} or greater. These 23 elements have an average efficiency to accelerated beam of over 1%.

Table 1 lists the product of these overall efficiencies with the thick target yields for some of the most interesting RIBs. Examination of this table shows that the proposed technique appears to have great promise. Of the 42 RIBs listed, 16 have intensities greater than 0.5 pnA, the intensity presently used at the HHIRF for experiments with 4π detector systems. Fluorine and chlorine, which combine favorable production reactions and acceleration efficiency, are expected to be the most intense RIBs. It should be emphasized that Tables 1 and 2 address only the general potential of the technique and do not contain decay loss or release rate factors.

Table 2. Estimated overall efficiency from atoms to accelerated beam, excluding decay and target release losses.

Element	Electron Affinity (eV)	Positive Ion Efficiency (%)	Negative Ion Efficiency (%)	Tandem Transport Efficiency (%)	Overall Efficiency (%)
He	0.08	2.4	1.5	80 G	0.01
Li	0.62	14	9	80 G	0.50
Be	0.19	9.3	3	70 G	0.10
B	0.28	11	12	60 G	0.40
C	1.27	8.9	42	47 G	0.88
N	<0	–	–	–	–
O	1.46	8.5	45	35 G	0.67
F	3.40	–	100	32 G	16.0
Ne	<0	–	–	–	–
Na	0.55	27	5	30 G	0.20
Mg	<0	–	–	–	–
Al	0.46	25	14	28 G	0.49
Si	1.39	19	60	28 G	1.60
P	0.74	15	70	26 G	1.37
S	2.08	–	15.8	26 G	2.05
Cl	3.62	–	100	25 G	12.5
Ar	<0	–	–	–	–
K	0.50	42	1.8	24 G	0.09
Ca	0.04	30	0.4	23 G	0.01
Sc	<0	–	–	–	–
Ti	0.2	29	4	21 G	0.12
V	0.5	31	10	21 G	0.33
Cr	0.66	31	10	21 G	0.33
Mn	<0	–	–	–	–
Fe	0.25	27	6	11 F	0.09
Co	0.70	28	12	10 F	0.17
Ni	1.15	29	60	11 F	0.96
Cu	1.23	30	60	9.5 F	0.86
Zn	<0	–	–	–	–
Ga	0.3	40	7	9.0 F	0.13
Ge	1.20	31	62	8.6 F	0.83
As	0.80	26	75	8.5 F	0.83
Se	2.02	26	75	8.2 F	0.80
Br	3.36	–	100	8.2 F	4.10
Kr	<0	–	–	–	–
Rb	0.49	64	0.8	8.0 F	0.02

F or G denotes gas or foil stripping in the tandem terminal. An additional 50% reduction is included to account for transport losses.

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