THE ORNL RADIOACTIVE ION BEAM PROJECT WITH THE ORIC ACCELERATOR

D. K. Olsen, G. D. Alton, C. Baktash, D. T. Dowling, J. D. Garrett, D. L. Haynes, C. M. Jones,
R. C. Juras, S. N. Lane, I. Y. Lee, M. J. Meigs, G. D. Mills, S. W. Mosko, B. A. Tatum, and K. S. Toth

Oak Ridge National Laboratory*
P. O. Box 2008
Oak Ridge, Tennessee 37831

and

H. K. Carter and J. Kormicki

Oak Ridge Associated Universities
Oak Ridge, Tennessee 37831

ABSTRACT

The ORNL project to produce medium-intensity, proton-rich, radioactive ion beams (RIBs) for astrophysics, nuclear physics, and applied research with the Holifield Heavy Ion Research Facility (HHIRF) accelerators has been approved. Radioactive atoms will be produced by fusion reactions in an Isotope Separator On-Line (ISOL)-type target-ion source assembly using light ion beams from the Oak Ridge Isochronous Cyclotron (ORIC). The radioactive atoms will be converted to negative ions using either (1) direct-surface ionization or (2) charge exchange following positive ionization. After acceleration to approximately 300 keV from a high-voltage platform, these negative ions will be injected into the 25-MV tandem accelerator for acceleration to higher energies. Beams of up to mass 80 will be accelerated to energies greater than 5 MeV/nucleon. For some radioactive beams, intensities greater than 1 pnA are possible.

1. INTRODUCTION

During the last few years, substantial interest has developed in the scientific opportunities presented with accelerated radioactive ion beams. This interest has led to the development and proposed development of RIB facilities in North America, Europe, and Asia; international conferences on RIBs at Berkeley [1] and Louvain-la-Neuve [2]; and many workshops on specific aspects of RIB technology and science. This paper describes the ORNL RIB project [3] which has been recently approved.

The reconfiguration of the two accelerators of the HHIRF will provide a quick and inexpensive first-generation, proton-rich, medium-intensity, ISOL-type RIB facility for North America. In the past, ORIC has served as an energy booster for stable heavy ions produced by the 25-MV tandem accelerator. To produce RIBs, this process will simply be reversed: the tandem accelerator will be injected with radioactive heavy ions produced by ORIC. In this case, the two accelerators will be coupled by an ISOLDE-type [4] thick-target and ion source assembly, mass separator, and charge exchange canal, all mounted on a 250-kV high-voltage platform in an existing shielded room. Light ions from ORIC, with an internal ion source, will produce radioactive heavy ions for tandem injection. Moreover, the existing UNISOR on-line isotope separator allows the timely development of the target-ion source hardware and chemistry.

2. EXISTING COMPONENTS

A central feature of the ORNL RIB project is that most of the main components already exist. The new hardware required for this RIB reconfiguration is shown in Fig. 1. The existing components include:

2.1 ORIC Accelerator

The k = 100 ORIC was designed for the acceleration of both light and heavy ions and was used initially for intense light-ion beams in the first years after its completion in the early 1960s. In the 1970s, ORIC was used mostly for heavy ion acceleration, and in the 1980s, ORIC was used mostly as an energy booster. 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 RIBs. For RIB intensity estimates in the ORNL proposal, 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. For first operation, 0.5 kW of extracted beam power seems readily achievable. Table 1 lists the main parameters of the cyclotron.

2.2 UNISOR

This on-line isotope separator has been operating since 1971, is managed and used by a consortium of university physicists, and provides extensive in-house experience. UNISOR, with its high-efficiency FEBIAD ion source, has allowed 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 thick target materials of interest. The chemistry and physics of the subsequent thermal diffusion, desorption, and ionization can, therefore, be studied without actual production of RIBs. [5]

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2.3 Tandem Accelerator

The tandem terminal presently operates at 25 MV, which is the highest electrostatic accelerator voltage in the world. The charge state fractions and transmission efficiencies through the tandem accelerator have been extensively measured and are well understood. With gas stripping, beams of mass 52 can be accelerated above 5 MeV/A with a total efficiency of 20%. With foil stripping, beams of mass 80 can be accelerated above 5 MeV/A with a total efficiency of over 8%. Beams of lower masses can be accelerated to higher energies with total efficiencies approaching 50%.

The tandem accelerator 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, thus maximizing the dc beam available from the RIB target ion source. In addition, other inherent advantages, such as simplicity, reliability, and excellent beam quality, are also available. One of the main difficulties with RIBs is the separation of analog and isobaric beams. The folded configuration of the tandem allows the separation of analog beams. More importantly, the excellent emittance ($< 1\ \pi$ mm mrad) and low energy spread ($< 1 \times 10^{-4}$) of the tandem beam will allow convenient use of the existing energy analyzing magnet for some separation of isobaric beams.

2.4 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 the present plan, room C111, shown in Fig. 1, will house the target-ion source, mass separator, and charge exchange canal on a 250-kV high-voltage platform system. In order to reduce potential radiation damage to electronic components during high-intensity operation, the platform system will consist, in fact, of two platforms, one for mechanical equipment and one for electronic equipment, connected by a HV conduit and separated by a radiation shielding wall. No new civil construction is required for the ORNL RIB project.

3. ADDITIONAL EQUIPMENT

The additional equipment required to produce RIBs is shown in Fig. 1. Except for a necessary change in elevation, the mechanical high-voltage platform could be fed by an existing 13-m-long beam line from ORIC. The high-voltage platform will be specified to operate at potentials up to 250 kV and with the ISOLDE-type source potential of 20 to 50 kV with respect to platform ground, will provide the nominal 300-keV energy which is presently used for tandem injection. Recent measurements with various beams have shown that the tandem transmission efficiency is essentially independent of injection energy between 200 and 300 kV. The ORIC beams will be transported from ground potential to the platform and the ISOLDE-type target-ion source through 250-kV and 50-kV acceleration tubes. Depending on the RIB, either positive or negative ions will be formed in the target-ion source. These ions will be accelerated to platform potential and mass analyzed to a single mass number with a first-stage magnetic mass analyzer. This mass-analyzed beam will be charge exchanged, if required, and accelerated to ground potential, ready for tandem injection. A 23-m-long beam line at an elevation of 2.3 m will be built to transport the negative ion beam through the east experimental room from the high-voltage platform to the tandem accelerator. Injection will be accomplished by merging the beam through the existing, de-energized, mass-analyzing tandem injector magnet. Figure 2 shows a vertical view of the new equipment required for RIB acceleration in the tandem. This new beam line will be reconfigured to be a second stage in the mass analyzing system.

4. EXPECTED ENERGY AND INTENSITY

The maximum intensities and energies for RIBs from the tandem accelerator for some of the most interesting and intense beams are listed in Table 2 for an initial ORIC beam power of 0.5 kW. With single stripping, masses up to about 80 can be accelerated to energies above 5 MeV/nucleon. The maximum currents for these beams 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 overall efficiency for converting 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, CeS_2, CaO, ZnO, NiO, Zr_5Ge_3, and SrO refractory target materials.

The overall efficiency for converting extracted atoms to accelerated beam on target is listed in Table 3 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 efficiencies were estimated from the Langmuir-Saha relation for a LaB_6 surface ionizer operated at 1370 K. 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. The transmission efficiency through the tandem accelerator is well understood and based on experience. The average overall conversion efficiency from radioactive atoms to beam on target is about 1% and varies widely, depending on the element.

The product of these overall conversion efficiencies with the thick target yields for some of the most interesting RIBs are listed in Table 2. Examination of this table shows that many of the RIBs listed have intensities greater than 0.1 pnA, the intensity that presently can be used at the HHIRF for experiments with 4π detector systems. Fluorine and chlorine, which combine favorable production reactions, surface negative ionization, and acceleration efficiencies, are expected to be the most intense RIBs. It should be emphasized that Table 2 does not contain decay loss or release rate factors. In addition, high positive ionization efficiencies for low-mass RIBs will require an ECR ion source. Figure 3 shows a summary of the process with average efficiencies with 2.0 kW of ORIC beam power for a generic "good case" radioactive beam. It will require about 1000 protons to produce one radioactive atom in a thick target and these radioactive atoms, with the tandem accelerator, should be delivered as beam on target with about a 1% efficiency, giving a factor of 10^5 between the RIB beam intensity and the ORIC beam intensity.

5. WORK IN PROGRESS

Presently, a substantial amount of work is in progress at ORNL to develop a RIB capability. Internal ion source operation of the ORIC accelerator is being restored and central region calculations have been completed [6] to optimize the ion source geometry in order to minimize beam losses and maximize extracted light-ion beam. UNISOR implantation studies have been initiated [5] and the engineering for an ISOLDE-type FEBIAD target-ion source is nearly completed. An exhaustive study of the various locations and configurations for the HV platform system and the overall layout has been completed. Numerous other tasks and studies are in progress. Studies have shown that the tandem accelerator acceptance is relatively insensitive to injection energy between 200 and 300 keV and that the new tandem potential stabilizer system will provide the long-term stability required for very low intensity beam operation, as well as isobar separation, while operating in the generating voltmeter mode.

In principle, several isobars with the same mass number could be produced in the target-ion source and accelerated through the tandem accelerator, giving a mixed beam of isobars on target. Up to and including the mass 80 region, isobars tend to be separated in mass by approximately one part in 10,000. Recent experimental studies have shown that with gas stripping, the tandem energy analyzing system may be capable of this mass resolution.

6. CONCLUSIONS

It appears that accelerator-based nuclear physics which, only a few decades ago, moved, in part, from light-ion to heavy-ion beams, is now starting to move, in part, from stable-heavy-ion to radioactive-heavy-ion beams. It also appears that the ORIC will start its fourth decade of operation as the light-ion driver for the first accelerated RIB facility in North America.

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Table 1. Oak Ridge Isochronous Cyclotron (ORIC) Parameters

Bending Limit (ME/q2)	100
Focusing Limit (ME/q)	75
Magnet System	
Pole face diameter	76 in
Number of compact sectors	3
Maximum spiral angle	30°
Minimum gap/maximum field	7.5 in/23.8 kG
Maximum gap/minimum field	28. in/13.2 kG
Main Coil Conductor	250 turns Al
Main Coil Power Supply	5000 A–350 V
Trim coils	10 pairs
Harmonic coils	4 pairs per valley
Weight	210 tons
RF System	
Configuration	Single 180° dee to ground
Maximum voltage per gap	70 kV
Maximum RF power	200 kW
Frequency range	6.7–20.1 MHz
Vacuum System	
Operating pressure	1×10^{-6} Torr
Pumps	Two 80-cm oil DP One 50-cm oil DP One 50-cm cryopump
Internal Ion Source	Cold cathode Penning
Extraction Channel	
One 60 cm long, 70 kV/cm, electrostatic deflector	
One 25 cm long, 3 kG, 5000 A, coaxial, sepum magnet	
One 100 cm long, 6.5 kG, 3000 A-3000 A, compensated iron, magnet channel	

Table 2. Estimated Maximum Beam Intensities and Energies from the ORNL Radioactive Ion Beam Facility*

Isotope	Beam Intensity (Ions/s)	Maximum Beam Energy (MeV/Amu)	Isotope	Beam Intensity (Ions/s)	Maximum Beam Energy (MeV/Amu)
^{10}C	4.3×10^{7}	13.0	^{63}Ga	1.8×10^{5}	6.1
^{11}C	5.0×10^{7}	13.0	^{64}Ge	1.8×10^{6}	6.0
^{14}O	1.4×10^{8}	13.0	^{68}As	1.1×10^{9}	5.9
^{15}O	3.3×10^{8}	13.0	^{69}As	1.3×10^{9}	5.9
^{17}F	1.1×10^{10}	12.7	^{70}As	1.0×10^{9}	5.8
^{18}F	5.8×10^{9}	12.3	^{70}Se	1.9×10^{8}	5.8
^{21}Na	4.3×10^{7}	11.2	^{71}Se	9.3×10^{7}	5.7
^{22}Na	4.3×10^{7}	10.7	^{72}Se	1.9×10^{8}	5.6
^{26}Si	1.2×10^{9}	8.8	^{74}Br	3.3×10^{7}	5.5
^{27}Si	1.0×10^{9}	8.8	^{76}Br	1.7×10^{7}	5.3
^{33}Cl	2.5×10^{10}	7.8	^{77}Br	6.8×10^{6}	5.3
^{34}Cl	2.2×10^{10}	7.5	^{77}Rb	1.4×10^{5}	5.3
^{37}K	6.5×10^{6}	7.0	^{78}Rb	1.2×10^{5}	5.2
^{38}K	3.3×10^{7}	6.8	^{79}Rb	1.2×10^{5}	5.2
^{58}Cu	1.0×10^{9}	6.3			

* These estimates are for 0.5 kW of ORIC beam power, isotopically pure targets, and do not include any decay, target release, or surface sticking losses.

Table 3. Estimated Overall Efficiency from Atoms to Accelerated Beam.[a]

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

[a] Excluding decay and target release losses.
[b] Metastable state.
[c] SI denotes direct surface ionization. CE denotes charge exchange.
[d] Scaled as discussed in the text.
[e] Measured efficiencies.
[f] F or G denotes gas or foil stripping in the tandem terminal.
[g] Includes an additional 50% reduction to account for transport losses to the tandem accelerator.

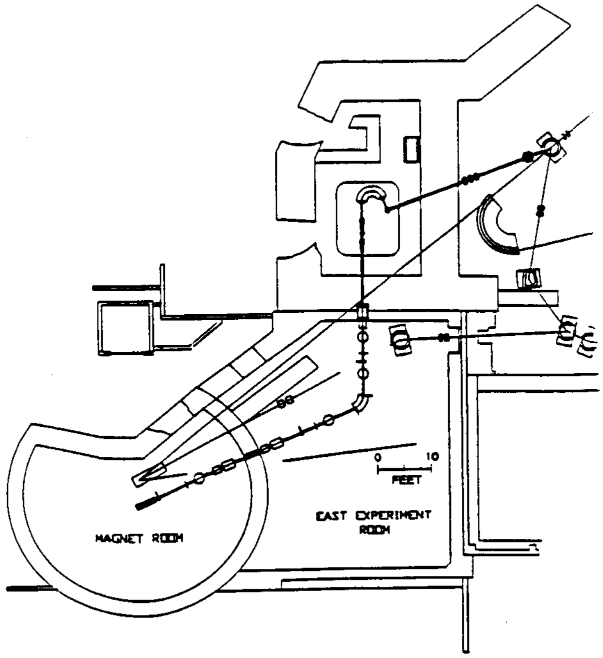

Figure 1. Additional hardware required to reconfigure the ORNL accelerator system to produce RIBs.

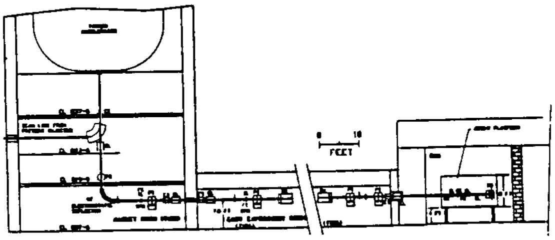

Figure 2. Elevation view of the ORNL RIB facility showing the HV platform and negative-ion transfer line to the tandem accelerator.

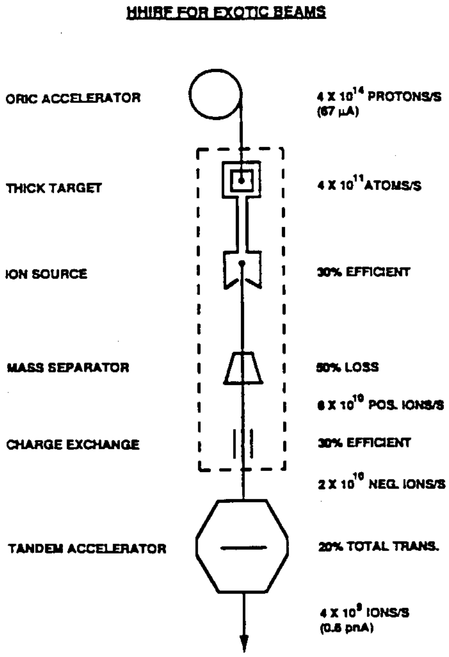

Figure 3. Summary of the ORNL concept and average efficiencies for a "good case" RIB produced with 67 μA of 30-MeV protons. About 10^{-5} of the primary beam of 0.6 pnA of RIBs would be produced as beam on target.