HRIBF: SCIENTIFIC HIGHLIGHTS AND FUTURE PROSPECTS*

JAMES R. BEENE

Physics Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37807-6368, USA

The Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory hosts a dedicated user program in nuclear physics using exotic beams. Vigorous and innovative research programs concentrating on nuclear astrophysics, nuclear structure and nuclear reactions are based at HRIBF, along with a Center of Excellence for Stewardship Science operated by Rutgers University and UNIRIB consortium. Recent work has concentrated on investigation of exotic nuclei beyond the N=50 and N=82 closed shells. HRIBF was developed out of an existing accelerator complex at ORNL at a modest initial cost. Projects to improve facility efficiency and reliability are underway. However, HRIBF will require additional investments to remain productive and competitive over the decade between now and the completion of the long-planned next-generation U.S. exotic beam facility. There are several additional ways in which a modest upgrade could substantially improve HRIBF performance and operation. The most promising and cost-effective of these appears to be addition of a high-power electron accelerator for production of neutron-rich species by photofission.

1. Introduction

The Holifield Radioactive Ion Beam Facility (HRIBF) has operated for more than a decade providing post accelerated beams of radioactive ions at energies well above the Coulomb barrier [1, 2]. Several years ago, HRIBF developed the capability to provide beams of neutron rich species generated by fission in actinide targets, at energies up to about 5 MeV/nucleon. An increasing fraction of our research program has been based on this unique neutron-rich capability.

HRIBF is currently able to deliver post accelerated beams of about 175 species of radioactive ion beams (RIBs). Of the ~175 RIB species, 32 are proton-rich and 143 are neutron-rich. More than 120 species have intensities in excess of 10^3 particles per second (pps), and about 60 have intensities more than

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10^6 pps. This beam list grows steadily; it is almost 50% larger than it was 5 years ago.

2. RIB Production Systems

HRIBF was developed at modest cost based on an existing accelerator complex at ORNL. Exotic beam species are produced by light ion beams (p, d, ^{3}He, and α) from the k=100 Oak Ridge Isochronous Cyclotron (ORIC). Beams are post accelerated by the 25MV tandem, the highest voltage electrostatic accelerator in the world. Maximum beam energies range from ~10 MeV/nucleon at A~40 to ~5 MeV/nucleon at A~135. The tandem requires negative ions for post acceleration. As a consequence ~30 additional RIB species of elements that do not form negative ions are available for experiments at low energy (~50 KeV) only. The RIB injector system, which we refer to as IRIS (injector for radioactive ion species), serves as the site for RIB production employing the isotope separator on-line (ISOL) method, provides mass and isobar selection and services the link to post-acceleration.

Two key measures of the quality of RIBs are the intensity of the desired RIB species and the intensity of unwanted isobaric species in the beam. High priority R & D efforts at HRIBF are devoted to developing target systems which maximize yield of desired species, and developing techniques which suppress unwanted species in the beam. Target technology has been improved slowly but steadily throughout the life of the facility. In addition, a variety of techniques have been developed to supplement the isobar suppression provided by brute force magnetic separation techniques. These techniques range from chemical effects in molecular ions to laser photo detachment methods [3, 4, 5]. In addition, well established techniques like ion beam cooling, species-specific ionization and resonance laser ionization [6, 7] have been investigated and improved for implementation at HRIBF.

2.1. *Ongoing Production System Improvements*

HRIBF was initially configured with a single injector for radioactive ion species (IRIS1). In 2003 a project was initiated to construct a second heavily shielded RIB production station. It initially provided a facility for testing and developing targets and beam manipulation techniques at full ORIC power. This production facility is now being incorporated into the facility as a fully independent second injector system, IRIS2. The elements of the IRIS systems operate in extremely hostile thermal and radiation environments. The additional redundancy offered by the availability of two IRIS systems will substantially

improve the efficiency and reliability of the HRIBF. In addition, IRIS2 has been designed with several newly developed beam manipulation and purification technologies in mind. The space available is much larger than on IRIS1, making allowance for future developments to be implemented. Furthermore, the IRIS2 facility is designed to operate with approximately three times more intense radiation fields than IRIS1.

3. Science Programs and Experimental Systems

Vigorous and innovative research programs concentrating on nuclear astrophysics, nuclear structure and nuclear reaction studies are based at HRIBF, along with a Center of Excellence for Stewardship Science operated by Rutgers University and the UNIRIB consortium [8]. The nuclear astrophysics program has carried out a series of high profile experiments with proton-rich radioactive beams of fluorine and beryllium isotopes relevant to rp-process nucleosynthesis and solar physics [9, 10]. Recent experiments have involved transfer reactions on neutron-rich nuclei near the N=50 and N=82 closed shells to provide information relevant to the r-process [11, 12]. The nuclear structure program has both an in-beam gamma-ray spectroscopy component and a decay spectroscopy component. Recent results in decay spectroscopy will be discussed at this conference by K. Rykaczewski [13] and J. A. Winger [14]. The in-beam gamma-ray spectroscopy program involves Coulomb Excitation and transfer reaction studies, primarily with neutron rich beams. These experiments are devoted to the study of nuclei near the N=50 and N=82 closed neutron shells, especially in the vicinity of the doubly magic nuclei ^{132}Sn and ^{78}Ni. Exploration of the evolution of shell structure in this region is a critical part of the near-term program in nuclear structure. Results on magnetic moment measurements will be discussed by N. Stone [15] and N. Benczer-Koller [16]. A recent highlight of the reaction program is a successful measurement of the near-barrier fusion of ^{134}Sn + ^{64}Ni to supplement the data on ^{132}Sn + ^{64}Ni obtained earlier [17].

The most cost effective way to improve the quality of experimental data coming from the HRIBF is to invest in powerful and highly efficient experimental detection systems. A variety of unique and highly optimized equipment is available at HRIBF [18]. All the research programs are actively engaged in developing improved experimental systems with uniquely powerful capabilities. Most of these projects will be discussed at this conference [8, 13, 18].

4. The Future of HRIBF

The HRIBF has demonstrated the capacity to produce important, high-profile results with the relatively small set of targeted proton-rich beams that have been developed to date. However, the focus of our experimental programs will, over the next several years, be centered on studies with our unique suite of neutron rich fission fragment beams. As the new and upgraded capabilities at other facilities which you have heard described at this conference become operational, this uniqueness will disappear. HRIBF scientific and technical staff has developed an integrated strategic plan for development of the facility which includes development of both forefront experimental tools and RIB production capabilities. We have searched for particularly cost-effective upgrades to the HRIBF that would make dramatic enough improvements to facility performance that it would continue to be competitive, at least within specific areas, to the world's best facilities until the long-awaited next generation rare isotope facilities come on line. Our conclusion is that the most attractive such upgrade, in terms of both cost effectiveness and performance is a capability based on photofission, driven by a high-power electron beam accelerator.

We have carried out an extensive program of simulations to define the performance of such a facility. We have considered first the potential performance of a baseline facility assuming ISOL target performance that has already been achieved at existing facilities. We set this baseline at an in-target fission rate of 10^{13}/s [19]. This is achieved with a modest-sized uranium carbide target with a total uranium mass of ~200g. The 10^{13}/s rate can be achieved with a 60 kW 25 MeV electron beam with a one radiation-length tungsten converter or 50kW 50MeV electron beam with a 1.5 radiation length converter. In either case the total power deposited in the target to achieve 10^{13} fission/s is approximately 10kW, and the maximum power density is ~200 W/g, essentially identical to that in currently used uranium carbide targets at HRIBF. The baseline 10^{13} fission/s rate is about twenty times larger than that currently achieved at HRIBF with 50 MeV proton beams. This factor does not provide a good measure of the increase in performance achieved with this baseline photofission facility. The photofission process is a substantially "cooler" process than 50 MeV proton induced fission (i. e., the fission occurs at a lower excitation energy). Consequently the number of neutrons emitted from the compound nucleus and from the final fission fragments is smaller, and the resulting fragments are more neutron rich. This is illustrated in figure 1 for Sn and Ge fission fragments. At the baseline rate the in-target yield of Sn isotopes

with A=132, 134, 136 and 138 are factors of 300, 900, 1400 and 10000 larger than those achieved at the present HRIBF facility using proton induced fission. The corresponding production rate of Ge isotopes with A=82, 84, 86 and 88 are 220, 1200, 3500 and 9000 times larger than present HRIBF rates. An idea of the reach of the photofission driven facility is provided by examples of the most neutron-rich species reached at a given post accelerated beam intensity, assuming current HRIBF target-ion source system and tandem post acceleration efficiencies. Intensities exceed 10^3pps out to ^{136}Sn, ^{141}Te, ^{86}Ge and ^{89}Se respectively. A plot of yields is shown in figure 2. We stress that these numbers refer to baseline fission rates which we believe can be reached with available target technology. Increases of factors of 3 to 5 beyond this seem entirely reasonable with improved target and ion source systems.

The estimated total project cost of adding a photofission driver capability to HRIBF is about $36M. This cost includes procurement of a commercial CW or near CW electron accelerator with beam power capability in the 100 to 200 kW range to allow room for progress well beyond the baseline rate.

Unfortunately, upgrades to provide comparable improvements in our proton-rich beam capability would be much more expensive. Consequently, we would continue to depend on ORIC to produce proton-rich beams. Since the large fraction of ORIC time devoted to neutron-rich beam production would be off-loaded by the photofission driver, we would have ample time to implement a plan of ORIC performance improvements without interrupting the research program. Significant, but much less dramatic, improvement in proton-rich beam intensities would eventually be available.

If the photofission driver concept proves to be as successful as we believe it will be, we would propose to add a modern superconducting linac to HRIBF as a post accelerator with the capability to accelerate A~140 beams to 10 MeV per nucleon. This would give a further increase in post accelerated beam intensity of factors ranging from 8 to 50 for beams now available with the tandem, while making the acceleration of beams of species that do not make negative ion possible.

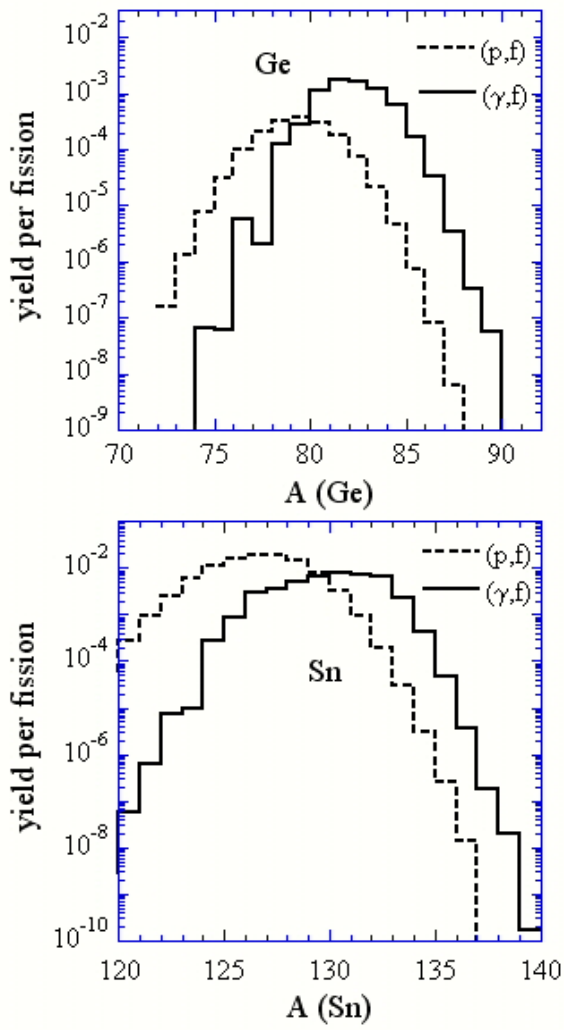

Figure 1. Yields per fission of Sn and Ge isotopes produced in 40 MeV proton induced fission on 238U, and photofission induced by bremsstrahlung from 25 MeV electrons.

5. Summary

HRIBF is a modest scale facility. We continue, however, to develop innovative techniques to produce unique and physically interesting beam species and intensities. Furthermore the experimental programs remain creative and productive. If we are to extend our contribution to the study of physics with rare isotope beams beyond the next few years, a major improvement in facility capability is necessary. We believe that the most promising direction is a photofission based upgrade to our neutron-rich capability.

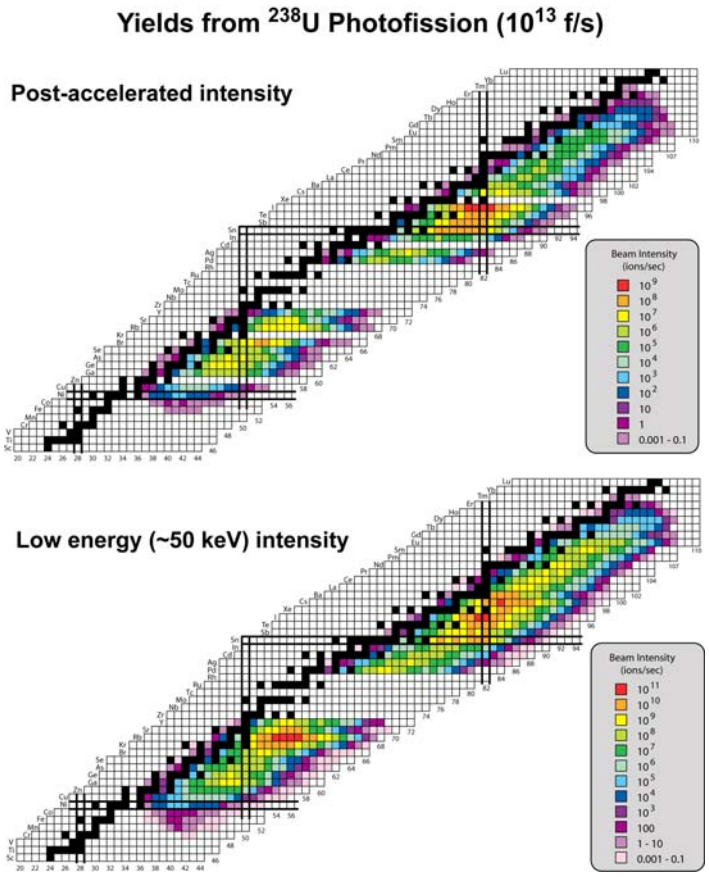

Figure 2. Predicted yields from a photofission driver based HRIBF at the baseline fission rate (10^{13} s^{-1}). Post-accelerated yields correspond to the 25 MV tandem.

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