Status of the FRIB project with a new fragment separator

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Abstract. The surprising variation of the cross sections for the production of the most neutron-rich nuclei by the fragmentation of $^{48}\text{Ca}$ and $^{76}\text{Ge}$ beams at Michigan State University (MSU) continues to show the importance of determining the properties of exotic nuclei. Future detailed studies of such exotic nuclei are being assured through the establishment of the Facility for Rare Isotope Beams (FRIB), a cutting-edge research facility to advance understanding of rare nuclear isotopes and the evolution of the cosmos, by the US Department of Energy at MSU. The new facility is expected to take something less than a decade to design and build and will provide a broad range of research opportunities for an international community. The facility is based on a superconducting-RF driver linear accelerator that will provide a maximum beam power of 400 kW for all beams ranging from uranium accelerated to 200 MeV/u, to lighter ions with increasing energy, down to protons at 600 MeV/nucleon. Rare isotope beam production at a beam power of 400 kW has never been done and presents a number of large challenges. The heart of the FRIB facility will be a next-generation three-stage projectile fragment separator specifically designed to handle the very intense primary and secondary beams.

1. Introduction
One of the important challenges facing nuclear physics is to push the study of neutron-rich isotopes to higher atomic number. The benchmark in this exploration is to find the maximum number of neutrons that can be bound for each atomic number. Often the delineation of the heavy limit of stability, called the neutron drip-line, itself has yielded surprises. Some years ago the heaviest bound oxygen isotope was shown to be $^{24}\text{O}$ while many theories predicted that the much heavier and putatively doubly-magic $^{28}\text{O}$ should be stable. Recently we found that heavy isotopes of aluminum are likely more bound than predicted [1]. Continuing this work, we report here the next step in this challenging exploration in the region about calcium.

The neutron drip line is only confirmed by experiment at present up to $Z = 8$ at ($^{24}\text{O}_{16}$) through years of work at various projectile fragmentation facilities. The neutron drip line has been found to rapidly shift to higher neutron numbers at $Z = 9$, i.e., $^{31}\text{F}_{22}$ has been observed several times, see e.g. [1]. The nuclide $^{30}\text{F}_{21}$ has been shown not to exist and $^{32}\text{F}_{23}$ is thought to be unbound based on systematics while the particle stability of $^{33}\text{F}_{24}$ remains an open question. The shift in stability of especially neutron-rich isotopes is predicted to continue at higher masses [2, 3, 4] and makes the search for the neutron drip line in this region even more challenging. The fragmentation of $^{48}\text{Ca}_{28}$ projectiles has produced a number of heavier nuclei in this region including $^{40}\text{Mg}_{28}$ and $^{42}\text{Al}_{29}$, but no clear limit has been established yet. [5] On the other hand,
Figure 1. The region of the chart of nuclides under investigation. The solid line is the limit of bound nuclei from the KTUY mass model [4]. Nuclei in the green squares were recently discovered [5, 1, 6], those in red squares are new in this work, and some of the cross sections for those in dashed boxes are shown in Fig. 2. The center of the new proposed island of inversion at $^{62}$Ti [8] is highlighted.

All nuclei up to $Z = 12$ with $A = 3Z + 3$ have been shown to be unbound. In the short term, the fragmentation of heavier stable beams such as $^{76}$Ge in which $^{52}$Ar was observed [6] is necessary in order to go beyond the previous work.

In the longer term, the production of the most neutron-rich nuclei will be an important component of the broad scientific programs at the next generation facilities such as FAIR in Germany, RIBF in Japan, and the recently announced Facility for Rare-Ion Beams, FRIB, in the United States. Michigan State University was recently selected by the US Department of Energy to be the site of FRIB. The proposed facility will provide primary beams at power levels up to 400 kW, compared to approximately 4 kW at the present National Superconducting Cyclotron Laboratory (NSCL) facility. In addition, all stable beams will be available at these...
Figure 2. The cross sections for the calcium isotopes are shown as a function of $Q_g$ using a variety of mass models, see text. Points are labeled by mass number.

high power levels and a new higher acceptance separator will provide significantly higher secondary beam rates. An overview of some of these features is given below.

2. Production of Neutron-rich Nuclei
In the most recent work at the NSCL a primary beam of $^{76}$Ge was fragmented and a search for new neutron-rich isotopes above $^{40}$Mg was carried out using the tandem fragment separator technique [1]. A 132 MeV/u $^{76}$Ge primary beam from the NSCL was used to irradiate a series of $^{9}$Be targets and finally a thick tungsten target located at the target position of the A1900 fragment separator [7]. The average beam intensity for the measurements of the most exotic fragments was 32 pnA. The A1900 fragment separator was combined with the S800 analysis beam line to form a two-stage separator system as described in Ref. [1]. Such a two-stage separator provides a high degree of rejection of unwanted reaction products and allows the identification of each fragment of interest. During the search for the most exotic fragments, a Kapton wedge (20.2 mg/cm$^2$) was used at the center of the A1900 to reject less exotic fragments at the A1900 focal plane by an 8 mm aperture. The transmitted fragments were identified by event-by-event momentum analysis and particle identification. The momentum acceptance of the A1900 was set to $\Delta p/p = \pm 0.05\%, \pm 0.5\%, \pm 1\%$ and $\pm 2.5\%$ as the production rate of the increasingly exotic nuclei decreased, always with an angular acceptance of 8.2 msr. The simultaneous measurement
of multiple $\Delta E$ signals, the magnetic rigidity, the total energy, and the TOF’s of each particle provided an unambiguous identification of the atomic number, charge state and mass number of each isotope.

Tarasov et al. [5] have shown that the cross sections for projectile fragments in this region have an exponential dependance on $Q_g$ (the difference in mass-excess of the beam particle and the observed fragment that is independent of the target in contrast to the older $Q_{gg}$ four-body analysis applied to low energy reactions) and deviations from the predicted yield may be used to identify anomalies in the mass surface such as the new island of inversion near $^{62}$Ti predicted by Brown [8] similar to the original island of inversion near $^{31}$Na.

Figure 2 shows that the $Q_g$ function using masses from a wide range of mass models and extrapolations, including Ref. [4] and Ref. [9], give similar results since the differences among mass models are small compared to the variation of $Q_g$. The figure shows that the logarithm of the cross sections for each isotopic chain falling on an approximately straight line except for the heaviest isotopes. On the other hand, most of isotopic chains with $15 \leq Z \leq 24$ can be fit with a single exponential slope of $1/1.8$ MeV [10, 11]. The heaviest members of the isotopic chains with $Z=19, 20, 21$ and $22$ break away from the uniform fit and the heaviest four or five isotopes have a shallower slope or enhanced cross sections. Recall that the masses of these most neutron-rich nuclei are not known but rather represent extrapolations. The observed increase in cross section might indicate that the excited precursors that give rise to the observed nuclei are more bound (i.e., less negative $Q_g$) than current mass models predict. One reason for a stronger binding can be deformation. In a shell-model framework, the wave functions of the ground and low-lying excited states of nuclei in the new island of inversion around $^{62}$Ti would be dominated by neutron particle-hole intruder excitations across the $N = 40$ sub-shell gap, leading to deformation and shape coexistence.

3. FRIB: the Facility for Rare-Ion Beams
The US Department of Energy announced that Michigan State University has been selected to design and establish the Facility for Rare Isotope Beams (FRIB), a cutting-edge research facility to advance understanding of rare nuclear isotopes and the evolution of the cosmos. The new facility is expected to take about a decade to design and build, and to cost an estimated $550 million and will provide a broad range of research opportunities for an international community. The facility is based on a superconducting-RF driver linear accelerator that will provide a maximum beam power of 400 kW for all beams ranging from uranium accelerated to 200 MeV/u, to lighter ions with increasing energy, down to protons at 600 MeV/nucleon. In addition, space will be provided in the linac tunnel and shielding in the production area to allow a future upgrade of the driver linac energy to 400 MeV/u for uranium and 1000 MeV for protons without significant interruption of the future science program. Space will also be provided in the production target area for other potential upgrades such as ISOL or even a second fragment separator. A schematic layout of the proposed FRIB facility and its connection to the existing NSCL facility is shown in Fig. 3. This facility layout has several important advantages, for example it allows the continued operation of the Coupled Cyclotron Facility (CCF) using fast, stopped and reaccelerated beams, it allows a relatively rapid connection of the new accelerator complex to the existing facility, and reuse of the experimental equipment.

Rare isotope beam production at a beam power of 400 kW has never been done and presents a number of large challenges. The production targets must be able to sustain very high power densities with the consequent thermal stress and radiation damage. Isotope production requirements include a maximum target thickness of $\approx 50$ mm with a 1-mm diameter beam spot, the ability to absorb (and dissipate) a continuous power of up to 200 kW, and a lifetime of more than one week (anticipated duration of typical FRIB experiment). Research and Development work to establish a target design that has these features is under way; a rotating multi-disk
Figure 3. A schematic view of the major components of the FRIB facility in relation to the existing NSCL facility.

graphite target with radiative cooling is under active study. In addition, a windowless liquid lithium target is being considered for use with the heaviest beams. Note that the beam dump for collecting the primary beam after the first separation stage has to be able to absorb up to the full 400 kW beam power although the beam spot size will be larger than that at the target. Research and Development on different beam dump concepts including a water-filled rotating cylinder is also under way. Nuclear interactions in the target and the dump will create very high radiation fields that will reduce the lifetime of the magnets that make up the fragment separator so that radiation resistant superconducting magnets will be needed.

The heart of the FRIB facility will be a next-generation three-stage projectile fragment separator specifically designed to handle the very intense primary and secondary beams. The conceptual design of the FRIB projectile fragment separator is shown in Fig. 4. The beam purity from the new separator will be at least two orders of magnitude higher than that possible from even the most modern one-stage separators. The first stage of the fragment separator, called the pre-separator, provides the initial rough-cut on the broad distribution of fragments, hosts a well-defined primary beam dump, and delivers the secondary fragments to the object point of the main separator without significant aberrations. The projectile fragments pass from the pre-separator into two subsequent high-resolution stages, based on a reconfiguration of the existing A1900 fragment separator used in the work described above.
Figure 4. The present conceptual design of the fourth generation fragment separator for the FRIB facility. The ion-optical layout is shown in the inset.

There is the opportunity for a pre-FRIB science program using the existing in-flight separated beams from the existing CCF and the new ReA3 reaccelerator presently under construction. Users will be able to mount and test equipment and techniques and push nuclear science forward with a variety of thermalized and reaccelerated fragmentation beams so that the science program will seamlessly continue on when FRIB is complete. This transition will allow for a continually evolving science program during the time FRIB is under construction that will form the basis of the research program at FRIB.

Acknowledgments
It is important to note that the work reported here was carried out by a large group of people at the National Superconducting Cyclotron Laboratory. The reader is referred to the author list in Ref.[10] for the names of the participants in the projectile fragmentation study. The FRIB project is made up from an even larger group with a leadership team headed by C.K. Gelbke (director) and T. Glasmacher (project manager), with G. Bollen, B.M. Sherrill, and R.C. York. The design and extensive calculations for the performance of the next-generation fragment separator described above come from M. Hausmann, B.M. Sherrill, and M. Portillo.

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