Expansion of the radioactive ion beam program at Argonne

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Abstract. The Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory (ANL) provides a wide range of stable ion beams and radioactive beams which have contributed to our understanding of nuclear structure and reactions. Until now, most radioactive ion beams at ATLAS were produced in flight using light-ion reactions such as \((p, n)\), \((d, n)\), \((d, p)\), \((d, ^{4}\text{He})\), and \((^{3}\text{He}, n)\). Within the next few months, the radioactive ion beam program at ATLAS will acquire much extended, new capabilities with the commissioning of a new facility: the CALifornium Rare Isotope Breeder Upgrade (CARIBU). CARIBU will supply ion beams of \(^{252}\text{Cf}\) fission fragments, which are thermalized in a gas catcher. The singly- and doubly-charged ions extracted from the gas catcher will be mass-separated and either delivered to a low-energy experimental area, or charge bred with a modified ECR source and subsequently reaccelerated by the ATLAS facility. Properties of hundreds of these neutron-rich nuclides will be investigated using ion traps, decay stations, the newly commissioned HELical Orbit Spectrometer (HELIOS), and other available experimental equipment such as Gammasphere and the FMA. HELIOS was constructed to take advantage of rare ion beams, such as those provided by CARIBU, through light-ion transfer reactions in inverse kinematics, and represents a new approach to the study of direct reactions in inverse kinematics which avoids kinematic broadening. Experiments are currently being conducted with HELIOS, and first results with the \(d(^{28}\text{Si}, p)\) and \(d(^{12}\text{B}, p)\) reactions have shown excellent energy resolution.

1. Introduction
Radioactive ion beams have played an important role for studies of nuclear structure and astrophysics. We have been surprised many times when our models of nuclei that are based on the properties of stable nuclei do not accurately characterize the properties of nuclei far from stability. Indeed, studies of the single-particle strength near closed shells, pair correlations, and collective aspects of nuclear structure have provided valuable insight, and much has been learned about explosive stellar phenomena and the origin of the elements from experiments using radioactive ion beams.

Many more radioactive ion beams are available today than in the past. The earliest radioactive ion beams accelerated by the ATLAS facility at ANL used a two-accelerator method in which one accelerator produced the radioactive isotope, such as \(^{18}\text{F}\) produced at the University of Wisconsin, which was then transported to Argonne and used as an ion source for the ATLAS accelerator [1, 2, 3]. This method provided radioactive ion beams for only a few long-lived isotopes; whereas, the majority of radioactive ion beams available at Argonne today are produced via an in-flight method and can have lifetimes on the order of milliseconds. This latter method uses a primary beam from the ATLAS accelerator which hits a cryogenically cooled gas target...
of either protons, deuterons, or $^3$He, and the reaction products are subsequently focussed, rebunched, and transported in flight to the experimental areas. \[4\]

The number of radioactive ion beams will be increased significantly in the very near future with the addition of CARIBU. This new ion source will provide neutron-rich isotopes from a 1-Ci $^{252}$Cf source which can accelerated by the current ATLAS facility. $^{252}$Cf has a 3\% fission branch, a 2.6 year half-life, and the nuclides available from $^{252}$Cf are quite complementary to existing facilities, including those which use particle-induced fission of uranium as a source of radioactive ions.

2. CARIBU

CARIBU, shown in Fig. 1, is a new source of ions that will make hundreds of neutron-rich nuclei available for acceleration by the ATLAS facility [5]. A key component of CARIBU is the gas catcher, which is composed of three parts: the ion source, the stopping volume, and the extraction cone. As part of the ion source, 1 Ci of $^{252}$Cf was electrodeposited onto a flat 0.1″-thick Ta backing covering an area of 5 cm in diameter. This $^{252}$Cf source sits inside the gas catcher and is covered by a gold foil for protection and confinement. Fission fragments from the $^{252}$Cf source pass through the gold foil and an additional aluminum degrader such that the residual energy of the fragments is lost to collisions with approximately 150 Torr of purified helium gas inside the 50-cm diameter stopping volume of the gas catcher. Although the flow of helium gas through the extraction cone of the gas catcher will carry fission fragment ions, this process is slow and inefficient for the extraction of short-lived isotopes. Therefore, the stopping volume and extraction cone consist of parallel plate electrodes which permit the application of electric fields: a DC gradient along the length of the gas catcher reduces the time the ions spend inside, and a ~ 2-MHz RF field applied such that adjacent plates with opposite phases form an RF carpet which helps to recenter the ions, thereby increasing the efficiency of the device. In the end, about 45\% of the fission fragment ions are extracted within 5-20 ms, and since the fission fragment ions are thermalized in helium gas, most of the neutron-rich nuclides are extracted from the gas catcher in a singly- or doubly-charged state due to the high ionization potential of helium.

Once the ions are extracted from the gas catcher, they pass through a radio-frequency quadrupole (RFQ) structure that forms a differentially pumped system. Here, the ions are guided with a DC gradient along the length of the RFQ and confined with RF fields applied in a similar fashion as those on the gas catcher. Since the mass of helium is significantly different from those of the fission fragments, the inherent mass selection of the RFQ allows the fission fragment ions to be guided along the length of the RFQ while the helium gas is pumped away. Due to the cooling of the ions through gas collisions in the RFQ, the transverse emittance of the ions is $3 \pi$ mm mrad, and the ions have an energy spread of only 1 eV. After two sections of RFQ structures, the residual gas pressure is sufficiently low for electrostatic acceleration of the ions by 50 kV for injection into the beam transport section.

Following the RFQ structures, a particular $^{252}$Cf fission fragment is selected with a compact isobar separator consisting of two 60-degree magnets with a 50-cm bending radius which provides a mass resolving power of 20,000. Since the fission fragments are far from stability, the masses of nearby isobars for a particular fission fragment are sufficiently different that a mass resolving power of 20,000 is quite adequate in most cases.

Once a particular fission fragment has been selected with the isobar separator, the fragment can then be directed to one of two beamlines. The fragment is either delivered to a modified ECR source, where the ions are charge bred to a higher charge state and subsequently reaccelerated through the ATLAS facility, or the fragment is sent through a low-energy beamline to a 'stopped' beam experimental area where mass measurements, lifetime measurements, laser spectroscopy, and decay studies can be performed. The low-energy beamline itself consists of a gas-filled
Figure 1. Layout of the CARIBU facility at Argonne. Fission fragments from a 1-Ci $^{252}$Cf source are thermalized in a gas catcher, extracted, and guided through RFQ coolers to an isobar separator where a particular nuclide is selected. This nuclide can then be delivered to either the low-energy beamline towards a ‘stopped’ beam experimental area, or a modified ECR source for charge breeding.

The RFQ structure at 50 kV which serves three purposes: to stop and cool the ions from the isobar separator, to accumulate the ions, and to bunch the continuous stream of ions injected into the RFQ. Before the ion bunches are sent to the stopped beam experimental area, they pass through a pulsed tube to convert the 50 kV beam to a lower potential as required for the particular experimental apparatus.

The first of three $^{252}$Cf fission sources has been installed in the CARIBU gas catcher. Once sufficient testing has been completed with the 2.5-mCi source, this source will be replaced with the 100-mCi, and eventually the 1-Ci, source. Initial experiments in the stopped beam experimental area are expected to begin by the end of the summer 2010 with the 100-mCi source, and the full experimental program with the 1-Ci source is anticipated by the end of the year. Further information about CARIBU, including expected yields, can be found online at: http://www.phy.anl.gov/atlas/facility/caribu_beams.html.

3. HELIOS

Ion traps, decay stations, the newly commissioned HELIOS, and other available experimental equipment such as Gammasphere and the Fragment Mass Analyzer (FMA) will be able to take advantage of the ion beams provided by CARIBU. For example, one of these devices, the Canadian Penning Trap (CPT) mass spectrometer, makes precise mass measurements of ions using a Penning trap located in the bore of a 5.9 T superconducting magnet. The results from previous measurements made by the CPT with a 100-$\mu$Ci source show a two-neutron separation energy which decreases with neutron excess more quickly than predicted by the 2003 atomic mass evaluation. If this trend were to continue with increasing neutron number, the location of the neutron dripline and the path of the astrophysical $r$ process would be closer to stability than previously thought. With CARIBU, more than 100 neutron-rich nuclides whose masses have never been measured will be accessible with the CPT.
Figure 2. Schematic of the HELIOS concept. From the left, ion beams travel along the magnetic field axis through a hollow Si detector towards a target. Charged particles emitted from the target undergo helical trajectories and reach the detector array in a time equal to one cyclotron period. If necessary, coincidences with recoils detected in a forward detector may be used.

Many properties of nuclei close to stability have been studied through transfer reactions such as \((d,p)\), \((^3\text{He},d)\), and \((\alpha,t)\) in ‘normal’ kinematics where light ion beams strike heavy, stable targets; however, using similar reactions for the study of the nuclei further from stability requires radioactive targets, which are difficult to produce. Instead, targets of light ions are used together with heavy radioactive ion beams to study the properties of nuclei through reactions in ‘inverse kinematics’. Traditional spectrometers, which measure the ejected particles as a function of angle, encounter difficulties in separating adjacent nuclear states in the inverse kinematics regime; much of the information contained in the forward angles in the center-of-mass system is compressed into a small energy interval at backward angles in the lab frame. This kinematical compression affects the energy resolution that can be obtained and makes particle identification difficult.

HELIOS is a new concept which avoids the kinematic compression from reactions in inverse kinematics. As shown in Fig. 2, the concept involves a beam of ions which enters the spectrometer along the magnetic field axis of a large-bore, homogeneous, superconducting magnet and strikes a target. Particles emitted from the target undergo helical trajectories and return to the magnetic field axis after one cyclotron period. With a hollow silicon detector array positioned along the axis of the magnetic field, the position along the field axis from the target, the flight time with respect to the pulsed beam, and the energy are measured. Since the cyclotron period is unique for every mass-to-charge ratio, \(m/q\), a measurement of the flight time
of the particles serves as a means of particle identification, while measurements of the energy and position on the array determine the center-of-mass energy and scattering angle. [6]

The HELIOS superconducting magnet has a maximum field strength of 2.86 Tesla, and the bore of the magnet is 92.5 cm in diameter and 235 cm long. Housed within the magnet is the Si detector array which consists of 24 position-sensitive detectors where the position-sensitive axis is along the axis of the magnetic field. The array itself forms an open square, with six 700-µm thick, 12 mm × 56 mm silicon wafers along each of the four sides. Tests of the array have shown the intrinsic energy resolution to be < 50 keV (FWHM) for protons.

A study of the excited states in $^{29}$Si via the $^{d}(^{28}$Si, $^{p}$)$^{29}$Si reaction served as a commissioning experiment for HELIOS. [7]. Targets of deuterated polyethylene were bombarded by a $^{28}$Si beam accelerated to 6 MeV/u by the ATLAS facility with an average beam current of 25 ppA. With the detector array fixed in position throughout the experiment, the range in center-of-mass angles was achieved by placing the target at three different positions. For the ground-state transition in $^{28}$Si($^{d}$, $^{p}$), this angular range corresponded to 51°. Particles emitted from the target were easily identified by their flight time relative to the 82-ns period of the ATLAS beam RF structure.

The first radioactive beam experiment with HELIOS studied the properties of low-lying states in $^{13}$B populated via the $^{d}(^{12}$B, $^{p}$)$^{13}$B reaction. Using the existing in-flight capability, a radioactive 75-MeV $^{12}$B secondary beam of up to $10^5$ ions/s was produced by bombarding a cryogenic deuterium gas cell [4] with a primary $^{11}$B beam accelerated to 81 MeV with the ATLAS facility. The $^{12}$B beam then passed through the Si detector array inside HELIOS before striking a 73-µg/cm² CD₂ target. The outgoing protons were detected in the Si array, and backgrounds were reduced by requiring a coincidence between these protons and recoiling $^{13}$B ions detected at forward angles in a Si telescope. A resolution of $\sim$ 100 keV (FWHM) in the excitation energies of $^{13}$B was observed which was sufficient to resolve the 3.48- and 3.68-MeV positive-parity doublet in $^{13}$B as shown in Fig. 3. Angular distributions for these two states were also obtained, and combined with relative spectroscopic factors, the spin and configuration of these states were constrained. Further details are provided in Ref. [8].

Figure 3. Spectrum showing the resolution of the 3.48/3.68-MeV doublet in $^{13}$B.
4. Summary
Radioactive ion beams have provided valuable insight into nuclear structure and astrophysics. The first such beams were available at the ATLAS facility in the mid 1990s with long-lived isotopes produced via the two-accelerator method. Since then, many more radioactive ion beams have become possible with in-flight techniques. The latest technological advance in the production of radioactive ion beams is the gas catcher, a device which is a key component of the new CARIBU facility that will provide neutron-rich isotopes from a 1-Ci $^{252}$Cf source. Experimental equipment will be able to take advantage of the ion beams provided by CARIBU, including HELIOS, a powerful new tool designed to study transfer reactions in inverse kinematics while avoiding the effects of kinematical compression that plague conventional spectrometers. As more radioactive ion beams become available, the properties of many more nuclei will be accessible to experimental studies.

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