Experiments with Radioactive Beams at ATLAS

K. E. Rehm^a, I. Ahmad^a, J. Blackmon^b, F. Borasi^c, J. Caggiano^a, A. Chen^d, C. N. Davids^a, J. Greene^a, B. Harss^a, A. Heinz^a, D. Henderson^a, R. V. F. Janssens^a, C. L. Jiang^a, J. Nolen^a, R. C. Pardo^a, P. Parker^d, M. Paul^e, J. P. Schiffer^a, R. E. Segel^c, D. Seweryniak^a, R. H. Siemssen^a, M. S. Smith^b, J. Uusitalo^a, T. F. Wang^f, I. Wiedenhöver^a

^a Argonne National Laboratory, Argonne, IL 60439

^b Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

^c Northwestern University, Evanston, Illinois 60208,

^d Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520,

^e Hebrew University, Jerusalem, Israel,

^f Lawrence Livermore National Laboratory, Livermore, California 94550

Abstract.

Various beams of short- and long-lived radioactive nuclei have recently been produced at the ATLAS accelerator at Argonne National Laboratory, using either the so-called In-Flight or the Two-Accelerator method. The production techniques, as well as recent results with ⁴⁴Ti ($T_{1/2}=60$ y) and ¹⁷F ($T_{1/2}=64$ s) beams, which are of interest to nucleosynthesis in supernovae and X-ray bursts, are discussed.

INTRODUCTION

The availability of beams of unstable nuclei at various facilities worldwide has allowed to investigate questions in several areas of nuclear physics that previously could not be addressed. For example, nuclei at the neutron or proton drip line exhibit new structures, such as skins and halos, which have been shown to strongly influence other reaction channels such as transfer or fusion. The effects of neutron-proton pairing can best be studied in heavier $N=Z$ nuclei, which beyond ⁴⁰Ca are β -unstable. In nuclear astrophysics it has been known for some time that a large fraction of the elements above $A \sim 20$ is produced in explosive nucleosynthesis where the reactions occur on such a rapid time scale that unstable nuclei produced in these processes do not have time for β -decay, but rather continue to react with protons, neutrons or α particles. Nature has no difficulties producing these unstable, short-lived nuclei in the stellar furnaces. In the laboratory, however, it was only during the last decade that some of these important reaction rates could be studied.

BEAM PRODUCTION

The majority of the radioactive beams are presently produced either via the isotope-separation- online (ISOL)

technique or with the projectile-fragmentation method. In the former the radioactive material is produced with a high-current driver accelerator or at a reactor. At high enough temperatures some of the nuclei effuse from the target material, are ionized and accelerated with a post accelerator. In the latter technique a high-energy heavy-ion beam is fragmented in a thin target, and the fragments, after electromagnetic selection are used directly in the experiment. Because of the production technique, the ISOL beams show better beam qualities compared to fragmentation beams. On the other hand the effusion from the target is for many nuclei a relatively slow process and, thus, short-lived nuclei are more efficiently produced with the fragmentation technique.

At the ATLAS accelerator at Argonne National Laboratory we have used modifications to the two techniques mentioned above. For longer-lived isotopes ($T_{1/2} \geq 2$ h) the irradiated material can be extracted from the production accelerator and converted into a suitable chemical form allowing to produce beams of nuclei that, because of their chemical properties, are difficult to extract using conventional ISOL techniques. Examples for these radioactive beams produced by the two-accelerator method are ¹⁸F or ⁵⁶Ni.

For shorter lived nuclei we have used the in-flight method to produce beams of e.g. ¹⁷F ($T_{1/2} = 64$ s) or ²⁵Al ($T_{1/2} = 7.18$ s). In this technique a high intensity

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FIGURE 1. Schematic of the experimental setup used to produce short-lived radioactive beams via the in-flight technique.

(d,n) or (^3He ,n) reactions secondary beams of unstable nuclei which are separated from the primary beam and transported onto a secondary target that is to be studied. An example for this technique is the production of a ^{17}F beam via the $d(^{16}\text{O}, ^{17}\text{F})n$ reaction. In this case a few ppm of the primary ^{16}O beam particles are converted into ^{17}F in the deuterium gas cell and transported through a 12m long beamline/separator system onto target. With a 100 pA primary ^{16}O beam a ^{17}F intensity of 2×10^6 has been achieved. The experimental setup is shown schematically in Fig.1.

A superconducting bunching resonator, located 10 m upstream from the production target provides a time focus of the primary beam at the gas cell, minimizing the longitudinal emittance of the secondary beam. The ^{17}F particles produced via the inverse (d,n) reaction are emitted within a cone with an opening angle of a few degrees. A superconducting solenoid located after the target is used to capture the particles within this cone and to focus them through a 22° bending magnet that separates the secondary $^{17}\text{F}^{9+}$ particles from the primary $^{16}\text{O}^{8+}$ beam. The selection of the particles according to their magnetic rigidity results in a suppression of the primary beam by a factor of $\sim 3 \times 10^{-7}$. The debunching resonator located about 3 m after the production target can be used to improve the energy spread of the secondary beam. By making use of the energy-time correlation and choosing the RF phase of this resonator appropriately the energy resolution of the secondary beam has been improved by a factor of 3 (see Fig.2).

The 400 keV energy spread achieved for the ^{17}F beam translates into a 23 keV spread in the c.m. system for a study of the $p(^{17}\text{F}, ^{14}\text{O})\alpha$ system.

The beams produced with these two techniques at the ATLAS accelerator, including their energies and intensities, are summarized in Table.1.

FIGURE 2. Effects of the debunching resonator on the energy distribution of a 60 MeV beam of ^{17}F

Details for some of the ion beams produced with the two-accelerator or the in-flight technique can be found in Refs.(1, 2, 3).

ION SOURCE AND ACCELERATOR

For the production of radioactive beams via the two-accelerator method a negative sputter source SNICS(4), dedicated to radioactive material, has been installed at the Tandem accelerator which is one of the two injectors of the superconducting heavy ion accelerator ATLAS. It has quite large efficiencies for certain elements(e.g. $\sim 1\%$ for fluorine) and it's compact geometry makes decontamination after a run much simpler. For elements with small electron affinity (e.g. Ti^-) molecules (e.g. TiO^-) have been used.

The beam intensities of the radioactive beams extracted from the ion source are usually too weak to either stabilize the terminal voltage of the tandem accelerator or the timing of the bunched beam which is required for injection into the superconducting RF accelerator. For this reason a wedge-shaped Bicron Corporation plastic scintillator was mounted on a photomultiplier and installed in the vertical plane behind the tandem 90° analyzing magnet. Timing signals from this scintillator were used to stabilize the time-of-arrival of the beam pulse by adjusting the phase of the pre-tandem buncher(5).

Another problem that had to be addressed was the tuning of the RF accelerator and the beam transport system. In some cases the stable isobar which is present in the source material can be used (e.g. ^{18}O for a ^{18}F beam).

Table 1. Radioactive ion beams produced at ATLAS

Beam	$T_{1/2}$	Production Method	I_{source} [sec ⁻¹]	I_{target} [sec ⁻¹]	E/A [MeV/u]
¹⁸ F	110m	two-accelerator	5×10^7	3×10^6	0.6
⁵⁶ Ni	6.1d	two-accelerator	2×10^7	6×10^4	5
⁵⁶ Co	77d	two-accelerator	1×10^8	3×10^5	5
⁴⁴ Ti	60y	two-accelerator	2×10^7	5×10^5	2-7
¹⁷ F	65s	in-flight	5×10^7	3×10^6	3-6
²¹ Na	22.5s	in-flight	2×10^7	5×10^5	5
²⁵ Al	7.2s	in-flight	1×10^7	2×10^5	5

In other cases, however, the intensity of this beam could overwhelm the detector system. For this reason the whole accelerator was tuned with a pilot beam which has the same magnetic rigidity and velocity as the beam of interest. For 250 MeV ⁵⁶Ni¹⁰⁺, a pilot beam of 125 MeV ²⁸Si⁵⁺ was used while for ⁴⁴Ti⁸⁺ the pilot beam was ⁶⁶Zn¹²⁺.

EXPERIMENTAL RESULTS

In the following results from two recent experiments are discussed in more detail.

Study of the ¹⁷F(p,α)¹⁴O Reaction

The relatively long half-life of the nucleus ¹⁴O ($T_{1/2}=70.6$ s), produced via the ¹³N(p,γ)¹⁴O reaction limits the energy production in the hot CNO cycle. ¹⁴O is, therefore, considered a bottleneck which is only broken when, at higher temperatures, breakout via the ¹⁴O(α,p)¹⁷F reaction starts to become possible. Because of the difficulties with a direct measurement of the ¹⁴O(α,p)¹⁷F reaction, which requires a low energy ¹⁴O beam and a He gas target, the inverse reaction ¹⁷F(p,α)¹⁴O was studied to get information about the properties of excited states in ¹⁸Ne.

In the experiment CH₂ targets with thicknesses of 100 or 500 μg/cm² were used. The energy and the scattering angle of the outgoing particles (p and ¹⁴O) were measured in coincidence with two position sensitive double-sided annular silicon strip detectors. The measurement of the four quantities θ_α , E_α , θ_{14O} and E_{14O} allowed for a clean identification of the ¹⁷F(p,α)¹⁴O reaction with a detection efficiency of about 65%. The measured cross sections are shown in Fig.3.

The circles represent measurements with a thin (100μg/cm²) target, while the crosses are the results from

FIGURE 3. Cross sections measured for the ¹⁷F(p,α)¹⁴O reaction. The symbols are explained in the text

a 500 μg/cm² target. The horizontal bars, shown for one point only, indicate the energy interval covered by the target thickness. The dotted line is the expected thick target yield using parameters from Ref.(6), while the solid line is that for the thinner target. The dashed line represents the direct component estimated in Ref.(7). The difference between the observed and the expected cross sections is due to incorrect spin-assignments for particle-unbound states in ¹⁸Ne and to the omission of higher-lying states in Ref.(6).

FIGURE 4. Measured excitation function for the $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ reaction. The solid line corresponds to a calculation done with the code SMOKER (see text for details).

Study of the $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ Reaction

Nuclei of ^{44}Ti are produced in the last stages of a supernova event in the so-called alpha-rich freeze-out(8). The recent observation of γ rays associated with the decay of ^{44}Ti from Cassiopeia A showed that the ^{44}Ti afterglow can be used to locate individual supernovae remnants. With the launch of the next-generation gamma-ray observatory INTEGRAL, new supernovae remnants are likely to be discovered. The amount of ^{44}Ti generated in a supernova is governed by a subtle interplay between the nuclear reactions that produce it and those that destroy it. For the latter the $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ reaction has been shown(9) to have the strongest influence.

This reaction was studied with the recently developed ^{44}Ti beam at ATLAS. The material was produced via the $^{45}\text{Sc}(p,2n)$ reaction using a 50 MeV, 20 μA proton beam from the injector of Argonne's Intense Pulsed Neutron Source. After a 70 hour long irradiation, 1.3 μg of ^{44}Ti were produced which was chemically separated from the Sc material. The $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ reaction was studied in inverse kinematics using a ^4He gas target and the Fragment Mass Analyzer for separating the ^{47}V particles from the incident beam. Details of the experimental setup can be found in Ref.(10). Figure 4 shows the measured cross section for the $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ reaction in comparison with results from the statistical model code SMOKER (11).

While at the higher energies good agreement with the theoretical predictions is observed the falloff towards

lower energies is slower than predicted resulting in cross sections that are about a factor of two larger than the SMOKER predictions. This translates to an astrophysical reaction rate which is higher by at least a factor of two than earlier theoretical predictions (12). This higher rate results in a reduction of the amount of ^{44}Ti produced in supernovae explosions. However, changes in other reaction rates which have not been measured so far, could effect the ^{44}Ti yield as well.

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