ANL/PHY/CP--87906

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NOV 21 1995

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Review of Work Related to Ion Sources and Targets
for Radioactive Beams at Argonne

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Abstract

A group including many ANL Physics Division staff and ATLAS outside users has discussed the possibilities for research with radioactive ion beams and prepared a working paper entitled "Concept for an Advanced Exotic Beam Facility Based on ATLAS." Several subgroups have been working on issues related to ion sources and targets which could be used in the production and ionization of radionuclides with high power primary beams. Present activities include: a) setting up an ion source test stand to measure emittances and energy spreads of ISOL-type ion sources, b) experiments to evaluate methods of containing liquid uranium for production targets, c) experimental evaluation of geometries for the generation of secondary neutron beams for production of radionuclides, d) setting up an ISOL-type ion source at a neutron generator facility to measure fission fragment release times and efficiencies, and e) computer simulations of an electron-beam charge-state amplifier to increase the charge states of 1^+ secondary beams to 2,3 or 4 $^+$. The present status of these projects and future plans are reported below.

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Introduction

There is currently a great deal of interest in the wide variety of nuclear physics research which could be done with an advanced Isotope Separator On-Line (ISOL) based radioactive beam facility. A working paper¹ entitled "Concept for an Advanced Exotic Beam Facility Based on ATLAS" was put together in early 1995 by many of the Argonne Physics Division staff members and outside users of ATLAS. The concept utilizes a driver linac which can deliver a variety of light heavy ions, from mass 1 to 40, with beam power of up to 100 kW at energies of 100 MeV per nucleon. These beams would produce intense yields of radionuclides in the production target/ion source complex by several different nuclear reaction mechanisms. This paper reviews the current status of R&D efforts related to various aspects of this critical component of any radioactive beam facility. The topics are divided into three closely related sections below. The first addresses issues associated with high power densities in the production targets and the resulting high radiation environment; the second, quantitative evaluation and refinement of ISOL-type ion sources to optimize emittances, energy spreads, and release efficiencies; and the third, evaluation of the tradeoffs between the use of 1^+ ion sources plus stripping, higher charge-state ion sources such as Electron Cyclotron Resonance types, and charge-state breeders of the Electron-Beam Ion Source types.

Radioactive Beam Production Target Geometries

Beams of light heavy ions at 100 MeV per nucleon produce very high power densities in the production targets. Hence, two-step geometries in which the high power is deposited in material physically separated from the ion source are desirable. One such method uses a 100 MeV per nucleon deuteron beam stopping in a neutron producing target which is situated adjacent to an

ISOL-type ion source containing ^{238}U for the production of neutron-rich fission products. This geometry was proposed in Ref. 2 and then tested by an ANL/MSU collaboration³ with a 200 MeV deuteron beam at the NSCL. The deuteron beam was stopped in a 25 mm thick solid uranium disk and the resulting neutrons induced fissions in a separate 1 mm thick uranium sample. Induced activities, including ^{132}Sn and ^{140}Xe , in the 1 mm samples were detected via germanium gamma detectors and identified via their characteristic gamma energies and known half-lives. The measured yields indicated production rates of 10^{13} ^{132}Sn per second in a 100 g/cm^2 uranium sample when scaled to the full primary beam power of 100 kW. Further R&D is required to develop a rotating target wheel capable of dissipating such primary beam powers. Designs which are an evolution of the proven meson production targets at LAMPF will be investigated. The present LAMPF rotating polycrystalline graphite wheels⁴ run continuously in vacuum for months at a time and dissipate 14 kW.

A variation on the neutron generating geometry discussed above can be used to produce neutron-rich light isotopes such as ^6He and ^9Li via fragmentation of beams such as ^{15}N or ^{18}O . Again, a rotating wheel of beryllium or graphite could be used to stop the primary beam (range $\sim 3\text{ g/cm}^2$) and dissipate its power, while the neutron-rich light fragments with ranges of 10-19 g/cm^2 would travel forward and be stopped inside the ion source with very high efficiency. Using this method accelerated radioactive beams with intensities in the 10^6 to 10^{10} particles per second range are predicted (including realistic estimates of delay losses and ionization efficiencies⁵).

Other production target/ion source configurations which will be utilized in a new high intensity radioactive beam facility include the various versions currently in use at ISOLDE⁶ upgraded for higher beam power. One such upgrade, by the RIST collaboration⁷, has had

preliminary tests already at ISOLDE and is scheduled for high power tests at the Rutherford Appleton ISIS facility in 1996. The use of refractory metal foils of materials such as tantalum, and various liquid targets of materials such as lanthanum and gold, in conjunction with 200 MeV deuteron and 400 MeV alpha particle beams at the proposed ANL facility would provide high yields of proton-rich nuclides via the (d,xn) and (α,xn) reactions (see yield predictions in Ref. 1). However, development is required to use these target configurations at high beam power with light heavy ions, which have higher stopping powers than the high energy protons which are used at ISOLDE.

Conceptual designs are also currently under development to deal with the high radiation environment in the vicinity of the production target and ion source for the radioactive beams. The target areas must be shielded by several meters of steel and concrete to attenuate the prompt fast neutron radiation while irradiations with the primary beam are in progress, and special handling and containment procedures must be developed to deal with residual activities from induced radiation. For the prompt radiation, calculations⁸ with both the NSCL shielding code⁹ and LAHET¹⁰ indicate that a cube of steel and concrete shielding 7m x 7m x 7m is adequate. The residual activation levels in the vicinity of the target of an IsoSpin Laboratory-class radioactive beam facility¹¹ are calculated to be a few thousand Rads/hour after about one week of decay following an irradiation¹². Estimates of the activities of specific isotopes have also been made¹³. Remote handling and containment procedures as presently used at the meson factories (LAMPF^{14,15}, TRUIMF¹⁶, and PSI¹⁷) and nuclear facilities¹⁸ will have to be adapted. A survey of commercially available telerobotic systems which may be applicable to handling and maintenance of highly activated target, ion source and beamline components was carried out during the

summer of 1995 and an informal report is available.¹⁹ Because of the intense radiation near the production target, it is imperative to use radiation stable materials²⁰ and radiation hard designs for all subsystems in this area.

Tests of ISOL-type Ion Sources

The base-line concept for the ANL Exotic Beam Facility assumes the use of proven ISOL-type ion sources⁶ which produce singly-charged radioactive beams with high efficiencies for a wide variety of elements⁵. These ion sources are capable of producing beams with excellent transverse emittances^{21,22} and narrow energy spreads²³, but there are few systematic studies of these parameters. Since the designs of both the isobar separator and first accelerator structures of a radioactive beam facility depend critically on these ion source parameters, the ATLAS Tandem Negative Ion Source Test Stand²⁴ is currently being refurbished to test and study ISOL-type positive ion sources. As a first step, a Gill-Piotrowski type high-temperature plasma ion source²⁵ has been installed and operated just before this conference. Systematic studies of its emittance and energy spread will begin in the near future.

Other important parameters of ion sources for radioactive beam applications are the release times and absolute ionization efficiencies. To carry out systematic studies of these parameters another test area for ISOL-type ion sources is currently being constructed at the Dynamitron Facility of the ANL Physics Division. The immediate plans are to construct a shielded cave in which to operate the Gill- Piotrowski plasma source. A 3.5 MeV deuteron beam from the dynamitron will be used to generate a secondary neutron beam for irradiation of ²³⁸U in the ion source target cell, as indicated in Fig. 1. A schematic view of the shielded cave which is currently under construction at the Dynamitron Facility is shown in Fig. 2. The shielding will be

adequate to run pulsed deuteron beams up to 100 microamps with average currents of 1 microamp.

The yields from the Be(d,n) reaction with the pulsed beams will be 2×10^{10} neutrons /Sr-sec at zero degrees²⁶. Using a low-density target of porous graphite impregnated with natural uranyl nitrate²⁵, and the close-coupled geometry indicated in Fig. 1, neutron-rich fission products such as ¹³²Sn and ^{140,142}Xe will be produced in the target at rates of approximately 10⁶/sec at 100 microamps. Nuclides which are released by the target matrix and ionized by the plasma source will be collected at the end of a short beam tube and identified via gamma spectroscopy as indicated in the geometrical layout in Fig. 2, thereby enabling quantitative efficiency and release rate studies.

To increase the density of the uranium targets it is also desirable to develop a practical method of using liquid uranium. Liquid targets of other elements such as Ge, Sn, La, Au, and Pb have been frequently used at ISOLDE for many years²⁷. However, the containment of liquid uranium for such applications has proven to be problematic. Currently tests of an alloy called TRIBOCOR²⁸ is being evaluated with the help of the Reactor Engineering Division at Argonne as a potential candidate for containing liquid uranium in ISOL sources. If the off-line tests of these crucibles are successful, they will be also tested on-line in the ion source test facility at the Dynamitron described above.

Charge-state/Stripping Options

The single most important figure of merit of an advanced accelerated radioactive beam facility is intensity of the beams available on target for research. The final intensity for a given beam is the product of many factors: the primary production rate of the nuclide of interest, the overall release

and ionization efficiency at the target/ion source complex (including decay losses due to time delays), the efficiency of the mass or isobar separator, and finally the overall efficiency of the acceleration and beam transport process. However, these factors are interrelated because the ion source parameters such as charge state and emittance determine in many ways the efficiencies of the systems which follow. For example, it would be very efficient to combine a proven high efficiency 1^+ ISOL-type ion source with an accelerator capable of accelerating the 1^+ beams to full energy without stripping; but, this process would be cost prohibitive and probably not even technically feasible. Hence, compromises are generally made either by using higher charge state ion sources or stripping to higher charge states after various stages of preacceleration.

In the benchmark design for the IsoSpin Laboratory presented in the white paper¹¹, it is proposed to use 1^+ ISOL-type ion sources followed by preacceleration and foil stripping at about 200 keV per nucleon, and then further acceleration and a second foil stripping at about 1 MeV per nucleon, with about 20% stripping efficiency at each stage. P. Bricault has done a detailed analysis of the total acceleration voltage required as a function of the two energies at which the stripping is done.²⁹ However, in order to gain about a factor of two in overall final intensity at the expense of more voltage required in the accelerator, the Argonne concept¹ is to do the first stripping much earlier, at about 8 keV per nucleon. At this velocity there are data³⁰ for several ions from krypton to uranium which show that stripping by helium gas from 1^+ to 2^+ , 3^+ , or 4^+ can be done with efficiencies of 44%, 35%, and 35%, respectively, for Kr (to 2^+), Ta (to 3^+), and U (to 4^+). At these energies helium yields anomalously high charge states and efficiencies relative to other gases due to its high ionization potential and corresponding high orbital electron velocity³¹. At these energies the gas thickness required to reach the equilibrium charge state distribution is

about 10 cm at 10^{-2} torr. Since there are few data available to determine the optimum pressures and energies for this stripping stage, the Physics Division Dynamitron will also be used to do some systematic studies of these charge state distributions and efficiencies. The Dynamitron can easily produce the 0.5 to 3 MV beam energies for krypton and xenon beams required for these studies. It may be possible to increase the percentage of beam in the 2^+ charge state, for example, by stripping at slightly higher energies and using less than the equilibrium gas thickness.

At this time the only class of ion sources which are proven to be useful for the production of a wide variety of radioactive beams with high efficiencies and good emittances are the ISOL-types (for 1^+ ions) as developed over the past 20-30 years at facilities such as ISOLDE⁵. Hence, the current ANL concept¹ is based on the use of this type of ion source. However, there are several projects in progress around the world to apply higher charge-state sources such as Electron Cyclotron Resonance^{32,33} and Multicusp³⁴ ion sources to the production of radioactive beams. There are also new concepts in the category of "charge-state breeders" which may lead to useful devices in the future. One type, proposed by the REX-ISOLDE collaboration³⁵, uses a large Penning ion trap to accumulate radioactive ions from a standard 1^+ ion source followed by breeding to high charge states in a batch transfer process in an Electron Beam Ion Source (EBIS). Another concept, for which computer simulations are currently in progress at Argonne³⁶, is an EBIS-type stripper which could operate in a DC mode. For the near future it does not appear that any of the newer ion source or charge-state breeder concepts will replace the well established ISOL-type sources for a general purpose radioactive beam facility which requires high intensities for a wide variety of beams including the mass range of $A=100-200$. The new concepts are likely to be most useful, at least initially, for fairly specialized applications.

This work was supported by the U.S. DOE Nuclear Physics Division under contract W-31-11-ENG-38.

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Figure Captions

Figure 1. A schematic section view of the high temperature plasma ion source modified to be close coupled to a neutron generating target. Neutrons are produced by 3.5 MeV deuterons in a beryllium target located 5 cm from the uranium sample in the ion source. Not all components of the ion source are shown.

Figure 2. Schematic plan (upper) and elevation (lower) views of the geometry of the cave which is currently under construction for testing ISOL-type ion sources at the Dynamitron Facility. The overall cave dimensions are approximately 2.5 m x 2.5 m x 3. m, with steel for the inner shield material and concrete for the outer. The deuteron beam from the Dynamitron enters from the right and is stopped in the beryllium target as indicated in Fig. 1. Fission fragments are produced in the natural uranium sample in the plasma ion source, extracted, ionized, and accelerated to a catcher at the end of the short beam tube. The product nuclides are identified via gamma spectroscopy at the beam stop outside the shielded cave.

Fig. 1

Fig. 2