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Authors
Alonso, J.R.
Feinberg, B.
Kalnins, J.G.
et al.

Publication Date
1989-10-01

UC-413

LBL-28114

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the Radioactive Nuclear Beams 1st
International Conference, Berkeley, CA, October 16–18, 1989,
and to be published in the Proceedings

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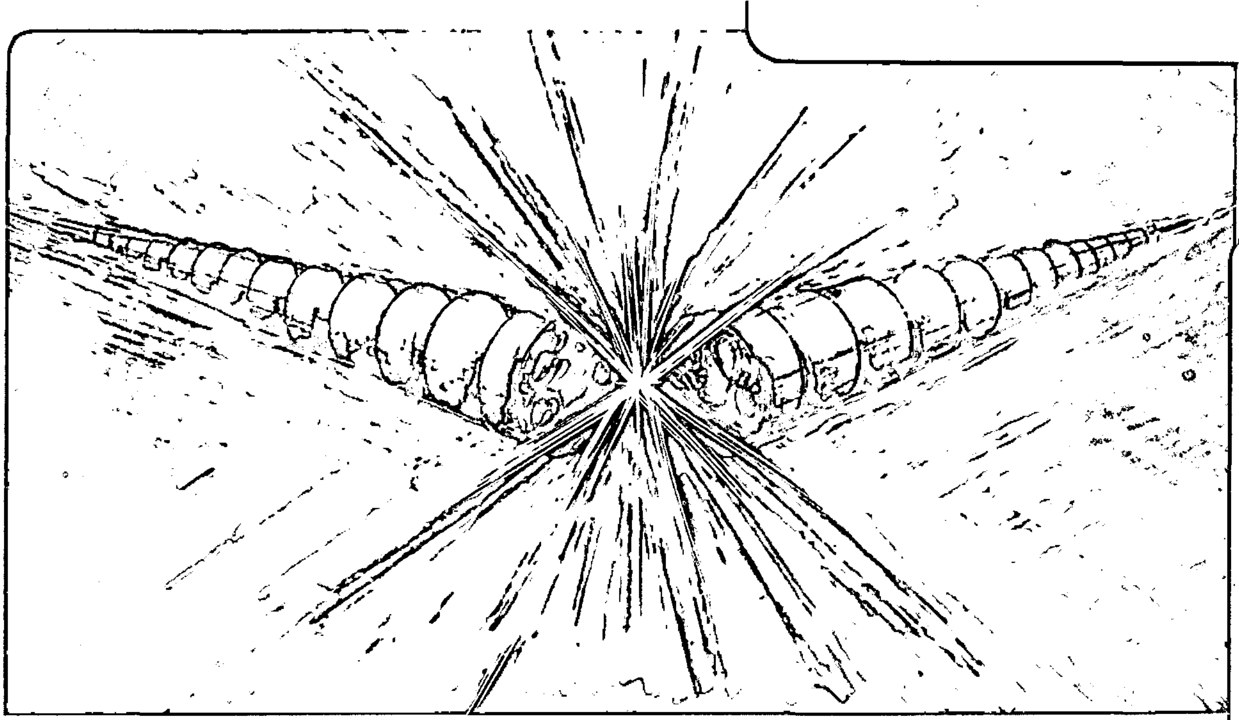

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

LBL-28114

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J.R. Alonso, B. Feinberg, J.G. Kalnins, G.F. Krebs, M.A. McMahan

Accelerator & Fusion Research Division
Laboratory Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

and

I. Tanihata

RIKEN, 2-1 Hirosawa, Wako Saitama 351-01, Japan

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*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

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J.R. Alonso, B. Feinberg, J.G. Kalnins, G.F. Krebs, M.A. McMahan,
Lawrence Berkeley Laboratory, Berkeley CA 94720
and
I. Tanihata,
RIKEN, 2-1 Hirosawa, Wako, Saitama 351-01, Japan

ABSTRACT

At the Bevalac radioactive beams are routinely produced by the fragmentation process. The effectiveness of this process with respect to the secondary beam's emittance, intensity and energy spread depends critically on the nuclear reaction kinematics and the magnitude of the incident beam energy. When this beam energy significantly exceeds the energies of the nuclear reaction process, many of the qualities of the incident beam can be passed on to the secondary beam. Factors affecting secondary beam quality are discussed along with techniques for isolating and purifying a specific reaction product. The on-going radioactive beam program at the Bevalac is used as an example with applications, present performance and plans for the future.

INTRODUCTION

As the attendees of this conference will have observed, there are two principal mechanisms for producing radioactive beams. The first involves bombarding a target with a high intensity ion beam, generally protons, producing radioactive species at rest which are diffused out of the target and subsequently formed into a beam and accelerated. The second method passes a high-energy primary beam, parent species of the desired radioactive product, through a low-Z target where a significant fraction of the ions in the beam undergo nuclear peripheral fragmentation reactions. As the momentum change involved in such reactions generally is a small fraction of the total ion momentum, the secondary products have beam characteristics close to those of the primary beam, so can be transported, analyzed and brought to the desired experimental area with ease. This second method was pioneered at the Bevalac about twenty years ago, and has developed into one of the major programs at our facility. In this paper we will trace the development of the field, describe further the characteristics of these beams and their production mechanism, and briefly describe the programs at the Bevalac in this field.

HISTORICAL PERSPECTIVES

Experiments concerning the production, characterization and use of radioactive beams at the Bevalac have been going on since the early 1970's, even before the Transfer Line connecting the SuperHILAC and the Bevatron was built in 1974. With the first heavy ion beams from the Local Injector, the Heckman-Greiner group began studying the peripheral fragmentation reaction mechanism1) at high energies, and Tobias and Chatterjee discovered the possibility of producing radioactive species that could be implanted by this mechanism deep into biological tissues for tracer studies2).

With the commissioning of the Transfer Line and the advent of higher intensity beams, further applications of peripheral fragmentation for producing radioactive beams were developed. Crawford spearheaded a program of calibration of satellite instrumentation for NASA, where the ability to produce and identify a wide range of isotopes at a well-defined energy provided many vital calibration points for these cosmic ray instruments3). The first large-scale production of new isotopes was performed in 1979, in a short, but land-mark experiment where reaction products from a Ca-48 beam were analyzed and detected4). In a 24-hour run some 64 isotopes were observed, many for the first time. (See Figure 1.)

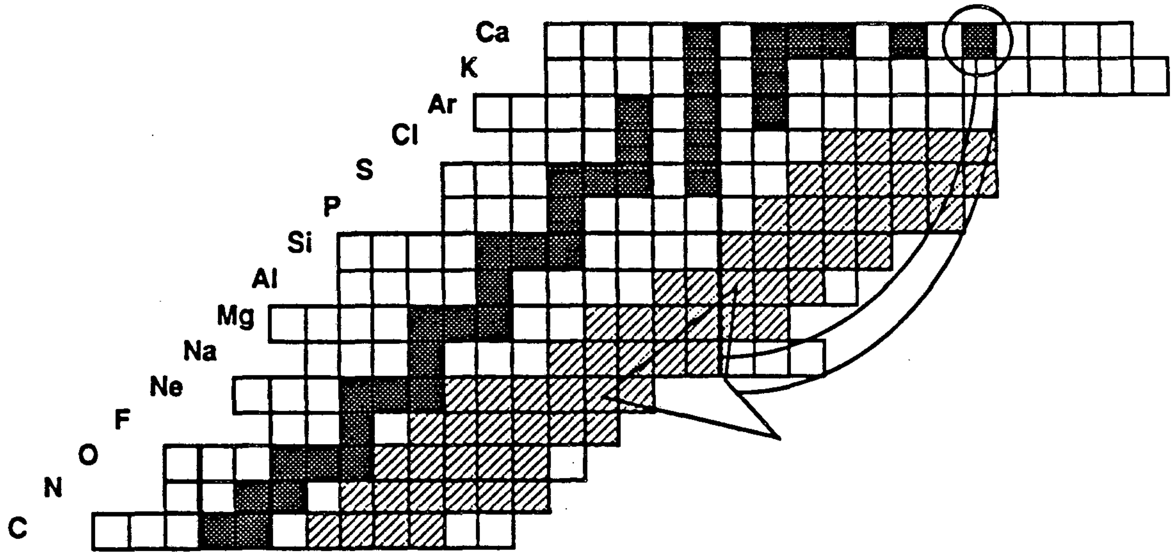

Fig. 1. Isotopes detected from fragmentation of Ca-48 (ref. 4)

The present program at the Bevalac has evolved from these early experiments, further descriptions will be given later in this paper. To demonstrate the depth of the program, however, it is sufficient to point to the twelve papers presented at this conference which are directly related to Bevalac work.

NATURE OF THE FRAGMENTATION REACTION MECHANISM

Mention should be made at this point of the review article by I. Tanihata$^{5)}$ which gives an excellent account of the ideas and techniques associated with fragmentation reactions for producing secondary radioactive beams.

The degree of violence in a heavy ion collision at energies well above the Coulomb barrier is directly related to the impact parameter between target and projectile nuclei. In central collisions most of the kinetic energy of the projectile is converted into excitation of the target-projectile system which results in the catastrophic dissociation of both nuclei. (See Figure 2a.) When the impact parameter is large, approaching the sum of the radii of the colliding nuclei, very little of the nuclear matter is involved in the collision (Figure 2b).

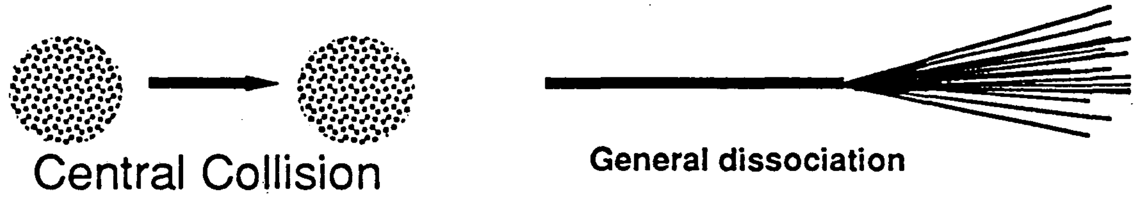

Fig 2a

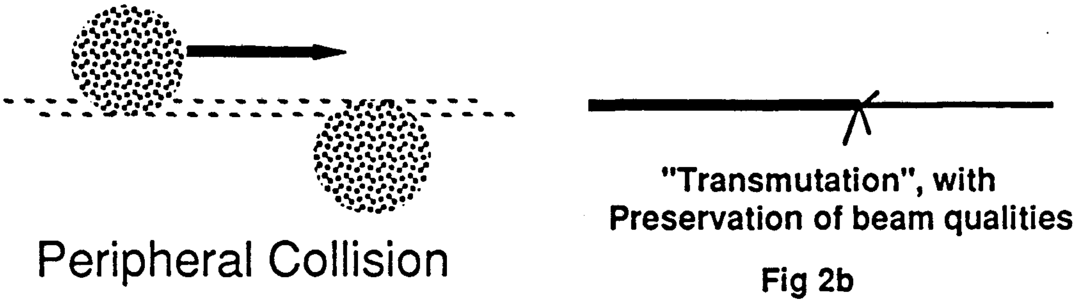

Fig 2b

As a consequence, little momentum is transferred between target and projectile, and the projectile retains most of its original kinetic energy. Figure 3 shows the momentum distribution of Be-10 fragments produced from primary C-12 ions at 2.1 GeV/nucleon, (Ref 1). There is a small downward shift in the average fragment momentum $<p_{\parallel}>$, and one sees a FWHM of about 250 MeV/c in the fragment momentum distribution, arising mostly from the effect of Fermi motion of nucleons in the interacting nuclei. As shown in the momentum diagram of Figure 4, the width of this distribution is negligible compared

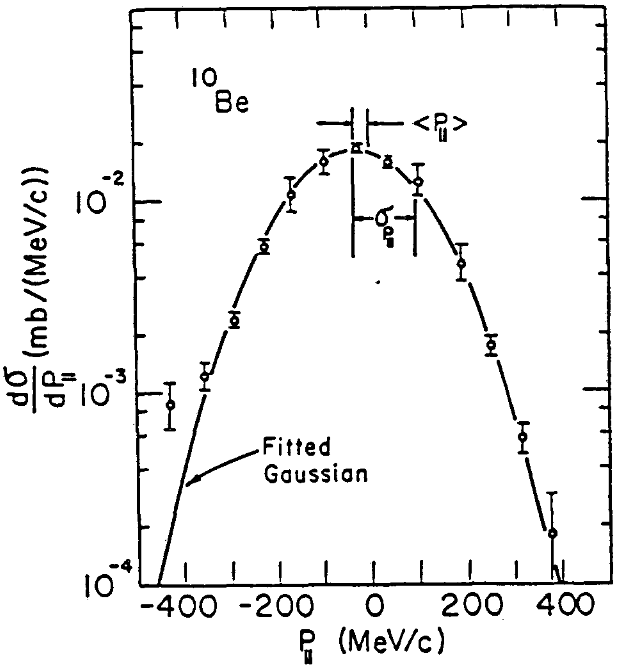

Figure 3. Fragment momentum distribution

to the primary beam momentum. Two important consequences of this type of collision are: the larger part of the projectile not involved in the collision, the spectator fragment, remains largely intact; and its velocity is close to that of the incident nucleus, thus preserving much of the beam quality of the incident beam. So, the secondary fragment can be conveniently transported from the target area, analyzed and purified according to its Z and A, and carried to an experimental area for study. Again emphasizing the point made in Figure 4, a key element of this process is the high degree of kinematic focusing obtained by the large ratio between incident momentum and the Fermi kick given to the product nucleus, thus placing a premium on the highest possible energy for the primary beam to make most use of this effect.. Referring to Figure 1 again demonstrates the wide range of isotopes which can remain as spectator fragments in this process, some produced with cross sections as high as 10 to 100 mb.

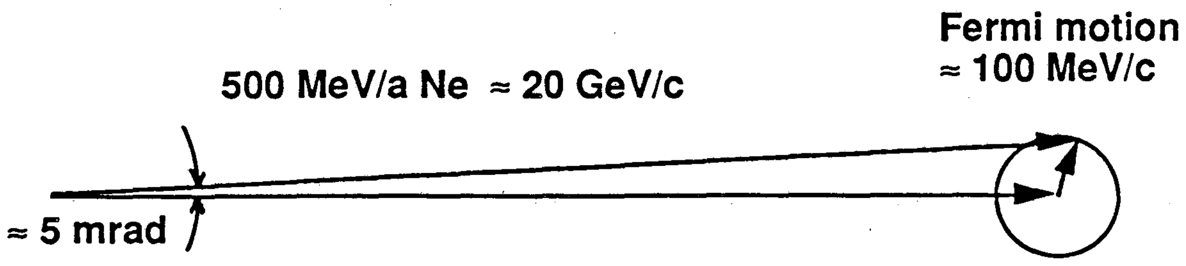

Figure 4. Kinematic focusing

TECHNIQUES FOR OPTIMAL PRODUCTION OF HIGH-ENERGY RADIOACTIVE BEAMS

Another benefit of using high energy is the ability to use thick targets to increase production of the desired isotope. At the Bevalac beryllium targets between 1 and 3 cm thick are normally used. The optimum target thickness is generally determined by balancing two effects leading to energy spread in the secondary beam. These, shown in Figure 5, are the Fermi spread due to the reaction itself $\langle p_{\parallel} \rangle$, and the difference in energy loss arising from where in the target the reaction takes place $\Delta(dE/dx)$. The extreme limits of this effect are shown in Figure 5 and correspond to the reaction occurring in the front or back surfaces of the target; the energy of the secondaries emerging from the target being decreased by an amount related to the dE/dx of the the secondary or the primary ions respectively. The optimum in production efficiency is achieved when these two effects are made approximately equal.

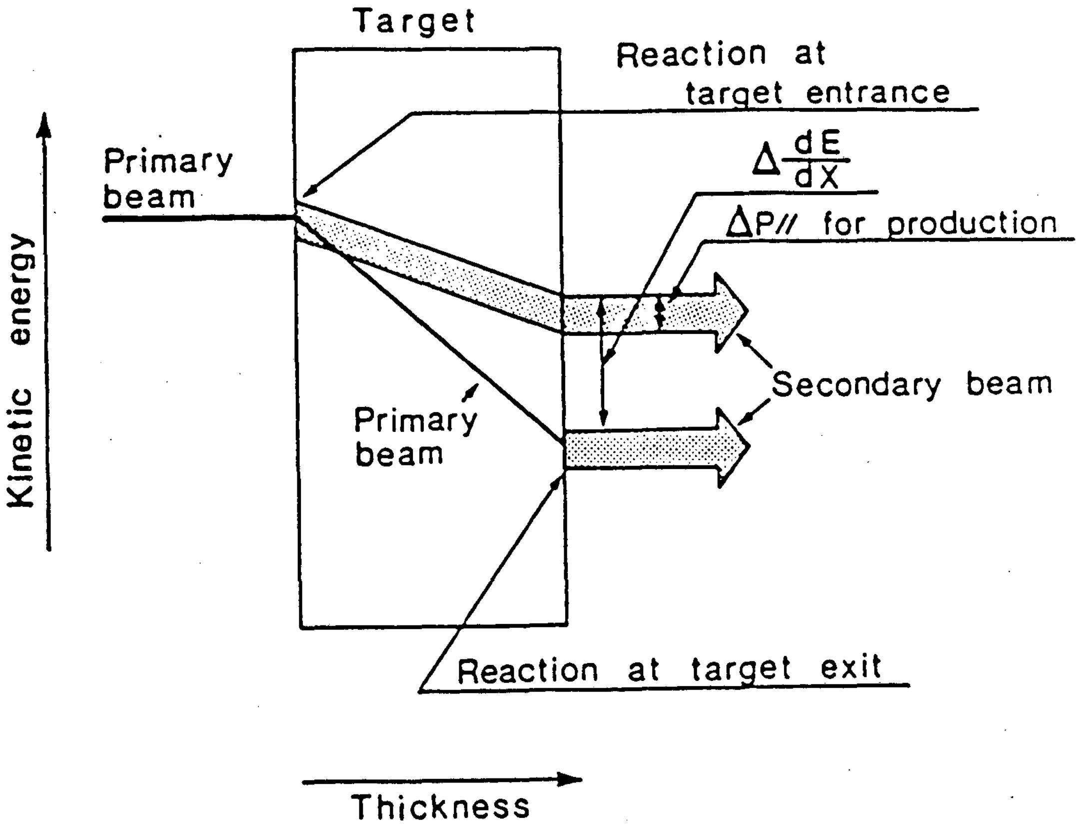

Figure 5. Schematic diagram for energy loss in a production target

The range of products coming from a thick target is quite broad; one must use the momentum of these ions to select the species desired. Normal magnetic analysis techniques can be employed. As the secondary ions all have very close to the same velocity, magnetic rigidity differences between, and hence separation of the products comes from different charge-to-mass ratios of the ions. Thus, Ne-19 will be focused at a different point than Ne-20, say, in a properly-designed beam transport line. Collimation at this focal point can select a given q/A set of ions. Although this will achieve a great degree of purification, selecting a single isotope requires another level of analysis.

Placing a degrader foil at this first focus, say behind the collimator, will introduce magnetic rigidity differences in the like-q/A ions, as different-q ions lose different amounts of energy in the degrader. Thus a second analysis section and another set of collimators will yield a monoisotopic beam of secondary products.

A technique for improving the energy spread in the beam is to employ a wedge-degrader. By placing a properly-designed wedge at a dispersed intermediate focus of the secondary beam the energy spread in the beam can be cancelled with appropriate energy loss in the wedge. This technique has been employed at the Bevalac to reduce by about a factor of 4 the momentum-distribution in a beam of Ti-43 ions6) .

ADVANTAGES AND DISADVANTAGES OF HIGH EHERGY FRAGMENTATION REACTIONS FOR RADIOACTIVE BEAM PRODUCTION

As stated above, kinematic focusing is most important for efficient transport of reaction products. At the Bevalac normal beam transport lines are employed, and the acceptance of these lines is critically dependent on the energy at which the ions are produced. Figure 6 shows for example that the acceptance of Beam 44 can vary by as much as three orders of magnitude when the primary beam energy is changed from 20 MeV/amu to 2.1 GeV/amu. At the highest energies the transport efficiency is quite high.

At Bevalac energies, the combination of kinematic focusing and thick targets leads to exceptionally high production efficiency. In routine operation for production of Ne-19 for radiotherapy patient diagnostic studies almost .2% of the primary Ne-20 beam is converted to Ne-19 and transported to the treatment room.

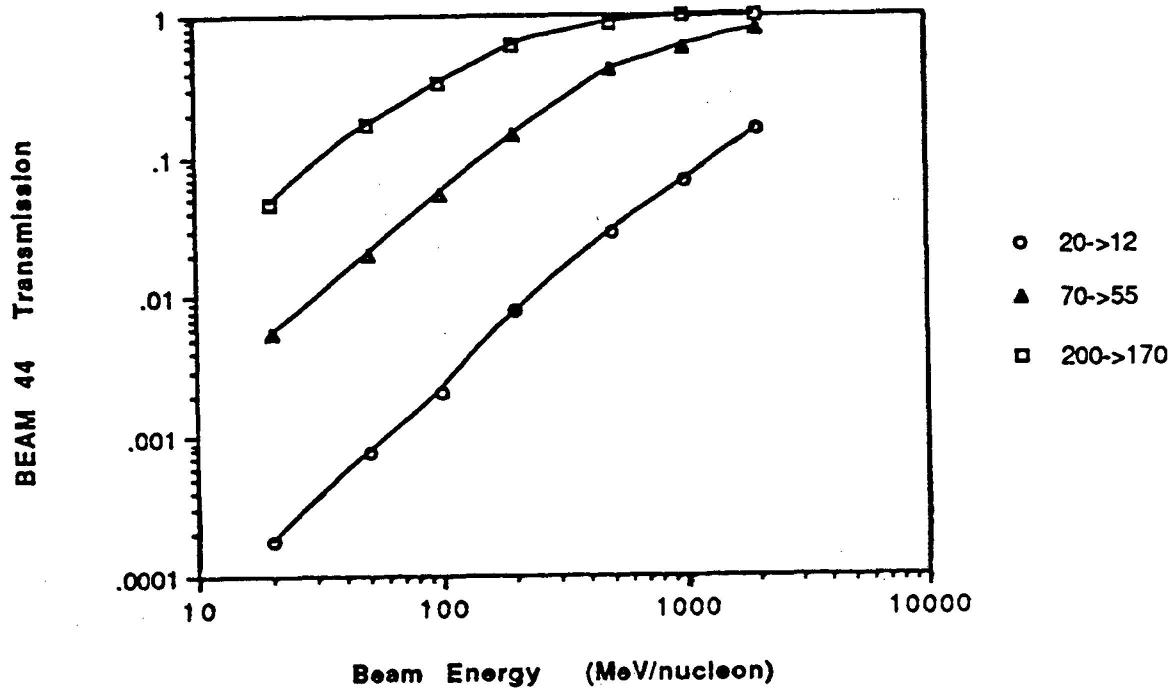

Figure 6. Beamline acceptance versus energy for three different secondary reactions: mass 20, 70 and 200 primaries going to masses 12, 55 and 170 respectively

The versatility of the fragmentation reaction process has been shown in Figure 1; we have seen that a very wide range of isotopes can be produced for study. The extensive studies at Ganil reported in this conference bear testament to this fact. Another advantage of high velocity production is the accessibility of isotopes with half-lives in the microsecond region. It is most likely that the definitive drip-line studies on both proton rich and neutron rich sides will be performed using this reaction mechanism.

Many properties of nuclei, such as radii and mass distributions can be performed at high velocities, where cross sections are relatively velocity-independent.

On the other hand, if experiments need to be done with beams of precisely-determined low energies, say in the few MeV/amu range, this type of reaction is at a clear disadvantage. Thus, many reaction cross section measurements of interest to the astrophysics community are not easily done at the Bevalac. It is expected, however, that the beam-cooling and deceleration capabilities planned for the ESR at GSI should overcome this problem.

PRESENT AND FUTURE PROGRAMS AT THE BEVALAC

Examples of radioactive beam characteristics for three currently active research programs at the Bevalac are given in Table I. The biomedical program utilizes Ne-19 for confirmation of treatment plans prior to irradiation of tumors in very close proximity to critical organs. Uncertainty of the range of the treatment beam due to tissue inhomogeneities in the beam path prior to reaching the treatment volume can cause errors in the stopping point of the beam of many millimeters, sometimes great enough errors to cause the beam to stop beyond or in front of the desired point. By detecting the positron-annihilation radiation from the stopped Ne-19, the stopping point of the beam can be accurately assessed. Over the past several years a significant number of the patients have had their treatment plans verified by this technique. Target yields of Ne-19 are close to 0.5%, with about a 30% transport efficiency of the produced isotope to the patient. Approximately one microcurie per pulse of the 20-second activity is deposited in the patient, ample for diagnostic studies.

Table I. Characteristics of Bevalac radioactive beams

	Biomed B1	HISS B42	B44
Acceptance {x',y'}	{±3.6,±5.0 mr}	{±3.6,±5.0 mr}	{±46,±16 mr}
Momentum (Δp/p)	±4.2%	±6.0%	±2.4%
Reaction	$^{20}\mathrm{Ne} \rightarrow {}^{19}\mathrm{Ne}$	$^{18}\mathrm{O} \rightarrow {}^{11}\mathrm{Li}$	$^{46}\mathrm{Ti} \rightarrow {}^{43}\mathrm{Ti}$
Incident energy	600 MeV/A	870 MeV/A	250 MeV/A
Cross section	≈100 mb	≈1 μb	≈5mb
Yield from tgt	0.5%	5×10^{-7}	2×10^{-4}
2ndary bm energy	550 MeV/A	800 MeV/A	90 - 60 - (1.5±1) (Paper G7)
Xport efficiency	30%	7%	10% (strong momentum selection)
Net yield (2nd/1st)	1/600	3×10^{-8}	2×10^{-5}
Primary ions	10^{10} ipp	10^{10}	10^{9}
2nd ions available	≈10^{7} ipp	≈10^{2}	≈10^{3} ß/sec

The Beam 42 program studies basic properties of s-d shell nuclei, such as radii and neutron-proton distributions in neutron-rich isotopes. As exotic nuclei are being produced the cross sections are low and maximum energy is used to make greatest use of kinematic focusing. Net yield of about 100 Li-11's per pulse were obtained in the HISS area, adequate for the studies performed. This beamline is capable of about 1/20 mass resolution; plans are now in place for bringing a new beamline, Beam 45, into the HISS area. This line, to be completed by Fall 1990, will have much greater analysis capabilities, and should provide resolutions into the mass 100 region.

In Beam 44, measurements of beta-decay properties and magnetic moments are made in the mass 40 region. The primary difference between this program and that in Beam 42 is that the object isotopes are produced, analyzed and purified, then stopped in a catcher to make the desired measurements. Consequently, the production energy for these isotopes, 250 MeV/amu, is a compromise between kinematic focusing and the need to stop the beam in a thin catcher. The beam energy is dropped to around 90 MeV/amu after the first analysis point, then is degraded to about 5 MeV/amu just upstream of the catcher. A monochromatizing wedge at the first degrader serves to reduce energy spread and increases the efficiency of the catcher by a significant amount. This catcher is in a highly uniform magnetic field and is surrounded by beta counters. Lifetime measurements are made directly with the counters, while magnetic moment measurements are made by first polarizing the beam in a tilted-foil stack just upstream of the target, then observing anisotropy in the up/down beta-decay rates, and destroying this anisotropy with NMR at the appropriate frequency. These studies are continuing, with emphasis on optimizing the polarization mechanism to improve measurement sensitivity.

SUMMARY

The fragmentation mechanism for radioactive beam production has been demonstrated to be highly efficient, and extremely useful for a wide variety of research programs. This fertile field, pioneered at the Bevalac, has been successfully transported to GANIL, and new beamlines are being commissioned at RIKEN and MSU. Although these facilities operate at significantly lower energy than that available at the Bevalac, they can make up with increased intensity for the loss of kinematic focusing. Without doubt the premiere facility for the next decade will be SIS, with its high energy, and the very sophisticated fragment separator line leading to the ESR complex. It will be with great excitement that we follow the development of this facility.

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* Work supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division, U.S. D.O.E., under Contract No., DE-AC03-76SF00098.

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LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720