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SOURCES OF RADIOACTIVE IONS*

Jose R. Alonso
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

Beams of unstable nuclei can be formed by direct injection of the radioactive atoms into an ion source, or by using the momentum of the primary production beam as the basis for the secondary beam. The effectiveness of this latter mechanism in secondary beam formation, i.e. the quality of the emerging beam (emittance, intensity, energy spread), depends critically on the nuclear reaction kinematics, and on the magnitude of the incident beam energy. When this beam energy significantly exceeds the energies typical 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 secondary product. The ongoing radioactive beam program at the Bevalac is used as an example, with applications, present performance and plans for improvements.

Introduction

The possibility of using short-lived radioactive species as projectiles has opened up vast new areas of research in fields as widely disparate as cancer radiation therapy, nuclear physics and stellar evolution. Significant activity has occurred in recent years; proceedings of a 1984 workshop [1] summarize not only research interests but also the current state of techniques and technology in this field of radioactive beam generation and applications. Further thoughts on present and future uses of such beams have been given in a review talk by Nitschke [2].

Production Mechanisms

Almost any nuclear reaction can be used as the initiator of a beam of radioactive ions. How the beam is actually formed is dependent on the velocity with which the new ion leaves the reaction site. Where this velocity is low, the ion is usually stopped close to the production site, and transported either mechanically, thermally or electrically to a high-efficiency ion source which serves as the beam-forming element. Ions normally emerge in a 1+ charge state, and can easily be transported to the area of study. Spallation reactions are used at ISOLDE in CERN [3], 600 MeV protons striking a heavy target producing large amounts of short-lived nuclei, while OASIS [4] at the SuperHILAC is representative of secondary ion spectrometers which utilize low energy heavy ion reactions for producing the species to be studied. The nature of the experimental apparatus makes the particular reaction dynamics irrelevant, all memory of the produced ion velocity is lost during the stopping, transport, and reionization process. Thus nuclei produced in compound nucleus, transfer, or deep inelastic reactions can all be studied.

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The compound nucleus reaction, especially with very heavy ions, produces recoil nuclei of sufficient energy to be transported through an analysis system to a low-background detector area. Examples of such experiments are SHIP at GSI [5] and SASSY at the SuperHILAC [6], both involved in transuranic element work. Although the nature of the reaction leads to relative uniformity in the recoil ion kinematics, the low recoil velocity and resulting broad charge state distributions of the ions lead to large experimental difficulties.

The most useful class of reactions for secondary beam formation are those in which the target serves only as the agent for transmuting the beam nucleus. Such reactions usually see the projectile nucleus barely grazing the surface of the target nucleus, exchanging a few nucleons or some energy, but preserving much of the incident energy and momentum. Thus the reaction products emerge from the target in a form which allows for satisfactory transport and analysis. We will see presently that the ease of such transport and analysis depends critically on the beam energy, but even at energies of a few MeV, this transfer reaction mechanism has generated secondary beams of useful intensity [7].

At higher beam energies (E > 100 MeV/amu) the grazing collision of two nuclei is referred to as a peripheral fragmentation reaction [8]; the "friction" generated by the small overlap area of the two barely-touching nuclei is responsible for emission of a few nucleons from the projectile. (Note, as the overlap area increases the collision gets more violent, allowing a wide range of reaction products. In the extreme case of a head-on collision, total disintegration can be seen; over 200 charged particles have been observed emerging from such a high energy central collision of gold on gold at the Bevalac [9].)

An example of the wide range of reaction products available from peripheral reactions can be seen in Figure 1. These yields were measured at the end of a 20 meter transport and analysis line, for a 200 MeV/amu 48-Ca beam on a beryllium target [10]. Note that cross sections for the most abundant products are in the tens of millibarns; we will see that these high values can lead to very attractive secondary beam

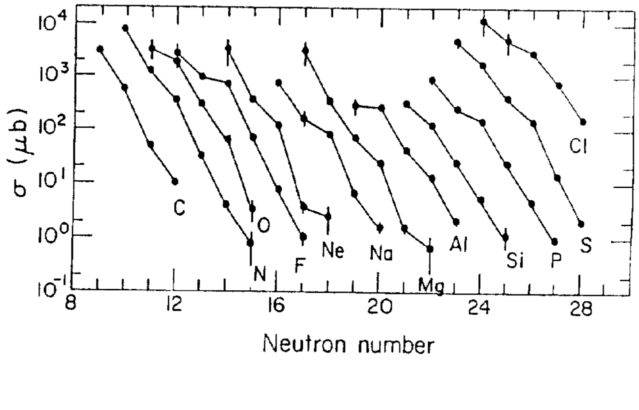

Figure 1.

Impact of Beam Energy

The scale of characteristic energies associated with nuclear reactions is generally fairly well fixed; Coulomb repulsion, binding energy for a single nucleon, Fermi motion of nucleons within the nucleus are all between a few and a few tens of MeV. Therefore the effect of a nuclear reaction on the momentum vector of the incident projectile is going to depend strongly on the ratio of the beam energy to these characteristic reaction energies. As an example, Figure 2 shows the range of angular deflection one would expect for an iron projectile nucleus striking a beryllium target as a function of projectile energy. The Rutherford scattering component, calculated for closest approach equal to the touching of the nuclear surfaces, drops to almost insignificant values above about 50 MeV/amu. The Fermi-motion component dominates throughout, but above a few hundred MeV/amu is at a level comparable with typical beam divergences encountered in accelerator beamlines. Consequently, at higher energies one should be able to produce secondary beams having transverse emittances not that different from those of primary beams.

This Fermi kick originates from the internal Fermi momentum of the nucleons directly involved in the reaction, and shows up as recoil of the projectile nucleus. Measurements of this Fermi kick [8] indicate that it is generally isotropic (contributing therefore to both angular divergence and energy spread), and quite constant at about 100 to 150 MeV/c, over a wide range of target, projectile and reaction product combinations.

Figure 2 shows that there are substantial advantages to using the highest possible energy for production of secondary beams. We will now discuss other factors which point to the same conclusion.

Secondary Beam Analysis

At sufficiently high energies, the first order impact of the peripheral collision is to not affect the projectile velocity at all. Thus one can start an analysis by assuming that all products coming from the target have the same velocity. To separate the various products by magnetic analysis, one then relies only on the difference in their charge-to-mass ratios. Again taking our example of a primary iron beam in a beryllium target, Figure 3 shows some of the reaction products and how much their rigidity differs from that of the primary iron-56. Note that 55-Fe and 54-Fe are rather widely separated from 56-Fe, but that isotopes of lighter elements, Mn and Cr shown here, fall very close to the iron isotopes, forming "families" of like q/A. As can be surmised from Figure 1, cross sections for products only a few nucleons removed from the primary beam are all roughly comparable, so that one would expect a fairly diverse atomic composition for each of these families. Thus, it may be easy to consider separating isotopes of a given element, but separating the members of a like q/A family will be more difficult. Techniques for doing this will be discussed later.

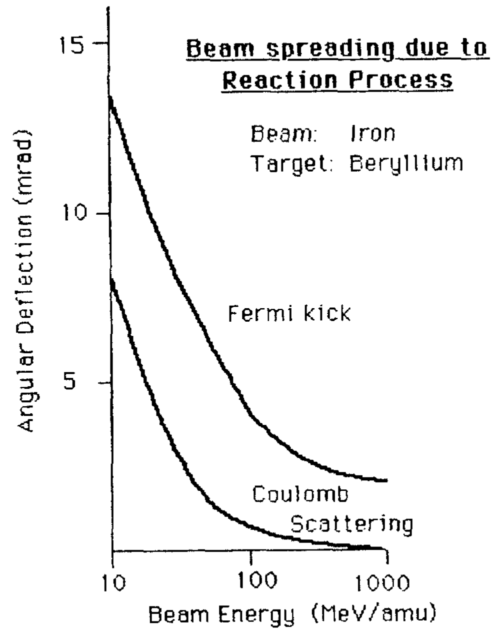

Figure 2.

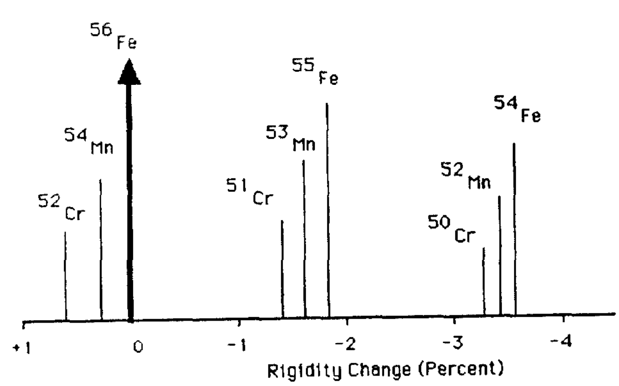

Figure 3.

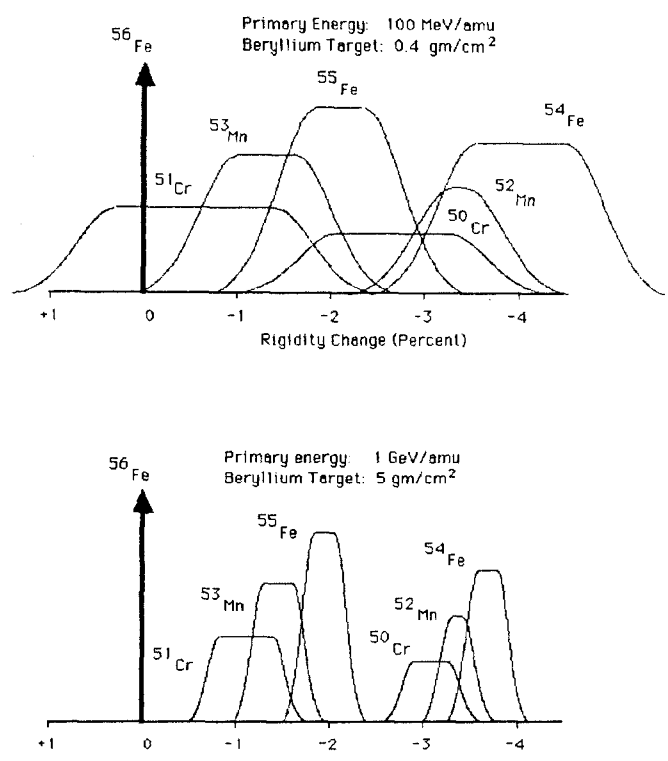

Figure 4.

Figure 3 represents an idealization of the spectrum of products emerging from a target. Several factors make things much more complicated. First of all, as mentioned in the previous section, Fermi motion contributes to energy spread of the reaction products. This will spread out the lines for each isotope (roughly into Gaussian-shaped distributions), generally causing overlap of all the members of a given q/A family. Note that this spreading becomes much more serious at lower energies, eventually causing overlap of adjacent families. Target effects also significantly influence the spreading of isotopic distributions, and will be discussed below.

Target Thickness Effects

Several important contributions to beam quality are directly attributable to the target, most notable is the energy-loss differential between the primary and secondary ions. This has a deleterious effect on the rigidity spread for the following reason. If the reaction occurs in the front surface of the target, then the new isotope undergoes energy loss through the whole target thickness. If on the other hand, the reaction producing the same isotope occurs at the back of the target, then it is the primary ion that has undergone the energy loss through the target. If the dE/dx of the primary and secondary ions are different, then the emerging secondaries will have a spread in energy. Since the reaction cross section is generally only slowly-varying with energy, the probability of a reaction taking place at any point in the target is roughly constant, the spreading observed will be flat and will depend on the target thickness and the difference in energy loss.

A figure of merit for target thickness can now be given; one wants as thick a target as practical, to maximize yield of the desired secondary, but should limit the thickness so that the target-induced spreading is no greater than the inherent Fermi-motion effect. Figure 4 shows the combined result of these two effects, at 100 MeV/amu and at 1 GeV/amu beam energies. The advantages of using higher energies are clearly seen. Note in addition that because dE/dx is so much lower for higher energy ions, the higher energy allows the use of a much thicker target, significantly increasing the yield of the desired ion, in this case by over a factor of ten.

A word about target materials should be interjected. All factors point to using low Z targets: lower dE/dx per atom, lower multiple scattering of the beam, higher ratio of peripheral to total reactions. As an example of the efficiency of the overall process, Figure 5 shows the net yield possible for the production of 11-C from 12-C [11]. For an energy loss of about 100 MeV/amu, almost 2% of the primary beam can be converted into the desired product, the bulk of the emerging beam falling within the acceptance of the Bevalac beam transport system. The target thickness exceeds one nuclear mean free path before a significant amount of energy is lost, leading to the falloff of the production curve due to exhaustion of the primary beam, and through reactions of the 11-C itself. For a similar energy loss in a lead target, production is down by a factor of four, and multiple scattering is doubled.

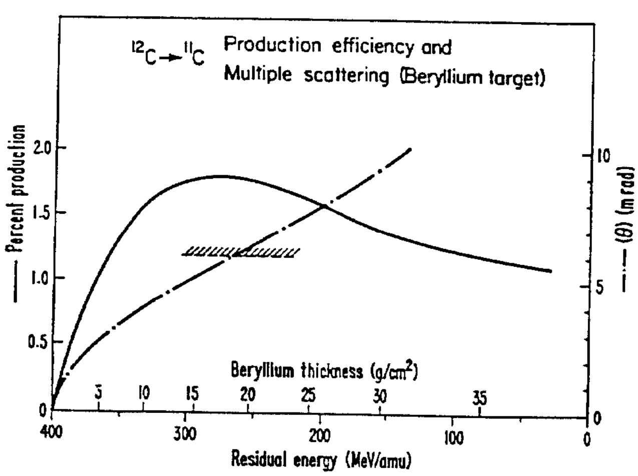

Figure 5.

Beam Line Design Features

It is important to note that the rigidity spectra shown in Figure 4 are intrinsic to the production process, and are in no way improved by any possible beam line or spectrometer design. These are the spectra that would be observed by a spectrometer of infinite resolving power. For production of a pure beam of a single isotope, one should start first with the highest possible energy of beam. In addition to all the advantages given above, high energies will also ensure that all ions are fully stripped, thus avoiding the problem of having desired ions in several different charge states.

If the intrinsic spectra allow for separation of individual q/A families, then certain design considerations in the transport system can help to achieve the goal of isotopic purification.

First of all, some angular spread in the secondary beam is unavoidable, due to the Fermi motion component and to multiple scattering in the target. To minimize the emittance growth of the beam, it is important that the primary beam be brought to the tightest possible focus at the target site.

Other aspects of a good beam line design are shown schematically in Figure 6. For maximum dispersion, a good-sized bend is introduced close to the first quads, bringing each q/A family to a focus at a different point on the first set of slits. The desired family is selected, and then is processed by the second set of elements. The family is passed through a degrader, and as each member has a different q, each will lose a different amount of energy, thus allowing separation at the next focus. The slight taper on the degrader is introduced to compensate for the dispersion at the first focus, all of the desired secondary ions will emerge from the degrader with the same energy, cancelling out the effects of Fermi motion and target thickness from the production target. (Note that this process has the effect of transferring longitudinal emittance (delta E) into transverse emittance, as the new source size is larger owing to the dispersion at the intermediate focus.) The net result of all this is that beam emerging from the second set of slits consists purely of the desired secondary isotope, with very little energy spread.

Applications

Several laboratories either have or are planning to develop the capability of generating the beams described above. Work at the CERN SC with heavy ions and Ganil has been reported by Dufour [12] and at MSU by Harwood [13]. At the lower energy available from these accelerators (E < 100 MeV/amu), secondary beam quality and intensity are not optimal, but nevertheless interesting work can be performed.

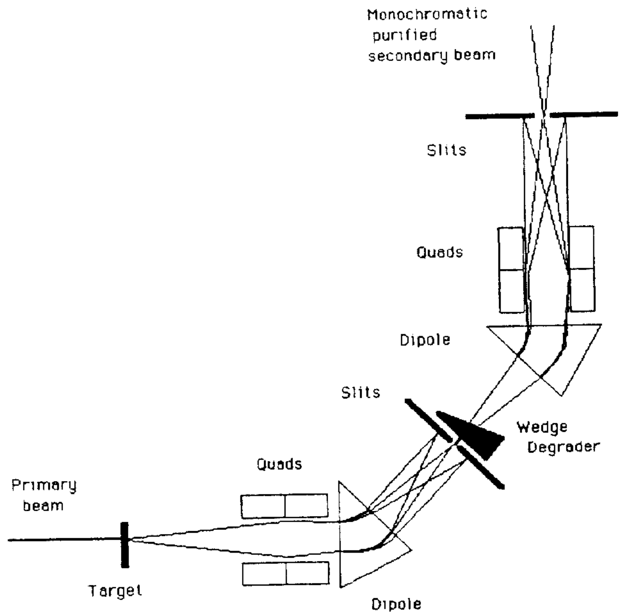

Figure 6.

The energy available at the Bevalac, up to 2 GeV/amu for light ions, is more suitable for such beam production [11]. For several years these capabilities have been exploited in various experimental programs at Berkeley.

Beams of 11-C and 19-Ne have been employed in the medical program [14]. As short-lived beta emitting tracers that can be implanted at any desired anatomical site, these isotopes have been used in blood-flow and organ-function experiments, as well as in human patients to verify the actual stopping point of the beam after traversing complicated structures in the body on its way to a tumor under treatment. This last application can be very important as there is no accurate way of calculating the total electron density along the path to the tumor, and some treatments require stopping the beam a few millimeters from a critical structure such as the spinal column. A direct measurement of the stopping point is viewed as extremely important for these very critical treatments. Intensities of these ions are quite good, approximately 1 microCurie per pulse of 19-Ne can be delivered into a patient.

Many nuclear science experiments using beams produced by peripheral fragmentation reactions have been performed also. New isotope searches [10,15] have been very fruitful, only a few hours of running time were needed to collect the data previously shown in Figure 1. Recent experiments in direct production of helium isotopes from 3 to 8 and measurements of their total reaction cross sections are shedding light on nuclear densities far from stability. These and other experiments are summarized by Tanihata [16], and represent a growing field of research at the Bevalac.

The external beam line system at the Bevalac is presently capable of the kind of isotope separation and purification discussed above up to mass 20. We are presently embarked on an improvement project which, with very slight changes in some magnet locations, and adjustments in optics, can increase the mass-resolving power up to at least mass 70. This project, to be completed by October 1985, will give us capabilities to significantly expand our work in this developing field of research.

Conclusions

High energy heavy ion beams are well suited to production of secondary beams of unstable nuclei of good quality and good intensity. We have seen that the production efficiency, beam quality and intensity are very tightly related with the energy of the primary beam, at energies above 100 MeV/amu these beam characteristics are significantly better than at lower energies. The demand for these beams, and the most interesting applications that are developing, all point to a growing emphasis on efficient production and delivery of these species for today's and tomorrow's heavy ion accelerators. After all, there are at least six times as many known unstable nuclei as stable ones, the challenge before us is to develop the full potential of these exotic projectiles.

Acknowledgements

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