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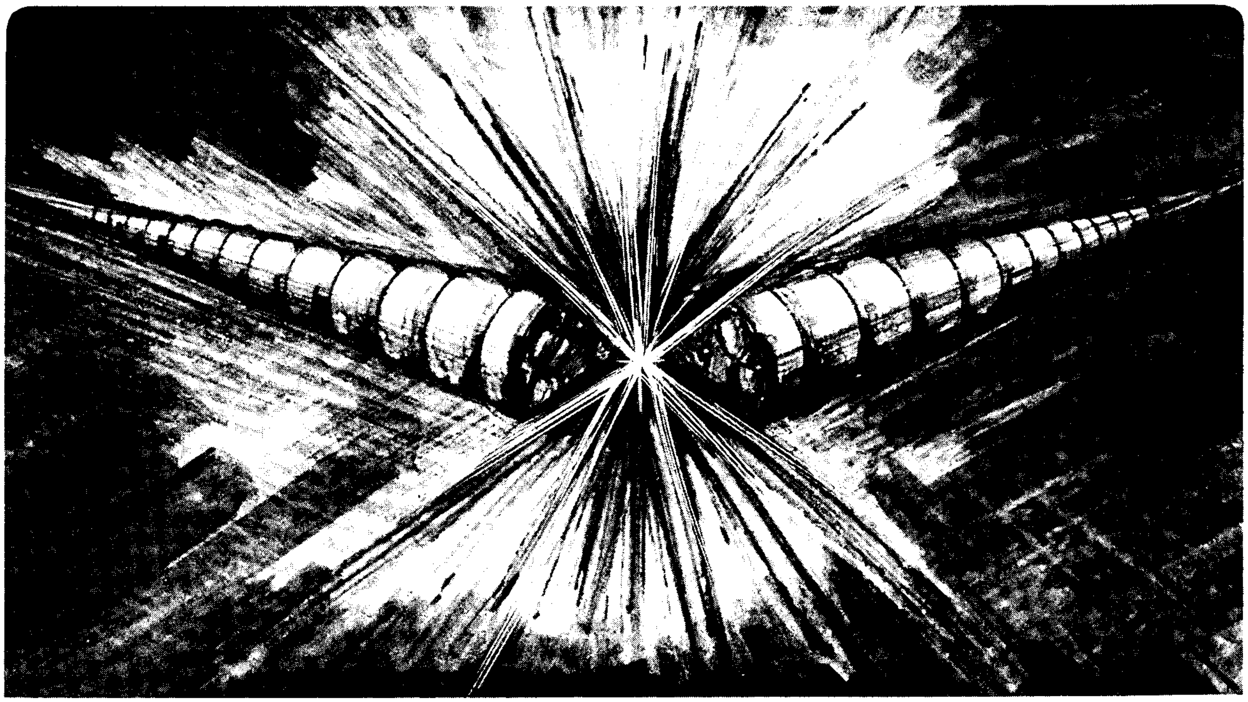

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Relativistic Radioactive Heavy Ion Beams at the Bevalac

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Relativistic heavy ion beams have been available now at Berkeley for over twelve years, and even from the earliest times the possibilities of unstable secondary beams were explored. Work by Tobias and Chatterjee[1] on autoactivation in beryllium catchers, and shortly thereafter extensive studies by Heckman, Greiner et al.[2] on the yields and kinematics of reaction products served to characterize peripheral fragmentation reactions as an important mechanism for secondary beam applications.

In such reactions, these authors found a few nucleons were removed from the projectile, which continued forward with essentially the same velocity it had prior to the collision. In addition, cross section and momentum transfer changed very little over a fairly wide range of beam energies and reaction products, being respectively around 10-40 millibarns and 100 MeV/c.

These high cross sections, and low momentum transfers pointed to the feasibility of using relativistic heavy ions to produce secondary beams of interesting purities and intensities for experimental applications. Beams of ^{11}C and ^{19}Ne were in fact produced and delivered to biomedical users of the Bevalac as early as 1978[3]. Since this time beams of these ion species have been used extensively in biomedical range measurements and implantation studies[4], and other projectile fragmentation nuclear science experiments have further illustrated the power of this technique for producing exotic nuclei. An example of this is Fig. 1 which shows isotopes produced by Westfall et al[5] in a ^{48}Ca fragmentation experiment. In this experiment lasting only one day, 14 new isotopes were discovered, and cross sections were measured for an extremely wide range of products.

From these experiences certain points can be made about secondary beams of relativistic heavy ions.

Production Considerations

To maximize the yield of a desired secondary ion, one should use the most target material for the least energy loss and multiple scattering of the beam. These both indicate lowest Z materials. Fig. 2 shows calculated yield of ^{11}C from ^{12}C as a function of beryllium target thickness, showing also the primary beam energy loss and multiple-scattering growth. Production peaks at about 1.8% for a 15 g/cm^2 target, then drops off as the secondary ion itself undergoes further reactions, and the primary beam attenuates and can no longer feed the ^{11}C channel. Note that the peak production yield is limited by the ratio of the cross section for the desired ion to the total reaction cross section, a condition reached in the above case. Similar calculations for heavier targets show much more energy loss and scattering for the equivalent production, for the heaviest targets a maximum is not reached before the ion is stopped.

Berman's work on photodissociation[6] indicates huge cross section enhancements for heaviest targets at high energies (2 GeV/amu); this process may yield significant improvements in beam intensities for selected species at high energies. How far down in energy one can gain benefits from this mechanism must still be explored.

Production yields, as indicated, depend critically on relative cross sections. In the 10 mb range we have seen a production efficiency of about 10^{-2}, fully 1% of the primary beam emerges as the desired secondary! From

Fig. 1 one sees large variations in production cross sections for ions far removed from the projectile mass, yields will thus also vary considerably. Note that to estimate the yield in the experimental area, as opposed to the production efficiency, one must also include transport efficiency, which is related to energy and angular spread in the production process. Thus cross section ratios only indicate upper limits of potential yield ratios or delivered beams.

To calibrate the above discussion, typical Bevalac beams are between 10^9 and 10^{10} ions per pulse (.25 Hz) in the light-ion region, so the most favorable secondary beam intensities can be as high as 10^7 to 10^8 ions per pulse. In fact our normal ^{11}C and ^{19}Ne running is with 1 x 10^7 ions/pulse in the Biomed area.

Transport Considerations

The key factor is that the higher the energy of the production reaction, the smaller the perturbation on the beam momentum and divergence. In fact, at Bevalac energies the qualities of the secondary beam come very close to matching those of the primary beam. The fact that the 1 milli-steradian acceptance Beam 40 spectrometer, where the "low energy" (212 MeV/amu) ^{48}Ca experiment was performed, showed 95% collection efficiency for fragments close to the projectile mass (even 15% for the very-distant carbon isotopes) attests to the benefits of high-energy kinematic focusing.

Higher energy also helps in minimizing target thickness effects. Energy variation in the secondary beam occurs depending on where in the target each ion is produced, as de/dx of primary and secondary ions are in general different. At high energies, though, de/dx for both is smaller, and total energy loss is a smaller fraction of the total energy. These factors all point to very high beam quality for the secondary beams. Note also, that one can apply a number of the normal beam transport techniques to even further improve the beam quality. For instance, putting the production target at the tightest possible waist, where normal beam divergence is large, will minimize the emittance growth of the beam due to scattering and reaction kicks in the target. We will see later that energy spread can also be improved.

Present Bevalac beam lines, largely inherited from the days of proton running, are not designed as high-acceptance lines, and still we can transport about 30% of the produced ^{19}Ne to the biomedical experimental area. Planned improvements in the next year should make the situation even better.

Beam Purification

Magnetic analysis systems for beam purification are effective for separating by rigidity, the ultimate resolution being dependent on beam quality (transverse emittance) and energy spread. An additional complication for secondary beams is the overlap of charge-to-mass ratios of different reaction products.

As was the case above, higher energies aid in the process of beam purification. In the Bevalac energy range, typical energy spreads of secondary beams are only about a few percent, allowing simple magnetic analysis to be enough to isolate adjacent isotopes of a given (light) element. One will see contaminants of like q/A coming through the slit system, e.g. ^{19}Ne, ^{17}F, ^{15}O are seen together, as were ^{9}Li, ^{6}He, ^{3}H in another recent experiment[7]. One can, however, by means of a degrader at the first analysis point separate the rigidities of the different Z components to allow good purification at a second analysis point. (This has not yet been demonstrated at the Bevalac, but there is little doubt it will work.)

Energy Analysis

The ultimate user of the secondary beam has need for some degree of energy uniformity in the beam. Again, beam optics can come to our aid. By introducing the right dispersive elements the beam can be spread out to an almost arbitrarily high energy resolution (limited again by transverse emittance). In the Biomed area, energy widths of collimated beams of the order of the range straggling are routinely seen, making ^{19}Ne Bragg curves as sharp as primary ^{20}Ne curves. (See Fig. 3). This resolution is achieved at the cost of intensity; much greater flux is available using a momentum - recombined tune, about a factor of five more beam intensity is obtained in a reasonably small focal spot (< 1 cm^2). One can also improve the energy spread in the beam using a wedge at the intermediate (dispersed) waist, with pitch set to match the dispersion so that beam emerges monochromatized. Experiments have indeed shown substantial sharpening in ^{11}C Bragg peaks using this wedge technique[8].

To achieve the highest energy resolutions for, say, low-energy experiments or for reaction studies of interest to astrophysics, may involve an inordinately large degree of effort. Nevertheless, by suitable intermediate degrading and analysis, even relatively large statistical energy fluctuations in the degrading process from the production energy to the energy of interest might be adequately compensated for.

Summary

The Bevalac has been demonstrated to be an efficient source of radioactive beams of good quality, and is attracting a growing body of users of this capability. Immediately on the table are an increasing demand by biomedical experimenters, leading up to eventual clinical use; and two most interesting nuclear science experiments, discussed in the next paper of this workshop. We are anticipating a substantial increase in interest and demand in coming years, and are planning beam line improvements to enhance transmission and purification efficiencies.

The Bevalac and its relativistic secondary beams may not be the panacea for all the desires of the research community, fluxes of 10^{12} ions/sec of ^{52}Ca will probably never be achieved, and half-MeV resolutions may be unattainable, but nevertheless there is a tremendously broad range of experimental work possible with these beams. Furthermore, active use, and exploration of the usable limits of these beams will go a long way in setting the specifications for the next generation of radioactive-beam facility.

ACKNOWLEDGMENT

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Figure Captions

Fig. 1 Production cross sections for isotopes observed in the fragmentation of 212 MeV/amu ^{48}Ca projectiles on a beryllium target.

Fig. 2 Calculated production efficiency for ^{11}C from ^{12}C as a function of beryllium target thickness. Fully 1.8% of the primary beam emerges as ^{11}C. Multiple scattering beam - broadening is also shown; the hashed line represents maximum divergence accepted by the Bevalac transport line to the Biomedical area.

Fig. 3 Bragg curve for (300 MeV/amu) ^{19}Ne delivered to the Biomedical area. Note total absence of primary ^{20}Ne (would have 5% longer range), but presence of ^{17}F and ^{15}O, contaminants with very similar q/A's.

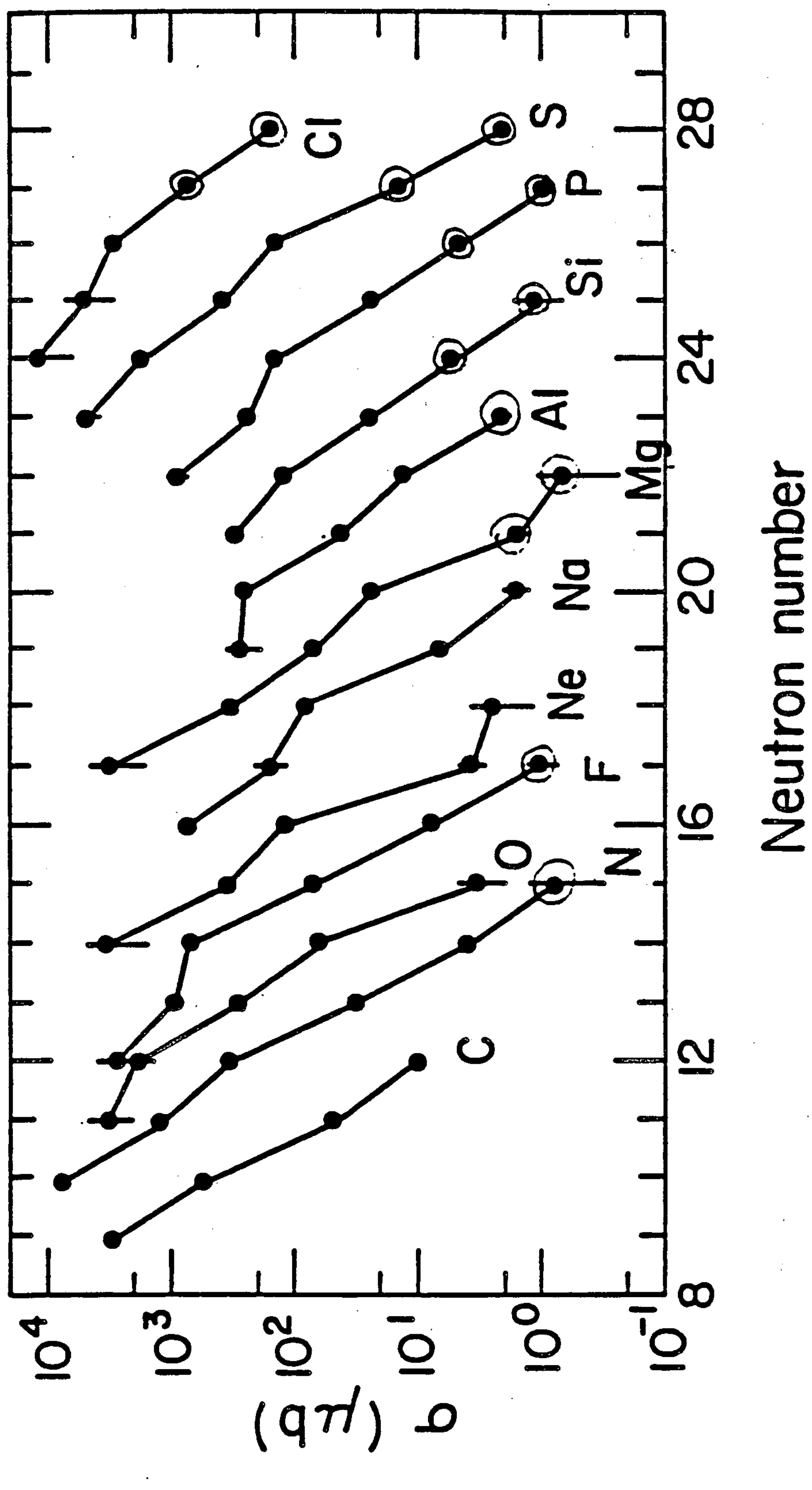

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Figure 1

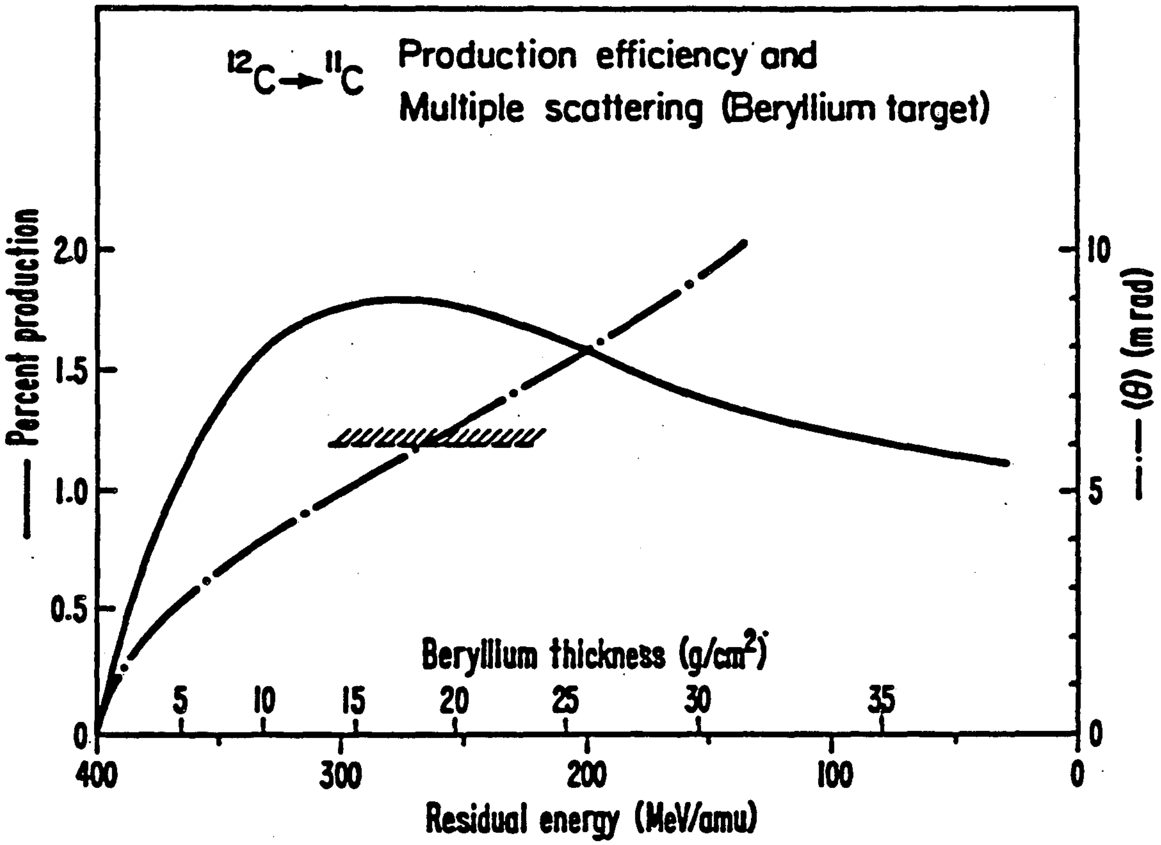

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Figure 2

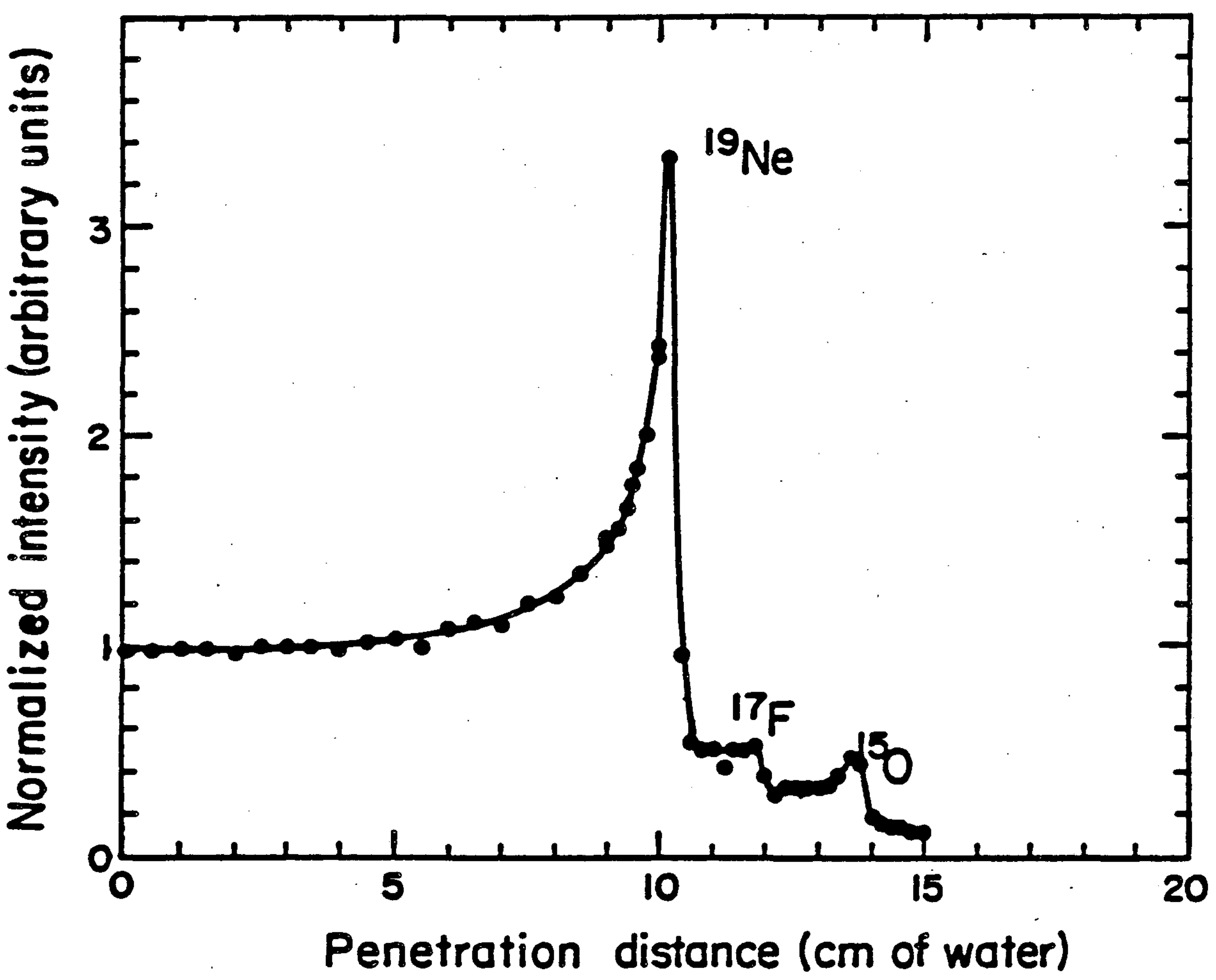

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Figure 3