ACCELERATION OF RADIOACTIVE ION BEAMS IN CYCLOTRONS*

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Abstract

The production of radioactive ion beams is reviewed. The major emphasis of this paper is on the cyclotron analogue beam method, which utilizes the capability of a high energy heavy ion cyclotron. The demonstration of this technique with the K500 cyclotron at Michigan State University is reported, where beams of $^3H^{1+}$ and $^6He^{2+}$ have now been successfully produced. The future portends a large development in the production of radioactive ion beams at high energy.

Introduction

The past 20 years has seen a tremendous growth in the capability of accelerating stable heavy ion beams, both in energy and in isotopic mass. Cyclotrons have made a major contribution in this technological achievement. Figure 1 is a nuclidic chart showing the ~ 300 natural occurring stable isotopes (black area) as a function of proton and neutron number. Many of these

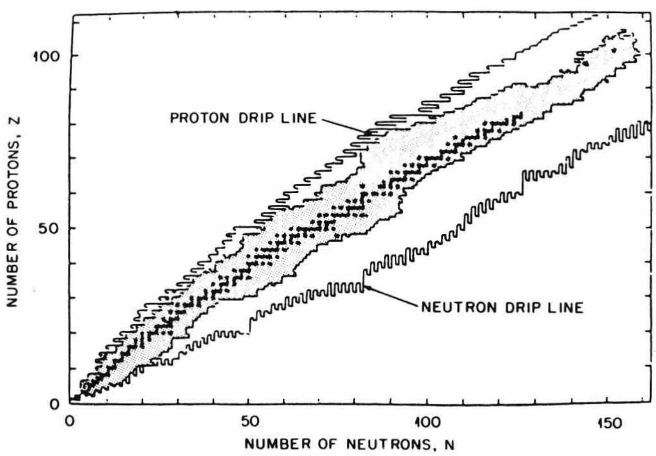

Fig. 1. Nuclidic chart shown as a plot of neutron number vs. proton number. Approximately 300 stable isotopes are shown in black and 1600 known radioactive isotopes are in gray. The white area include nuclei that have been predicted to be stable with respect to particle decay.

isotopes have not been accelerated to nuclear physics energies, but seem possible by the present generation of accelerators and ion sources. Figure 1 also shows the ~ 1600 radioisotopes (gray area) that have been identified and studied during the past 50 years. In the very recent years, a new frontier has opened, namely the production of radioactive ion beams (whose half lives are too short to be introduced in an ion source and accelerated in the conventional manner) at nuclear physics energies[1,2] and it now appears likely that cyclotrons will also make a major contribution in this mass region.

The present main scientific justification for radioactive ion beam development is the special data needs of the astrophysics community and their desires to elucidate the physics properties of certain radioisotopes that play a role in their solar models. Other possible areas of interest that would benefit from these developments are solid state physics, production of radionuclides and deep ion implantation. Since most of the participants of this conference are from nuclear physics laboratories, I have included a very recent nuclear physics result obtained from a series of radioactive ion beam experiments performed by Tanihata et al. at the Bevalac accelerator. Figure 2

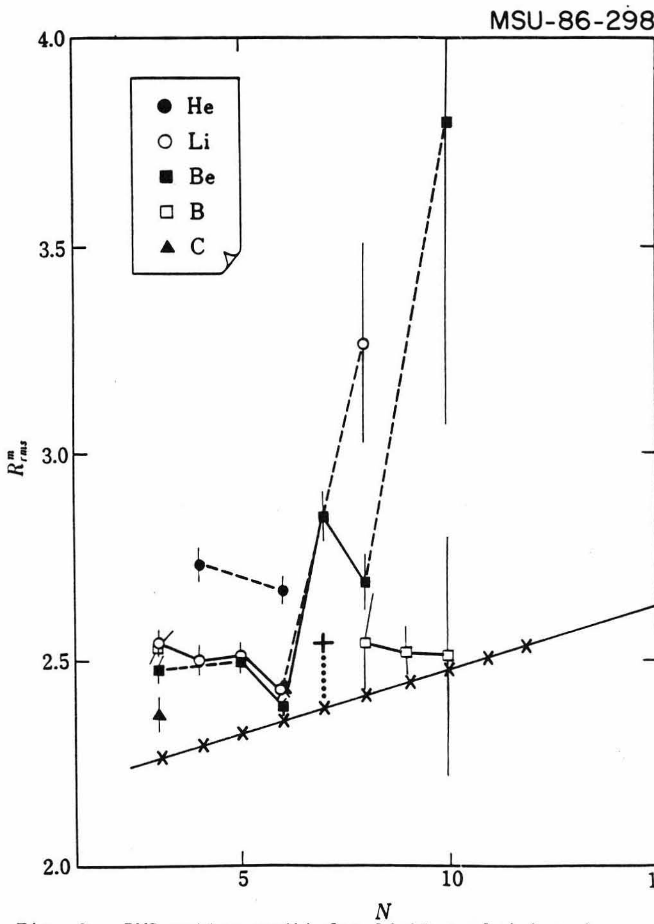

Fig. 2. RMS matter radii for light nuclei based upon a Glauber model analysis of measured reaction cross section are shown. The data are compared with the trend obtained from a typical spherical HartreeFock calculation (crosses). An improved calculation of ^{11}Be (plus sign) is based upon a shell model calculation for the orbit occupancies of the 1/2+ configuration combined with a Hartree-Fockcalculation for the radial wave functions.

is a measurement of the experimental mean nuclear radius as a function of neutron number for various light radioactive nuclei.[3] The theoretical predictions of the mean nuclear radius for spherical nuclei are shown (x - line) and does a very poor job of predicting these results. Alex Brown from Michigan State has modified this model for ^{11}Be (cross data point) and is getting better agreement.[4] The major point here is that experiments with radioactive beams are already making a contribution to our understanding of nuclear physics models and we would expect many more since these beams will test the models at extreme conditions of nuclear matter.

The primary purpose of this paper is to report on the various methods of producing and accelerating radioactive beams. In the first section I shall briefly describe the two accelerator-target ion source method. In the next section I shall report on the fragmentation method of making radioactive particles and finally I shall conclude with the cyclotron analogue beam technique.

Two Accelerator - Target Ion Source Method

The initial concept of making a radioactive ion beam, requires an energetic 1st stage accelerator, with its beam bombarding a target. The radioactive isotopes made at the target migrates to an ion source and are ionized, extracted and accelerated in a 2nd stage accelerator.

The first part of this technique has been amply demonstrated at the Cern ISOLDE facility[5], where a proton beam bombards a target located in the ion source of a mass separator. Figure 3 is a shortened version

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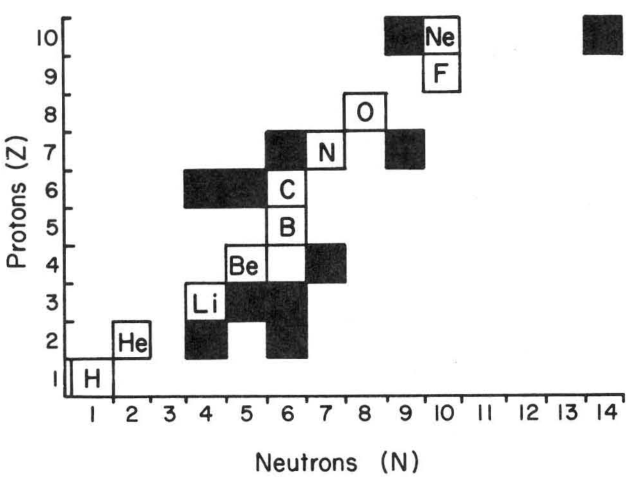

Fig. 3. A shortened nuclidic chart of the light radioactive isotopes produced at the ISOLIDE facility in Cern are shown in dark. The isotopes were made with a proton beam.

of the nuclidic chart showing the radioactive light isotopes made at this facility. Heavy ion accelerators have also been used to make radioactive ions in a target ion source and Fig. 4 is a picture of the Unisor facility[6] at Oak Ridge. The heavy ions are accelerated in ORIC or the 25MV electrostatic tandem accelerator.

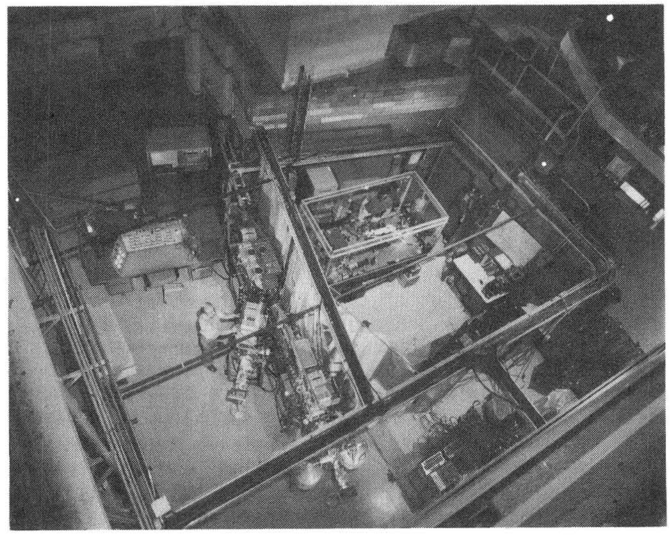

Fig. 4. A photograph of the Unisor facility at Oak Ridge. Heavy ions have been used at this facility to make radioactive isotopes.

Figure 5 is a 10 year old schematic drawing of the central region of the Oak Ridge ORIC cyclotron[7], showing the calculated orbit of a beam from the tandem accelerator being injected into the ion source of the cyclotron. It was proposed that radioactive ions would be made in this ion source, extracted and accelerated in the ORIC. This is the first proposal of using a cyclotron to accelerate radioactive ions to nuclear physics type energies. This proposal has not been implemented at Oak Ridge.

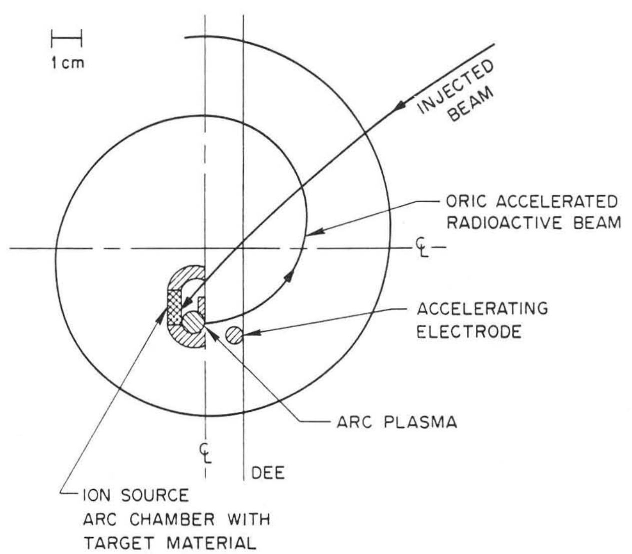

Fig. 5. A median plane view of the central region of the ORIC. The injected beam would impinge upon a target located next to the arc plasma column of a cold cathode ion source. Radioactive ions produced in the target would diffuse into the plasma column, be ionized, extracted and accelerated in the cyclotron.

Next I show a schematic drawing (Fig. 6) of an ion source facility that is being constructed at the Triumf Laboratory.[8] This figure shows a target ion source (proposed to be an ECR type) where the very intense Triumf proton beam will be used to produce radioactive ions. It is further proposed that the radioactive ions produced in this facility would be extracted and injected into a superconducting accelerator; the type not yet decided. This proposed facility would be an outstanding frontier device for accelerating radioactive ion beams.

Fragmentation - Beam Line Separator

With the successful completion of the Bevalac, it was experimentally discovered that the grazing collisions of high energy heavy ion nucleons, resulted in the production of nuclear fragments in large yields. The measured cross section yields[9] for different fragments obtained from interaction of a 212 MeV/u ^{48}Ca beam are plotted in Fig. 7. The most abundant cross sections are produced in the tens of millibarn and can potentially lead to large radioactive ion beams. Figure 8 is the integrated fragment production cross section for a variety of masses at three incident energies.[10] The yields are nearly equal over this range, where the lower energy per nucleon are within the capabilities of the K500 cyclotron at Michigan State and the Ganil accelerator. Several fragment angular distributions taken at MSU[11] are illustrated in Fig. 9 and indicates that the fragment production cross sections are sharply peaked in the forward direction of the incident primary beam. These experimental observations have led to the construction of a fragment separator in the external beam line of the Bevalac.

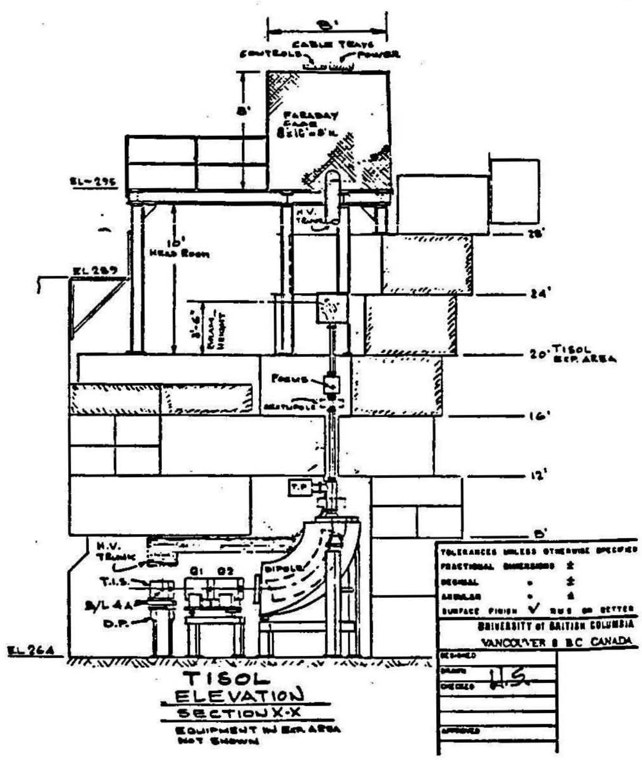

Fig. 6. The planned layout of a target ion source facility at Triumf is shown. The high intensity proton current of Triumf will be used to make radioactive ions.

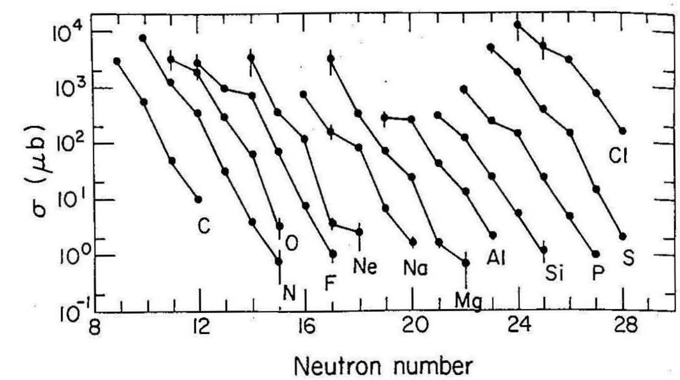

Fig. 7. The production cross section of neutron rich light isotopes observed in the fragmentation of 212 MeV/u ^{48}Ca ion on an 890 mg/cm^{2}Be target.

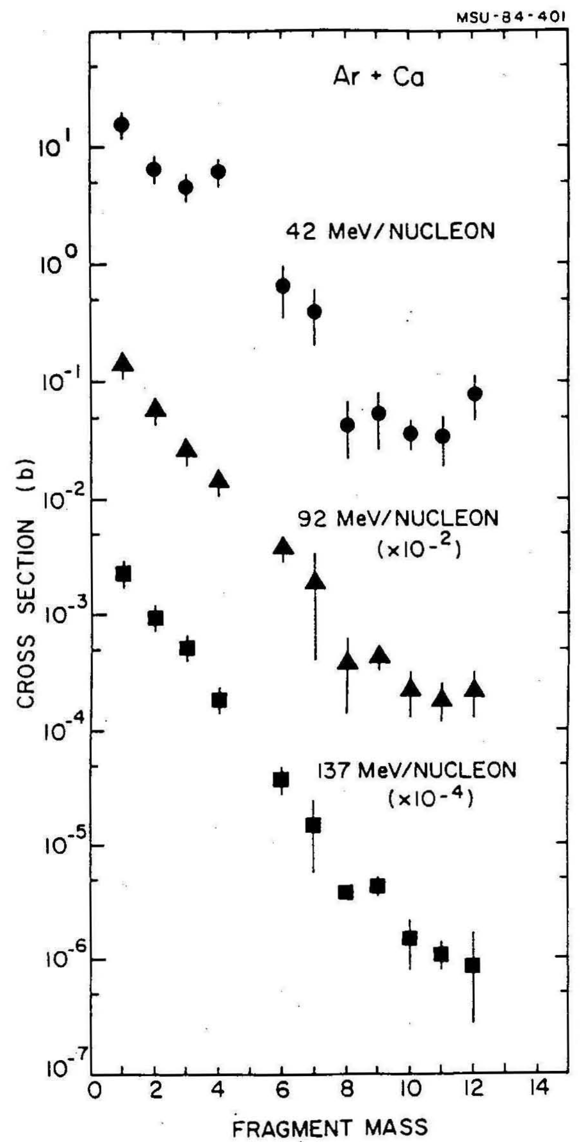

Fig. 8. The integrated fragment production cross section for Ar + Ca as a function of the fragment mass for several beam energies. The lower energies are within the capability of the K500 cyclotron.

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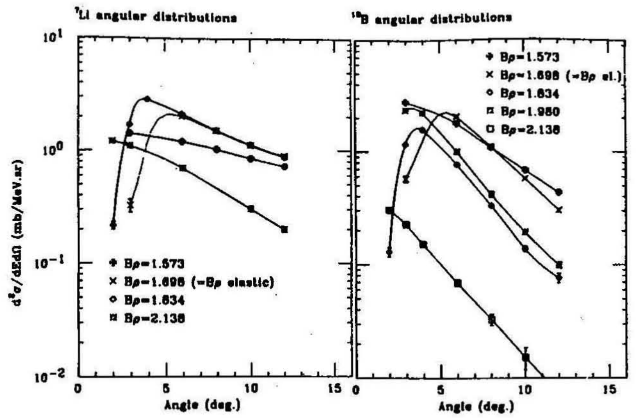

Fig. 9. Preliminary angular distribution for ^{16}O + ^{58}Ni at 35 MeV/u. Data for ^{7}Li and ^{10}B are shown for different rigidities.

Figure 10 is a schematic drawing of the fragment separator[12] in the secondary beam line at the Bevalac, where F1 is the target. This target is followed by a magnetic analysis system and finally by a detector that with time-of-flight makes it possible to identify

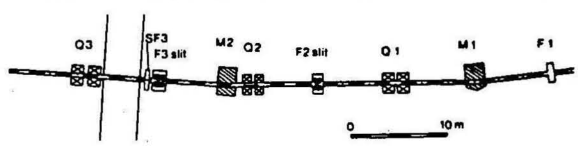

Fig. 10. The secondary beam line at the Bevalac for making radioactive isotopes. The target is located at F1, followed by an analysis system.

single isotopes. A similar fragment separator is now in operation at the Ganil accelerator.[13] Figure 11 is a Ganil measurement of the production of radioactive ion beams produced with an argon primary beam as a function of the Bρ of their analysis system. Such an external analysis system has also been studied at Michigan State by L. Harwood.[14] At the Unilac, a complex fragment production facility and storage ring is under design.[15]

Cyclotron Radioactive Analogue Beam Method

The heavy ion analogue beam method was developed approximately 15 years ago[16] and it is a technique for the tuning of the cyclotron for small intensity ion beams. A large intensity beam is first tuned in the cyclotron and its mass to charge ratio (m/q) is nearly equal to the mass to charge ratio of the low intensity beam. Figure 12 and 13 shows examples of analogue beams obtained from the ORIC and 88" cyclotrons. The 1971 ORIC data shows six analogue peaks which were obtained from a Penning ion source for the mass to charge ratio of 5. The 88" data was obtained this year for an ECR ion source[17] and shows over 15 beams for the mass to charge ratio of 4. These beams are all extracted with only slight variations in the rf frequency and appropriate changes in the feed material of the ion source. In the radioactive ion beam case, the analogue beam method means the mass to charge ratio of the primary beam, that fragments into the radioactive beam at an appropriately placed target, is equal to the radioactive beam mass to charge ratio.[18]

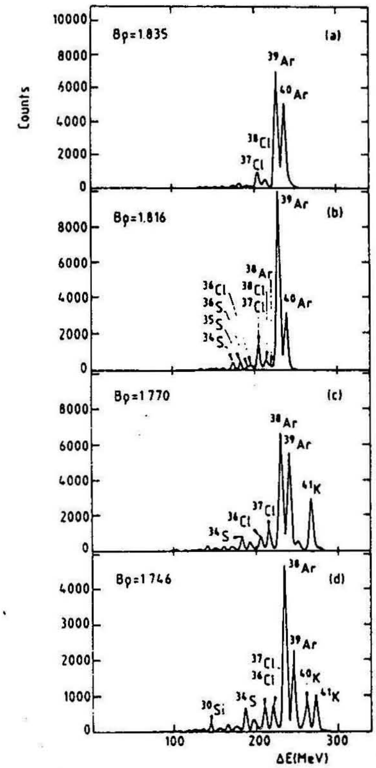

Fig. 11. A series of spectrum obtained at Ganil showing the effect of Bρ variation in their beam line on the purity of ^{38}Ar, ^{39}Ar and ^{41}K.

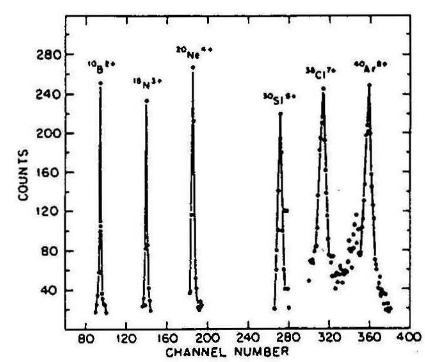

Fig. 12. Analogue beam spectrum produced from a Penning source at the ORIC cyclotron for the mass to charge ratio of 5.

Table 1 lists examples of primary and radioactive analogue beams. The radioactive beam is completely stripped of its electrons as would most probably happen in this energetic collision process. The table indicates that the very light elements and neutron rich radioactive isotopes comprise the mass region for this method.

Another heavy ion experimental result obtained during the past 10 years is the energy distribution of the light fragments.[19] For example, Fig. 14 shows the light particle fragment energies from the breakup of a 30 MeV/u carbon beam. This figure indicates that some

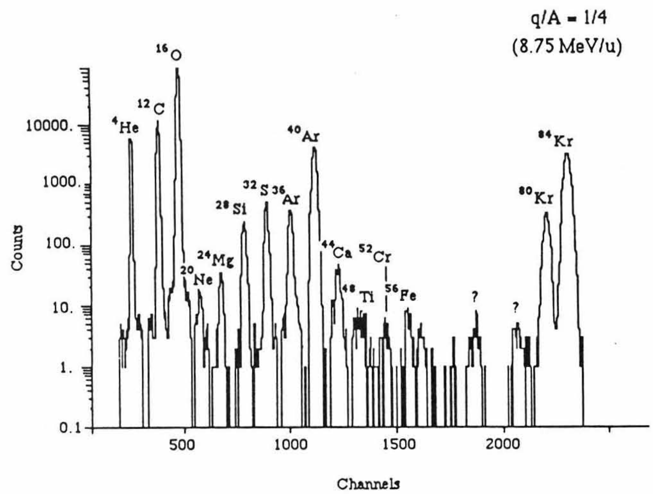

Fig. 13. Analogue beam spectrum produced from the 88" cyclotron facility using an ECR ion source for q/A of 1/4.

fraction of the fragmented trituum particles have an energy per nucleon greater than the energy per nucleon of the incident carbon beam. It has been realized that the Fermi motion of the nucleons in the projectile must be included in the final energy of the fragments, thereby making it possible to have fragment energies per nucleon equal or greater than the incident

Table I

Analogue Radioactive Ion Beams

Primary Beam	Fragment Beam	Lifetime
$^{6}Li^{2+}$	$^{3}H^{1+}$	12.3y
$^{12}C^{4+}$	$^{6}He^{2+}$	805 ms
$^{16}O^{4+}$	$^{8}He^{2+}$	119 ms
$^{16}O^{6+}$	$^{8}Li^{3+}$	844 ms
$^{18}O^{6+}$	$^{9}Li^{3+}$	177 ms
$^{22}Ne^{6+}$	$^{11}Li^{3+}$	8.7 ms
$^{22}Ne^{8+}$	$^{11}Be^{4+}$	13.8 s
$^{24}Mg^{8+}$	$^{12}Be^{4+}$	24 ms
$^{20}Ne^{8+}$	$^{15}C^{6+}$	2.45 s
$^{24}Mg^{9+}$	$^{16}C^{6+}$	.75 s
$^{25}Mg^{10+}$	$^{20}O^{8+}$	13.5 s

projectile. A recent theoretical calculation[20] of the relative cross section for making ^{6}He from a carbon beam as a function of energy (Fig. 15) shows a large value at the projectile energy. This means that after

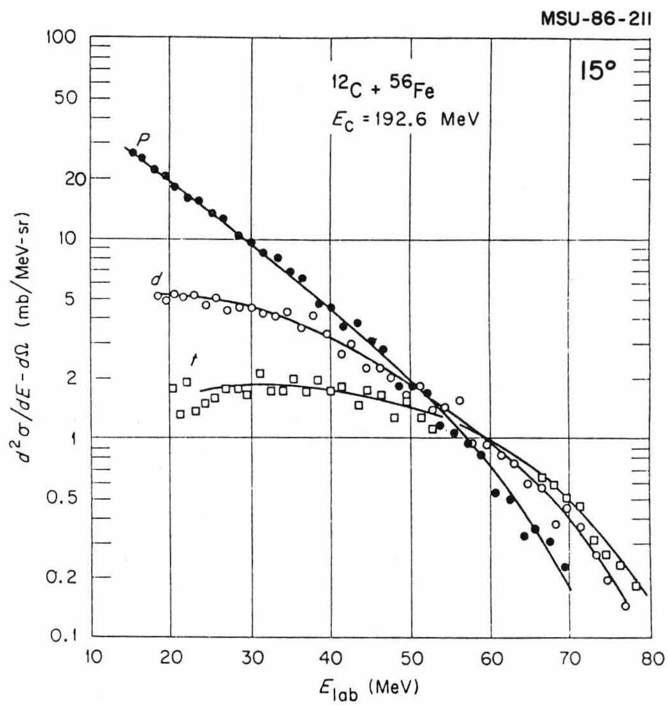

Fig. 14. An experimental measurement of the yields of light fragments from carbon upon an iron target taken in 1976. Some fraction of the tritium ions have an energy per nucleon greater than the carbon beam.

interaction of the primary beam with a target, some fraction of the radioactive analogue beam will have the same velocity as the primary beam and will continue to be accelerated in the cyclotron.

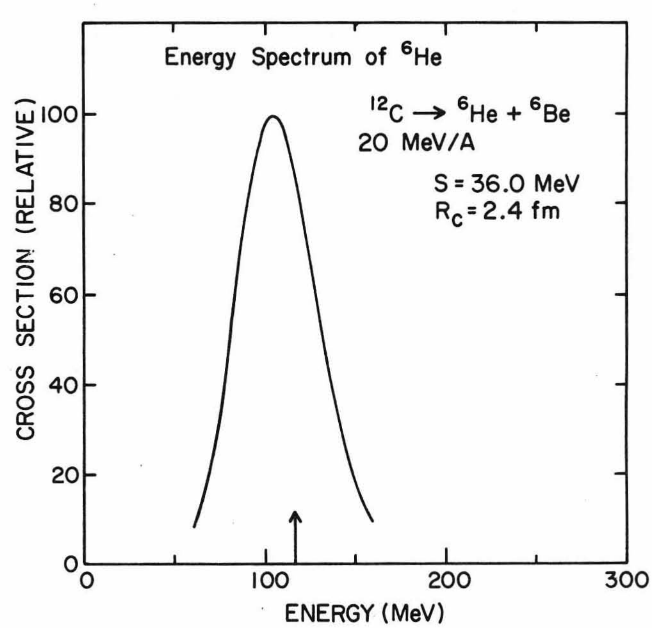

Fig. 15. A theoretical prediction of the fragments ^{6}He energy per nucleon relative cross section and shows a large valve for the cross section at the projectile energy per nucleon (arrow).

Figure 16 shows the initial concept of producing a radioactive ion beam from the K500 cyclotron. The figure shows the pole tips of the K500 and representative beam orbits. At ~ 15" radius, the primary beam strikes a target. Radioactive analogue ions made at the target in the forward direction (0°) and at the same velocity as the incident beam would continue to be accelerated. The primary beam will be

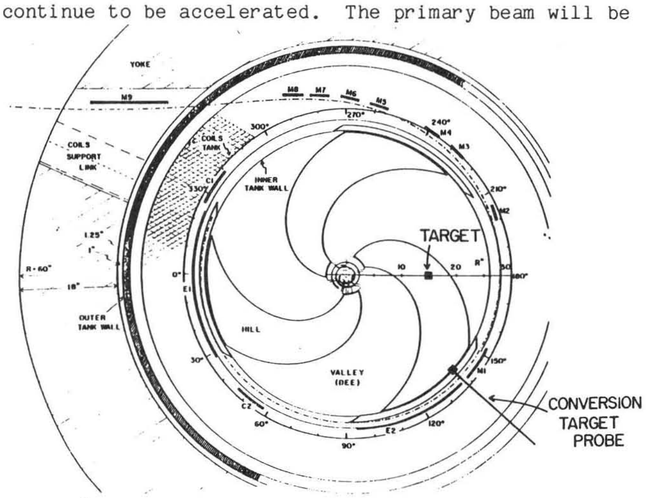

Fig. 16. A view of the lower half of the K500 cyclotron pole tips and extraction system. The initial concept for making radioactive ions had a target located at 15" radius. The concept now being investigated has the target located on the last turn (lower right corner).

stripped of electrons and lost in the cyclotron interior. The requirements for accelerating the radioactive ion beam to full radius of the cyclotron depends on how exact an analogue the beams are and the radius of the target. In the K500, one also has the capability of making fine adjustments to the cyclotron accelerating magnetic field thru the magnet trim coils. Figure 17 is the computed phase history plot[18] of converting a $^6Li^{2+}$ primary beam to $^3H^{1+}$ at 15" and indicates that these beams can be accelerated to full radius with the existing trim coils of the K500 cyclotron.

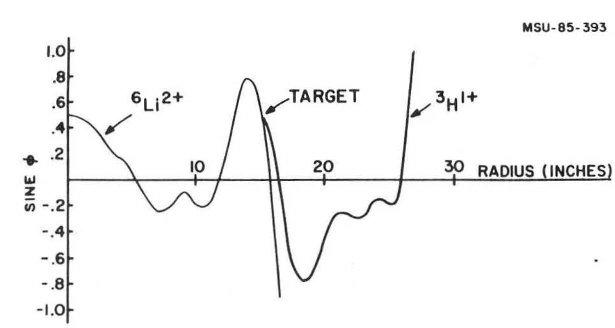

Fig. 17. The computed sine phase curve for $^6Li^{2+}$ going to $^3H^{1+}$ with a final energy of 30 MeV/u is shown. The fragment producing target was located at 15" for this calculation.

The studies at Michigan State has now focused on placing the conversion target at the outer radius of the cyclotron, primarily because of the ease of constructing the target probe and also better yields at higher energies. Figure 18 is a picture of the target probe used for the radioactive beam test and shows the target located at the probe end and an aperture located directly behind it, which provides a penetration space for the extracted beam. Experiments have been done with various carbon target thickness and all have produced radioactive beams. As the target increased from .010" to .125", the extracted radioactive current increased. Production rate is very sensitive to the radial position of the target. The increase of the beam current to target thickness and position has raised interesting questions as to the exact nature of production. One proposal being explored is small angle grazing at the target edge for the production mechanism.

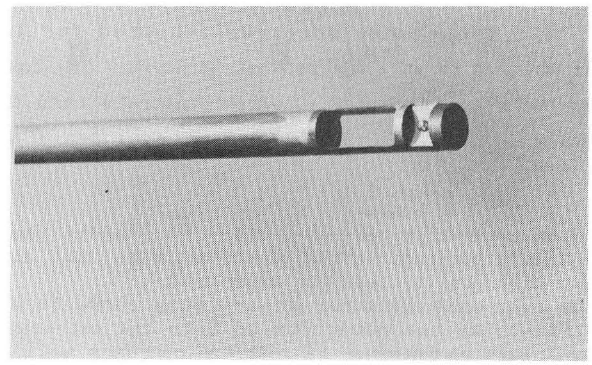

Fig. 18. The target probe is shown in the photograph. Carbon is used for the target and a thin stripper is mounted in the extraction slit behind the target.

In the initial experiment, a large count rate consisting of the primary beam (~10^6 ct/sec) was obtained for all target thickness. All equilibrium charge state calculation indicated that the primary beam should be completely stripped of electrons and thereby unable to follow the cyclotron extraction path. This unstripped beam result has been observed before and it was proposed that some small fraction of the totally stripped beam is able to recapture electrons at the target back interface. These primary beam ions can be reduced in intensity by a second stripping and a clearing magnet. A thin stripper was installed in the extraction path hole of the target probe and resulted in reducing the primary beam to less than 1 ct/sec in the K500 external beam line.

Figure 19 shows energy peaks of beam particles detected with a solid state silicon detector. The detector is too thin to stop the $^3H^{1+}$, hence producing the smeared peak seen at the lower energy. $^6He^{2+}$ is detected at a count rate of 200 particles per second. Small peaks are seen at the location for $^9Li^{3+}$ and $^{12}Be^{4+}$. Figure 20 shows an initial experiment of measuring the energy loss of ^6He for a series of absorbers. The detector for this experiment is mounted in air and the ^6He exits out the end of the beam pipe. In the first curve, the ^6He penetrates completely thru the silicon detector. As additional aluminum absorbers are added, the ^6He just completely stops in the detector and with additional absorbers the ^6He energy is degraded. Although we have not measured the radioactive analogue beam phase space parameters, it is assumed they are equal to the normally extracted beam quality of the K500[21], which is 10 mm-mrad in the radial direction and 7 mm-mrad in the axial direction

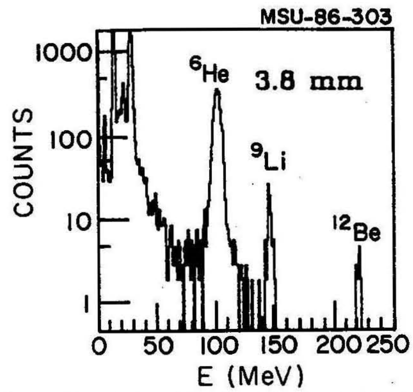

Fig. 19. The energy spectrum obtained for the fragmentation of an $^{18}O^{6+}$ beam at 35 MeV/u. The lower energy peaks are due to $^3H^{1+}$, which penetrate thru the detector. ^{6}He, ^{9}Li and ^{12}Be analogue peaks are identified.

and with an energy spread < .1%. This small phase space limits our radioactive beam count rate, but also gives a high quality beam for experiments.

Present K500 cyclotron primary beam currents are now limited by the power dumped into the extraction system. With an internal target, the currents will be limited by the ion source, which can be up to two magnitudes greater than the extraction limit. However, concerns on where the stripped primary beam is dumped inside the K500 has limited the initial beam currents. Examination of the cyclotron interior approximately one week after a test run showed no evidence of thermal damage, where the maximum primary current for $^{18}O^{6+}$ was 1.4 eμA. Increased radioactivation of the cyclotron interior is also a concern and studies on activiation are underway. No change in the cyclotron radiation environment was detected after the above run. With greater primary beam intensity, we expect to increase the $^6He^{2+}$ current.

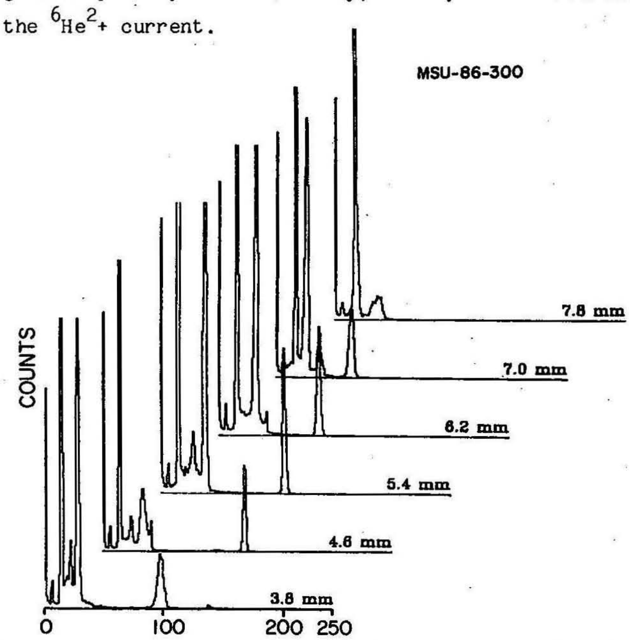

Fig. 20. A series of energy spectra obtained for the ^{6}He beam as various Al degraders were added before the detector. Initially (3.8 mm) the ^{6}He did not stop in the detector. The peaks at low energy are all caused by $^3He^{1+}$. This data represents the first preliminary experiment at Michigan State with ^{6}He.

Helium Acceleration History in Cyclotron

With the successful acceleration and extraction of ^{6}He from the K500 cyclotron, (the particles are accelerated across four dee gaps before extraction) all but one isotope of helium has been produced from cyclotrons and made available for experiments. Figure 21 is a histogram of the discovery and acceleration history of the various helium isotopes. ^{4}He was first

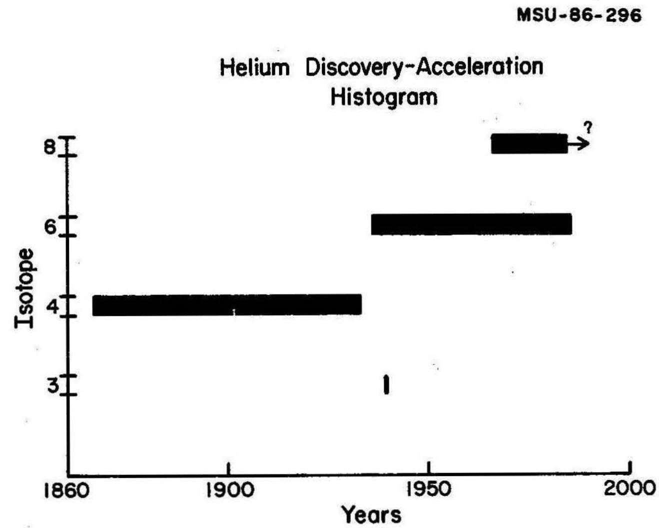

Fig. 21. A histogram of the discovery and cyclotron acceleration of the helium isotopes. Only ^{8}He has not been accelerated in a cyclotron.

discovered[22] in solar spectrum in 1868 and successfully accelerated in a cyclotron[23] by Lawrence in 1933. ^{6}He was discovered[24] in 1936 and accelerated in the K500 during this year, 1986. ^{3}He was discovered[25] at Berkeley by using the cyclotron as a mass separator. ^{8}He was produced for the first time at Berkeley, only 20 years ago, and has not yet been accelerated in a cyclotron. Within a short span of years, the acceleration of all helium isotopes at nuclear physics energies can be expected.

Conclusion

The production and acceleration of radioactive ion beams at nuclear physics energies is now underway. Cyclotrons are playing a major role in this technical development. The analogue beam method has been proven viable at Michigan State University and experiments continue to elucidate its performance capability. The future for radioactive beams at nuclear physics energies looks very promising and challenging.

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Addendum

After completion of this paper, it was realized that locating the conversion target on the last turn of the cyclotron internal beams removes the cyclotron resonance constraint, thereby allowing the extraction of non analogue beams. This greatly expands the possible radioactive ion beam list.