RIGIDITY ANALOGUE RADIOACTIVE BEAMS FROM A HEAVY ION CYCLOTRON*

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Abstract

We have successfully extracted several analogue radioactive ion beams from the K500 cyclotron at MSU and are performing experiments (e.g. $^3H^1+$ and $^6He^2+$). The requirement that the radioactive beams should be an analogue of the primary beams, i.e. the charge to mass ratios are equal, restricts the number of possible beams. We have realized that placing the primary beam target on the last accelerated turn removes the cyclotron resonance constraint, thereby greatly increasing the number of possible radioactive beams, such as $^{16}C^6+$, $^{21}O^8+$, and $^{14}B^5+$. The extraction system of the K500 cyclotron may be viewed as a special type of beam separator with the requirement that the magnetic rigidity of the radioactive ion beam equals that of the primary beam. Locating the primary beam target within the cyclotron allows the intensity of the radioactive beam to be limited by the ion source output or the internal beam power dissipation rather than the extraction system power dissipation. The radioactive ion beam may also be directed toward all experimental stations of the laboratory. New large K heavy ion cyclotrons will be able to produce these beams with the simple addition of a last turn target.

Introduction

Radioactive ion beams, e.g. $^3H^1+$ and $^6He^2+$, have been successfully extracted from the K500 cyclotron at Michigan State University.[1,2] These beams were produced by the nuclear reaction of a primary beam (^{12}C and ^{18}O) with a target located in the cyclotron acceleration region. The radioactive fragments produced at the target that meet very precise momentum and charge to mass ratios are further accelerated and extracted from the cyclotron. The target also strips the remaining electrons from the primary ion beams, thereby effectively separating it from the desired radioactive beam. The cyclotron acceleration requirements for producing radioactive ion beams are referred to as an exact analogue condition between the primary and radioactive beam and these conditions are given classically by the following equations:

$$\frac{q_p}{m_p} = \frac{q_f}{m_f} \tag{1}$$

$$\frac{B_p^2 \rho_p^2}{(E/A)_p} = \frac{B_f^2 \rho_f^2}{(E/A)_f} \tag{2}$$

Where p refers to the primary beam and f to the fragment beam. q is the ion charge state, m is the particle mass, B is the cyclotron magnetic field, ρ the ion radius of curvature and (E/A) is the energy per nucleon of the beams at the conversion target.

The conversion target location within the cyclotron accelerator region depends upon many operational requirements, but it was realized that locating the target on the last accelerated turn of the cyclotron would remove the normal analogue beam constraint and leave only the magnetic rigidity constraint:

$$(B\rho)_p = (B\rho)_f \tag{3}$$

In the following sections, the significance of this mode of radioactive ion beam production is described.

Rigidity Analogue Beams

Figure 1 is a schematic drawing of the K500 cyclotron showing the acceleration region. The target for making radioactive ions is located on the last accelerated turn of the beam. This target location implies that the radioactive ion is not accelerated to higher energy, hence it is not necessary for the radioactive beam to be in resonance with the cyclotron radio frequency, thereby removing equations (1) and (2) as a condition for radioactive ion beam production.

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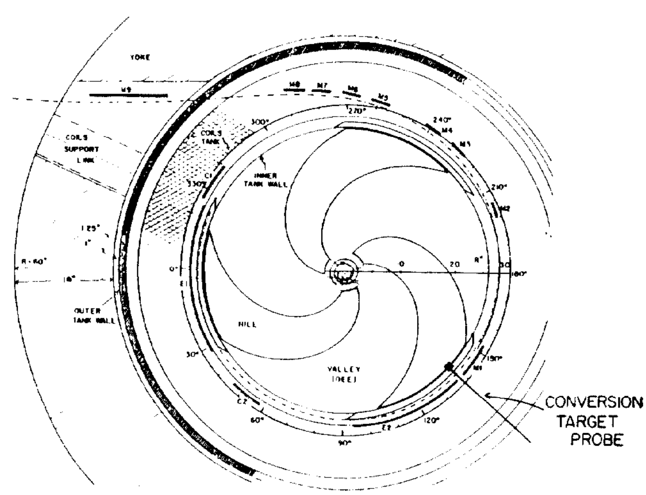

Figure 1. A view of the lower half of the K500 cyclotron, showing the pole tips, extraction system and magnet yoke. The conversion target for making radioactive ion beams is shown and is located on the last accelerated orbit of the cyclotron.

The cyclotron magnetic field levels are completely determined by the primary beam. Radioactive ions then must match the same orbit trajectories as the primary beam, i.e. have the same Bρ(equation 3). Radioactive ions that meet these conditions can be called rigidity analogue beams or momentum-matched beams.

The extraction channel of the K500 cyclotron is a combination of magnetic focusing and deflection elements and electrostatic beam deflection elements.[3] The magnetic elements of the K500 cyclotron are passive devices that are designed to extract all primary beam that is accelerated to full energy. Thereby these elements will be properly set for all rigidity analogue beams. The electrostastic elements can be adjusted to match the charge to mass ratio of the extracted ion and this relationship is given by:

$$V_f = \left[\left(\frac{m}{q}\right)_f \quad (E/A)_f\right] \left[\left(\frac{m}{q}\right)_p \quad (E/A)_p\right]^{-1} V_p \qquad (4)$$

Where V is electrostatic deflector voltage.

The sensitivity of the extracted beam intensity to the voltage setting of the elecrostatic deflectors in the K500, has been measured and is shown in figure 2. The K500 cyclotron has two electrostatic deflectors, separated by 120°. The voltage on these deflectors were varied, both separately and together, and the beam intensity extracted from the cyclotron was measured. The results indicate that for a 10% variation in deflector voltage, a value typical for a rigidity analogue beam difference, a large intensity primary beam is still detected on the external beam stop. This indicates that the electrostatic deflectors of the K500 cyclotron can not be used alone to separate primary and radioactive ion beams. In our initial test, a second stripper foil located after the second deflector was used to reduce the residual primary beam intensity to very low levels.

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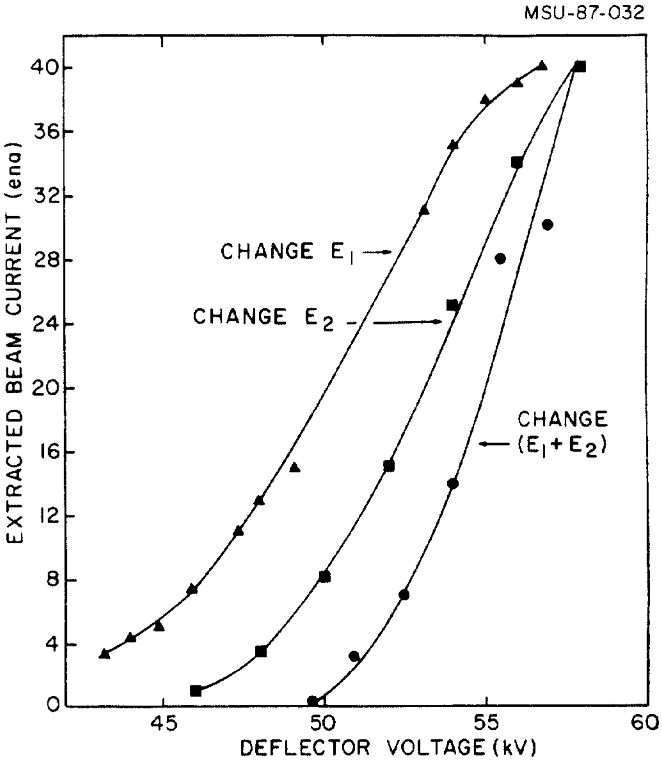

Figure 2. The beam intensity as measured on the K500 external beam stop (BSO) is plotted as the deflector voltage is changed. The measurements were first done with only variation in one of the two deflector voltages. The third curve ($E_1 + E_2$) was done with equal variation in both deflector voltages and the plotted voltage is the average voltage of both deflectors. A large primary beam intensity is detected for the setting needed for the rigidity analogue beams, thereby indicating that the deflectors alone can not be used to separate primary and radioactive ion beams.

Advantages of Rigidity Analogue Beams

There are two important advantages for tuning the cyclotron to rigidity analogue radioactive ion beams. The first advantage is the increase in the number of possible ion species. These ion species are the low mass, neutron rich isotopes. Figure 3, a short version of the nuclidic chart, indicates this region. An example is $^{16}C^{6+}$, m/q = 2.67, produced from the primary beam $^{18}O^{7+}$, m/q = 2.57, where the radioactive ion beam velocity will be 96% of the primary beam velocity.

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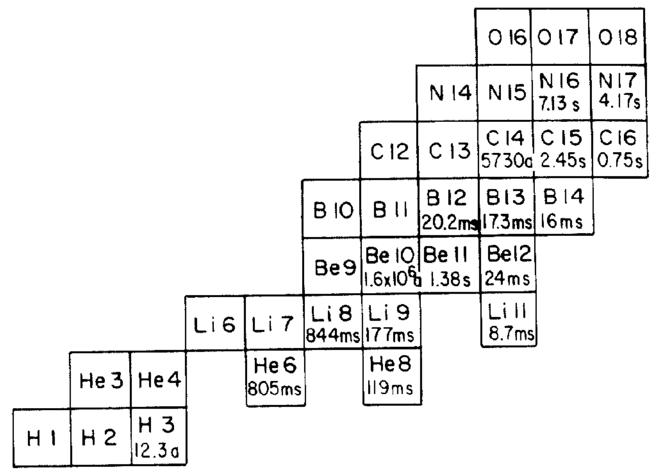

Figure 3. A shortened version of the nuclidic chart is drawn and the possible rigidity analogue radioactive ion beams are shown. They comprise the light mass, neutron rich isotopes.

The second main advantage is the beam intensity. The beam intensity depends on various parameters. One important parameter is the primary beam species, namely one that can be ionized easily within the ECR ion source. Table 1 lists the various options of primary beams for $^{6}He^{2+}$. The primary beam choice from ion source consideration would be $^{14}N^{5+}$. Figure 4, shows the beam intensity advantage of producing radioactive beams inside the cyclotron. The beam power that can safely be deposited on the K500 electrostatic deflector[4], 30 watts, before failure is several magnitudes below what can be produced by the ECR ion source for many primary beams. These primary beams, which are mainly dumped in the cyclotron, after stripping at the target, can be made to hit water cooled surfaces made of low z material which reduce the beam activation. Water cooled surfaces can easily withstand 10 kW of power. Computer calculations of stripped beams in the K500 cyclotron[6] indicate that the beam remains focused until collision with a median plane obstruction. The computer codes can be used to determine where to place the stripped beam target. With the above condition met, an approximate three order of magnitude increase for internal production of radioactive ions, versus external production from an extracted primary beam can be expected.

An intensity increase as a function of energy of the primary beam is expected from the data shown in figure 5. The cross section for fragmentation becomes sharply peaked in the forward direction. The cross section in figure 5 is quoted in arbitrary units. Above 15 MeV/u the fragmentation cross section is constant, hence the cross section value in figure 5d is

Table 1 - Primary Beam Options for Producing $^{6}He^{2+}$
$m_p/q_p \leq 3$, $A-z \geq 4$, $q < z$

Ion Source charge state	Primary Beams (Analogue)	Primary Beam (momentum matched)*			
3	^{9}Be				
4	^{12}C	^{11}B (.92)	^{10}B (.83)		
5	^{15}N	^{14}N (.93)	^{13}C (.87)	^{12}C (.80)	
6	^{18}O	^{17}O (.94)	^{16}O (.89)	^{15}N (.83)	^{14}N (.78)

* Relative velocity of radioactive beam to primary beam indicated in parenthesis.

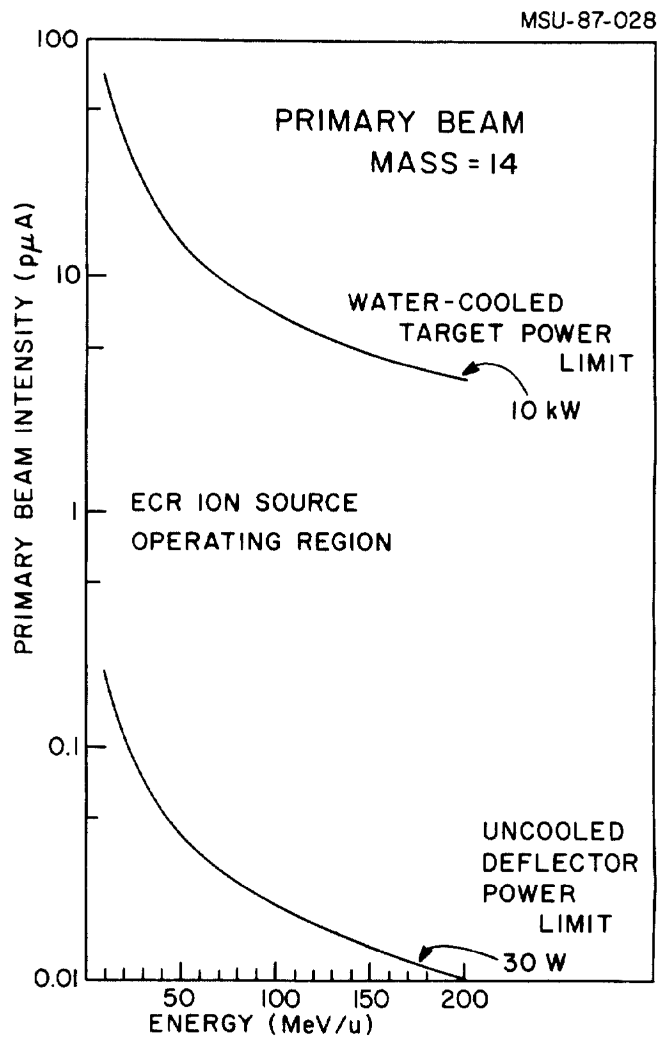

Figure 4. The primary beam intensity versus energy per nucleon is shown for two power levels. The lower level (30 W) is the present limit for the uncooled K500 extraction system. The upper curve (10kW) is for a water cooled surface. Currents as high as 10pμA of $^{14}N^{5+}$ are easily produced by the ECR ion source.

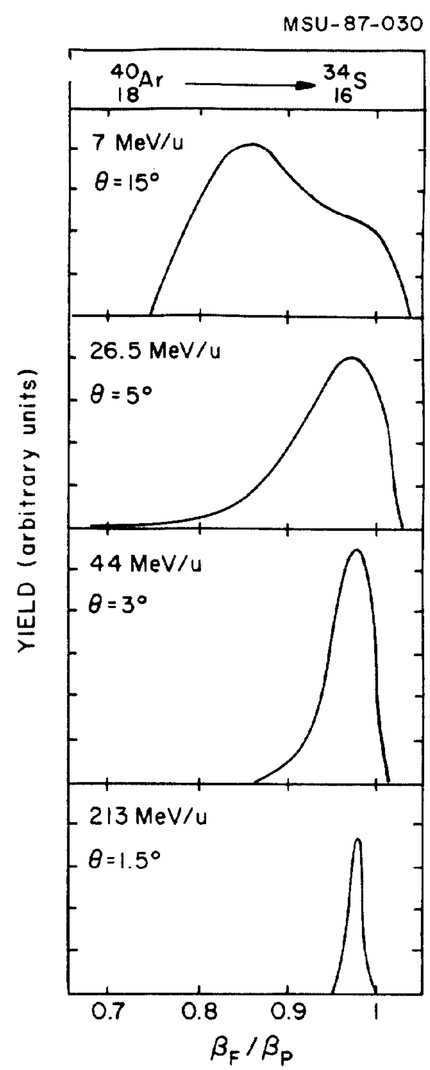

Figure 5. Velocity distributions of ^{34}S fragments for different energies of an ^{40}Ar beam. The fragments focus in the beam forward direction as the energy increases and below the primary beam velocity.

expected to be several magnitudes larger than in figure 5a, which is approximately the present energy capability of the K500 cyclotron. A large increase in the energy per nucleon will shortly be happening at MSU, where a new heavy ion cyclotron with an effective K of 1200 will be coming on line[8]. For example, a primary beam of $^{14}N^{5+}$ at an energy of 150 MeV/u will be possible. Figure 5 indicates that the peak of the fragmentation cross section is below the momentum of the primary beam and the rigidity analogue momentum requirement is precisely shifted in that direction. Hence it becomes possible to match the peak cross section with the radioactive ion beam acceptance in the cyclotron extraction system. Another intensity advantage of high energy is thicker targets. An uncertainty in the intensity question is the fragmentation cross section variation for a given radioactive ion specie (e.g. $^{6}He^{2+}$) as the primary beam specie (e.g. ^{14}N or ^{18}O) is varied.

Summary

The rigidity analogue beam method is expected to allow the production of a large number of radioactive ion beams. With the operation of the new heavy ion cyclotron at MSU, higher beam intensities are predicted. Experiments to verify these conclusions are planned after the completion of the K800 cyclotron.

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* This material is based upon work supported by the National Science Foundation under Grant No. PHY83-12245.