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A Fragment Separator at LBL for Beta-NMR Experiment (Lawrence Berkeley Laboratory)

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### Journal

Nuclear Instruments and Methods in Physics Research B, 70

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### Publication Date

1992-03-01



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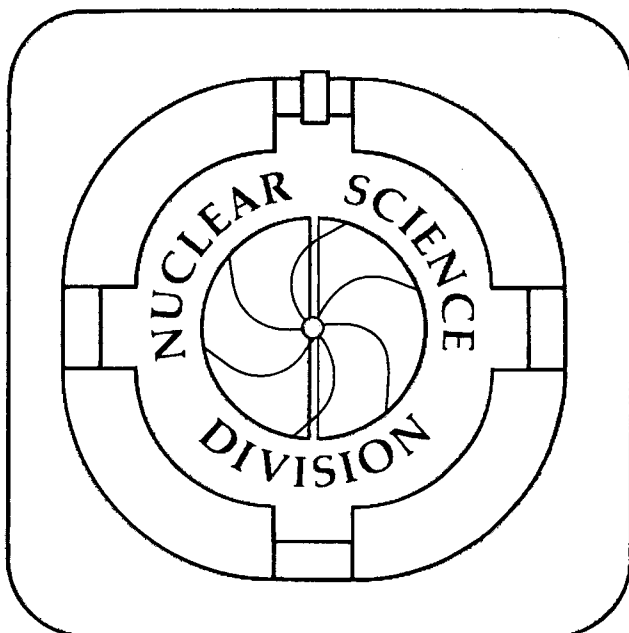
UNIVERSITY OF CALIFORNIA

Presented at the Twelfth International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications, Sendai, Japan, September 2-6, 1991, and to be published in the Proceedings

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March 1992



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

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The Beam 44 fragment separator was built at the Bevalac of LBL for NMR studies of beta emitting nuclei.  $^{37}\text{K}$ ,  $^{39}\text{Ca}$ , and  $^{43}\text{Ti}$  fragments originating from  $^{40}\text{Ca}$  and  $^{46}\text{Ti}$  primary beams were separated by the separator for NMR studies on these nuclei. Nuclear spin polarization was created in  $^{39}\text{Ca}$  and  $^{43}\text{Ti}$  using the tilted foil technique (TFT), and the magnetic moment of  $^{43}\text{Ti}$  was deduced. Fragment polarization was measured for  $^{37}\text{K}$  and  $^{39}\text{Ca}$  emitted to finite deflection angles. The Beam 44 fragment separator in combination with a proper polarization technique, such as TFT or fragment polarization, has been very effective for such NMR studies

## 1. Introduction

The projectile fragmentation process in high energy heavy ion collisions provides a good tool for producing a wide range of nuclei, even those far from the stability line on the nuclear chart[1]. The produced fragments can be transported in a beam line to the experimental area just like a primary beam, because of strong forward focussing character of the fragments. In order to use such secondary beams of projectile fragments for various kinds of study in nuclear physics, the beam must be purified using a proper separation technique. The Beam 44 fragment separator[2] was built at the Bevalac of LBL for that purpose. The separator has proven its usefulness in the half life measurements for the beta emitters  $^{20,21}\text{F}$ ,  $^{37,39}\text{Ca}$ , and  $^{43}\text{Ti}$ [3].

The Beam 44 separator is extremely useful for the study of the magnetic moments of  $f_{7/2}$  shell mirror nuclei using the beta-NMR technique[4], along with a proper polarization technique for the fragments, such as the tilted foil technique (TFT). The TFT is supposed

to be a universal method to polarize the nucleus[5]. Tilted foil polarization was created in  $^{39}\text{Ca}$ [6] and the technique was then applied to the magnetic moment measurement of  $^{43}\text{Ti}$ [7]. In an extension of the NMR studies, we measured the nuclear spin polarization of beta emitting fragments produced through the projectile fragmentation process at the finite deflection angles. Polarization of about 5% was observed for the beta-emitting fragments  $^{37}\text{K}$  and  $^{39}\text{Ca}$  produced in the  $^{40}\text{Ca}$  on Au collision.

The separation technique used for the present study is described in the following sections. For better understanding and simplicity, equations are treated non-relativistically. For the present energy region, the relativistic correction is reasonably small, i.e., within 10%.

## 2. Separation of $^{43}\text{Ti}$

An enriched  $^{46}\text{Ti}$  primary beam was extracted from the Bevalac once in 4 seconds at 240 MeV/u. The intense beam of  $8 \times 10^8$  particle/spill on an average was brought to a production target of 1.27 cm thick Be. The bombarding energy was adjusted to 214 MeV/u using an energy degrader placed right before the target. The energy degrader is composed of two Al wedges facing each other and the total thickness can be controlled continuously by changing the relative position of the two wedges. The  $^{43}\text{Ti}$  fragments emerging from the target at 92 MeV/u were separated from various fragments produced in the target using the Beam 44 fragment separator. The separator basically consists of two dipole magnets and an energy degrader at the dispersive focus located between the two dipoles as shown in Fig. 1. The rigidity analysis by the first dipole magnet with a pair of slit jaws provides separation of the

fragments based on the mass over charge ratio ( $A/Z$ ). The rigidity analysis by the second dipole magnet right after the energy-loss in the energy degrader provides another separation based on the ratio ( $A^{2.5}/Z^{1.5}$ ). Through these two kinds of analyses, only the desired nucleus was separated from the various fragments.

Since the velocity of a fragment is very close to the velocity  $v$  of the primary beam, the rigidity  $B\rho$  of the fragment with atomic number  $Z$  and mass number  $A$  is

$$B\rho = \frac{p}{Ze} = \left( \frac{m_u v}{e} \right) \left( \frac{A}{Z} \right) , \quad (1)$$

where  $p$  is the momentum of the fragment and  $m_u$  is the atomic mass unit, i.e.  $m_u c^2 = 931$  MeV. So, the fragments are separated based on the mass over charge ratio ( $A/Z$ ) by the rigidity analysis in the first half of the separator. Dispersion at the focus of the first dipole magnet is 1.7 cm/% and the horizontal magnification factor is 2.5. Considering the beam size of  $\pm 1.5$  mm at the target, the source size at the focus is  $\pm 3.8$  mm. So, the limit of the  $A/Z$  separation is 0.22%. The rigidity window, however, was set to  $\pm 1.8\%$  in the actual experiment to get the reasonable yield for the nuclei considering the velocity distribution of the fragment.

The fragment was then slowed by an energy degrader placed at the focus. The range  $R$  of the fragment was empirically expressed as[8];

$$R = k(A/Z^2)(E/A)^\gamma + CA , \quad (2)$$



where constants  $k$  and  $C$  are only dependent on the material, and the power  $\gamma$  of the energy term is very close to 1.75 for the energy region from 50 MeV/u through 100 MeV/u. The range can be also expressed using rigidity  $B\rho$  as follows:

$$R = k' \left( \frac{Z^{1.5}}{A^{2.5}} \right) B\rho^{3.5} + CA, \quad \text{where } k' = k \left( \frac{e^2}{2m_u} \right)^{1.75} \quad (3)$$

With the help of the equation, the new rigidity  $B\rho'$  after passing through the degrader having thickness  $d$  is expressed as;

$$B\rho' = \left[ B\rho^{3.5} - \left( \frac{d}{k'} \right) \left( \frac{A^{2.5}}{Z^{1.5}} \right) \right]^{\frac{1}{3.5}} \quad (4)$$

The fragments were thus separated based on the ratio  $(A^{2.5}/Z^{1.5})$  by the energy loss analysis followed by another rigidity analysis[8]. For the fragments near the stability line, this separation is almost the same as separation by neutron number  $N$ . The second term in the equation was about a half of the first term to get enough separation power.

In order to tune the whole separator exactly to the desired fragment, we established the following tuning procedure. The separator was first tuned with an abundant  $^{46}\text{Ti}$  primary beam whose rigidity after passing through the target was set to the planned rigidity for the  $^{43}\text{Ti}$  fragment. After the primary beam tune, the separator was optimized to the  $^{43}\text{Ti}$  fragment by scaling rules. That is, the energy of the primary beam was slightly adjusted in order for the  $^{43}\text{Ti}$  fragment to give the same rigidity, and the degrader thickness was adjusted. The energy degrader can be

rotated around the horizontal axis perpendicular to the beam direction, so that the thickness  $d$  can be controlled as  $(1/\cos\theta)$  by the rotation angle  $\theta$  of the degrader. From equation (4), the thickness  $d$  should be as follows to give the same rigidities  $B\rho$  and  $B\rho'$ .

$$d = k' (B\rho^{3.5} - B\rho'^{3.5}) \left( \frac{Z^{1.5}}{A^{2.5}} \right). \quad (5)$$

So, the thickness was adjusted with the scaling factor  $Z^{1.5}/A^{2.5}$  to keep the rigidities constant. The separator was thus optimized to the  $^{43}\text{Ti}$  fragment just by a slight adjustment of the primary beam energy and the degrader thickness without changing any current settings of the magnets.

Due to the energy compensation described later, the separation power of the energy loss analysis, however, was poor. However, the range analysis was efficient at separating out a single isotope from the same  $(A/Z)$  family. Since the range of the fragment is roughly proportional to the ratio  $(Z^{1.5}/A^{2.5})$  for a given rigidity as shown in equation (3), the fragment can be separated based on the ratio, just like the energy loss analysis. Another controllable energy degrader made of plastic placed at the final focus allows fine range control. The  $^{43}\text{Ti}$  nuclei was slowed down by the degrader and was implanted in a thin catcher. Thus, nuclei having different ranges were either stopped in the degrader or went through the thin catcher. Range distribution was observed as shown in Fig.2 by measuring the beta-ray counts as a function of the degrader thickness. The range distribution shows clear separation of  $^{43}\text{Ti}$  at the proper thickness setting, with small contributions at about the 1% level from the other mirror nuclei. As a result, a clean beta-ray time spectrum

was observed as shown in the same figure. From the analysis of the spectrum, the beta-decay half life of  $^{43}\text{Ti}$  was determined[3] to be  $(503 \pm 8)$  msec, which is in good agreement with the known value for the nucleus[9]. The analysis also showed a small contribution from  $^{42}\text{Sc}$  because of the close  $(Z^{1.5}/A^{2.5})$  ratios for the isotones.

### 3. Identification of the fragments

The fragments were identified through energy loss ( $\Delta E$ ) and time of flight(TOF) measurements. Energy loss was measured using a 400  $\mu\text{m}$  thick SSD (Solid State Detector) to identify  $Z^2$ . The TOF was measured by a pair of plastic scintillation counters placed at the first and the final focus with a flight path of 8 m. The TOF measurement identifies the ratio  $A/Z$ , because the velocity of the fragments with the same rigidity is proportional to the ratio  $Z/A$ .

Two dimensional maps of TOF and  $\Delta E$  were obtained as shown in Fig.3, and the fragments were successfully Identified. The two dimensional map was deformed due to the energy loss by the energy degrader. By a simple transformation of the two dimensional map,  $(Z)$  and  $(A/Z)$  were clearly identified, as is also shown in the figure. Production rates were also rather high for the V isotopes. It shows a high probability of charge exchange for the present energy range. So, a beam of the next mirror nucleus  $^{45}\text{V}$  can be also provided by the same primary beam at a reasonable production rate.

#### 4. Energy compensation

##### (Tilted foil polarization of $^{39}\text{Ca}$ and $^{43}\text{Ti}$ )

The TFT provides a universal and efficient technique for polarizing the fragment. The technique uses the polarization phenomenon in the orbital electrons around the nucleus through the asymmetric interaction between such electrons and the electrons at the tilted foil surface. So, the energy of the nucleus should be low enough to give as many electrons around the nucleus as possible.

Such a low energy secondary beam was obtained by suitable energy degradation and proper energy compensation. Since the energy spread in a fragment becomes larger in the energy degradation process, proper energy compensation is crucial. For this reason, the intermediate degrader was made of a wedge-shaped plastic plate. Since the fragment with higher energy goes through the thicker part of the wedge, the energy spread is compensated. Rotating the wedge changes the thickness gradient of the degrader for fine tuning.

The energy spread in the  $^{43}\text{Ti}$  beam which was originally  $\pm 3.6$  MeV/u at 92 MeV/u was reduced to  $\pm 0.5$  MeV/u at 60 MeV/u by the wedge degrader. This corresponds to the compensation limit, i.e.,  $\pm 0.22\%$  of the incident momentum, due to a finite source size of  $\pm 3.8$  mm at the focus. With the use of a thin Au foil of about 20 mg/cm<sup>2</sup> as a final degrader, the energy spread in the beam was further reduced, because of the negative curvature in the energy loss character for Au at energies below 2 MeV/u. The resultant energy of the  $^{43}\text{Ti}$  beam was as low as  $1.5 \pm 1.0$  MeV/u right before entering the tilted foil assembly.

Passing through the foil assembly, the  $^{43}\text{Ti}$  nucleus was polarized. The polarized  $^{43}\text{Ti}$  was implanted in a granular TiC crystal catcher placed

in a high magnetic field of 4.8 kOe to maintain the polarization. The tilted foil polarization of the  $^{43}\text{Ti}$  was measured by means of asymmetric beta decay. The NMR effects were detected as shown in Fig. 4 at an rf frequency  $780 \pm 70$  kHz for the NMR. From the measurement, the magnetic moment of  $^{43}\text{Ti}$  was deduced to be  $0.70 \pm 0.07$  nm[7]. Prior to the  $^{43}\text{Ti}$  experiment, tilted foil polarization was also observed for  $^{39}\text{Ca}$ [6], as shown in the same figure, using a similar technique.

## **5. Separation of $^{37}\text{K}$ and $^{39}\text{Ca}$ (Fragment polarization measurement)**

A  $^{40}\text{Ca}$  beam of  $10^9$  particles/spill was extracted from the Bevalac at 118 MeV/u. The beam was brought to a 380  $\mu\text{m}$  thick Au target. The energy loss of the beam in the target was small compared with the  $^{43}\text{Ti}$  experiment so that the momentum spread caused by the target thickness would be much smaller than the Fermi momentum. This condition was crucial for the fragment polarization measurement.

In this experiment, the primary beam energy couldn't be changed easily, because the energy degrader previously used for the purpose was to act as another target, and the target had to be thin, as already mentioned. Thus, the tuning procedure for the separator was slightly different from the previous one. After the primary beam tune, current settings for the whole separator were adjusted based on the scaling factor  $A/Z$ , as shown in equation (1). This was done in place of changing the incident energy. Since the rigidity after the energy degrader was also adjusted, the ratio  $\eta = B_p'/B_p$  stayed constant. Using the ratio  $\eta$  and the equation (1) for  $B_p$ , the equation (5) for the thickness of the degrader becomes;

$$d = k' (1-\eta^{3.5}) \left( \frac{m_{\text{UV}} v}{e} \right)^{3.5} \left( \frac{A}{Z^2} \right) \quad (6)$$

Thus, the thickness should be scaled by the factor  $A/Z^2$  this time. Adjusting the thickness  $d$  as shown in equation (6), the separator is optimized for the desired fragments and the fragments are separated as described in equation (4).

To determine how efficient the energy loss analysis was, distributions of the secondary beams were observed at the final focus. As shown in Fig. 5, beams of the fragments  $^{37}\text{K}$  and  $^{39}\text{Ca}$  were focused on the two different horizontal positions according to their  $A^{2.5}/Z^{1.5}$  ratios. So, either  $^{37}\text{K}$  or  $^{39}\text{Ca}$  was selected by defining the position at the final focus. The fragment polarization for the beta-emitting  $^{37}\text{K}$  and  $^{39}\text{Ca}$  nuclei was measured at angles around the classical grazing angle of the  $^{40}\text{Ca}$  on Au collision at 106 MeV/u. Large polarizations (about 5%) were observed for both nuclei, as shown in the same figure. The typical trend in the fragment polarization was understood by a simple model of the projectile fragmentation process. The observed fragment polarization expands the NMR studies on the beta-emitting fragments with the established separation technique for the projectile fragments.

### **Acknowledgement**

The present work is partially supported by U.S. DOE under contract No. DE-AC03-76SF0098. The study is also partially supported by the Monbusho International Scientific Research Program from the Ministry of Education, Science and Culture of Japan, and by the Oversea Cooperative Research from the Japan Society for the Promotion of Science.

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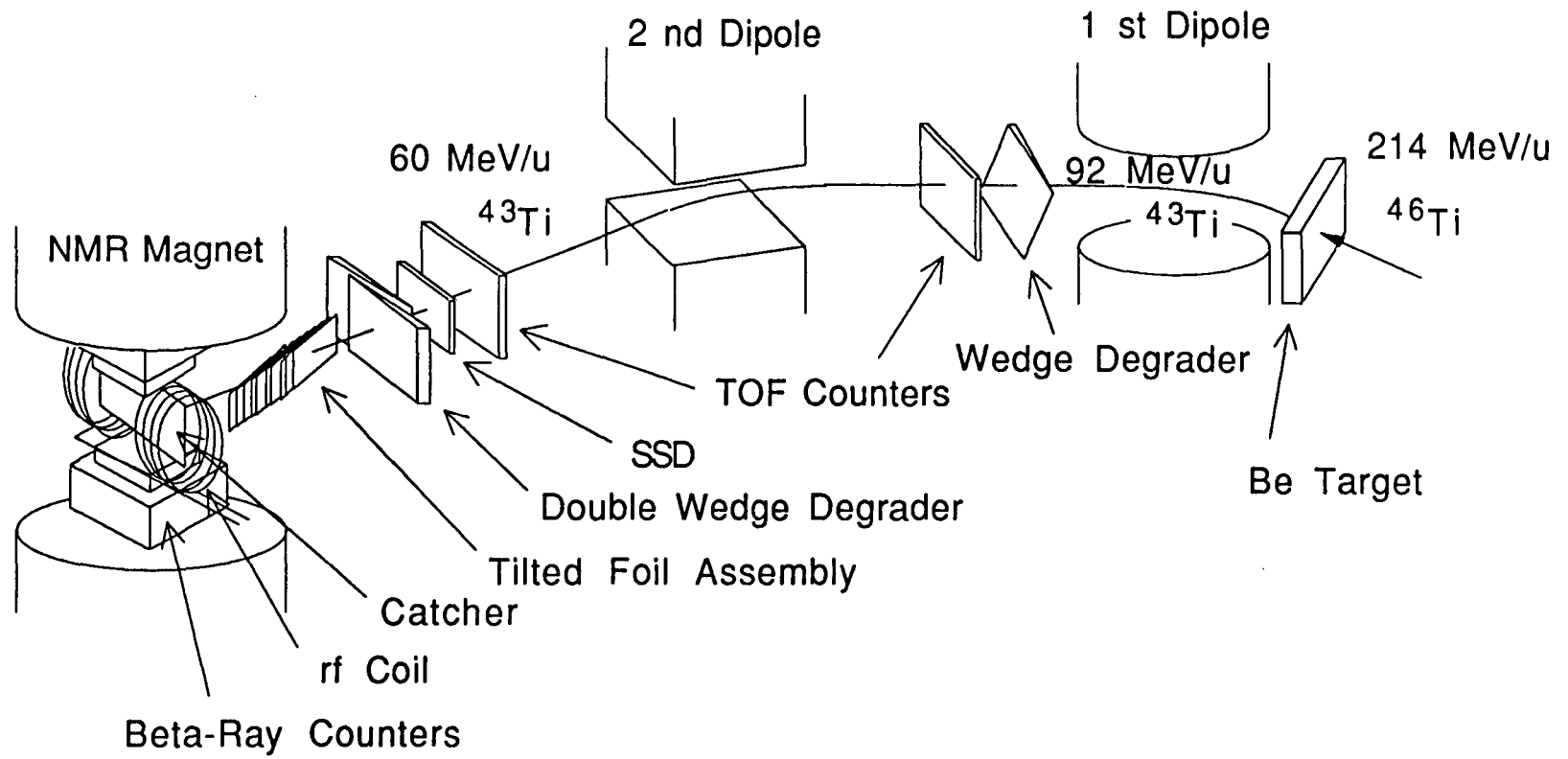


Fig. 1 Beam 44 Fragment separator.



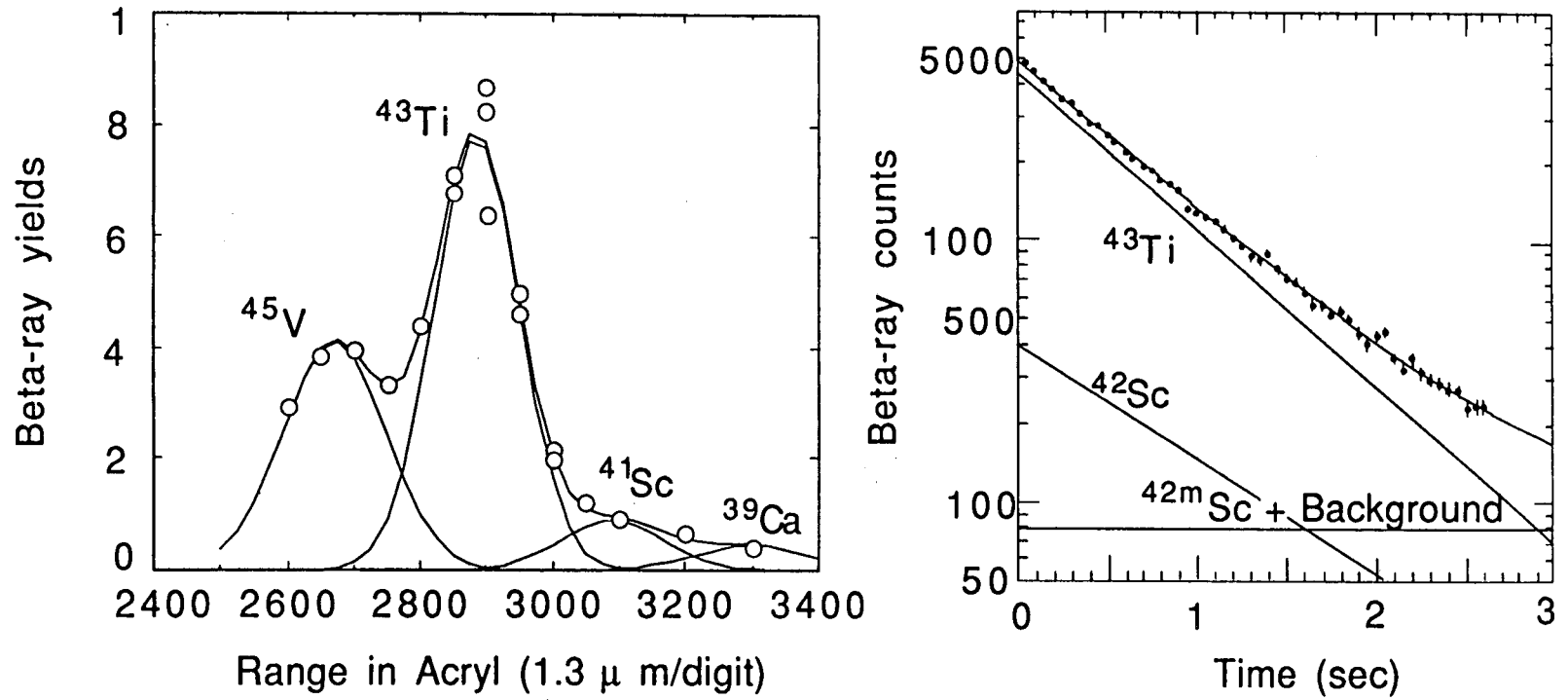


Fig. 2. Range distribution and the beta-decay time spectrum.

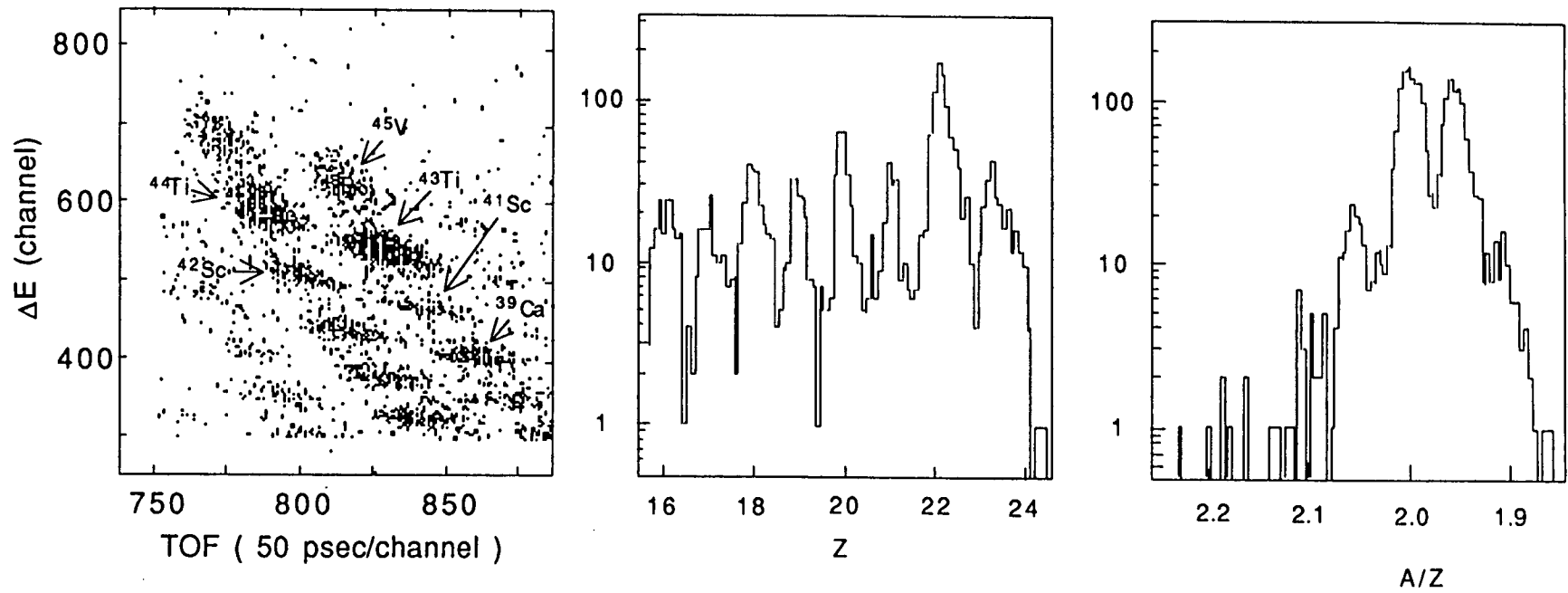


Fig. 3. Two dimensional map in  $\Delta E$ -TOF plane and  $Z$  and  $A/Z$  distribution.

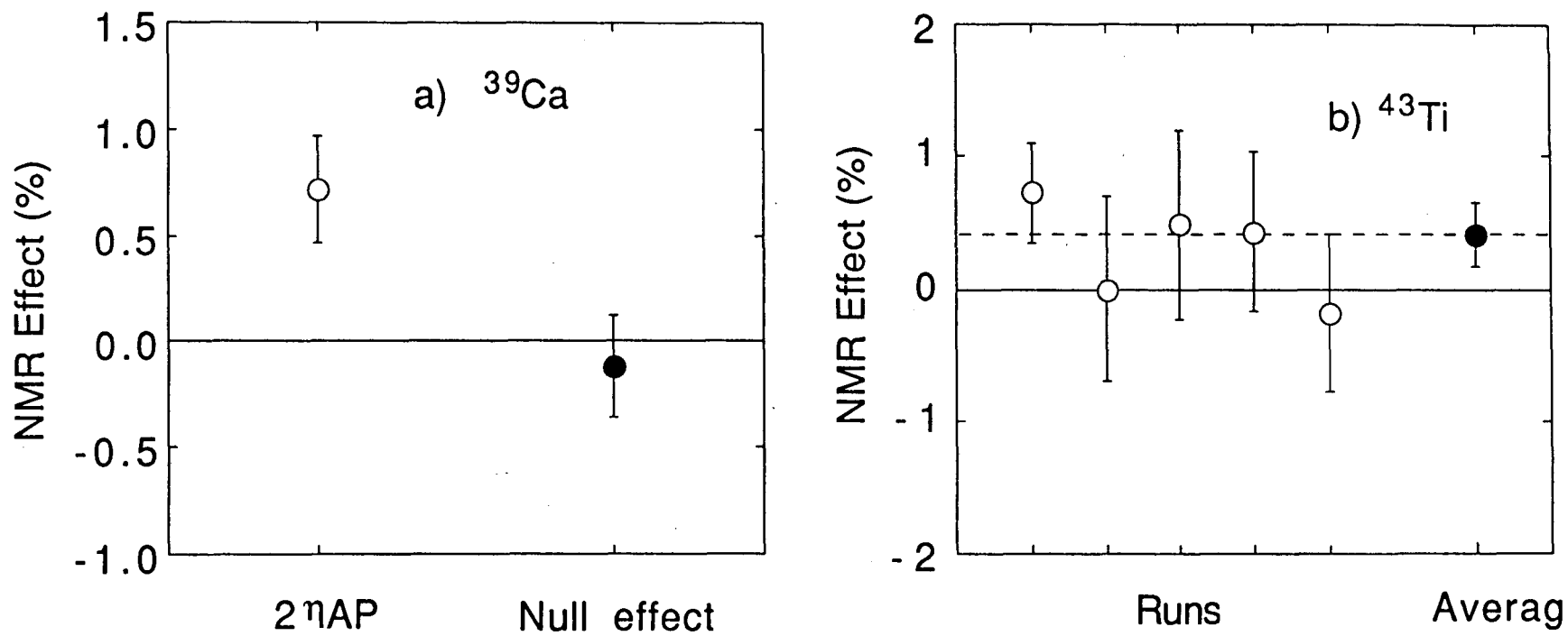


Fig. 4. NMR effects for  $^{39}\text{Ca}$  and  $^{43}\text{Ti}$  polarized by the TFT.

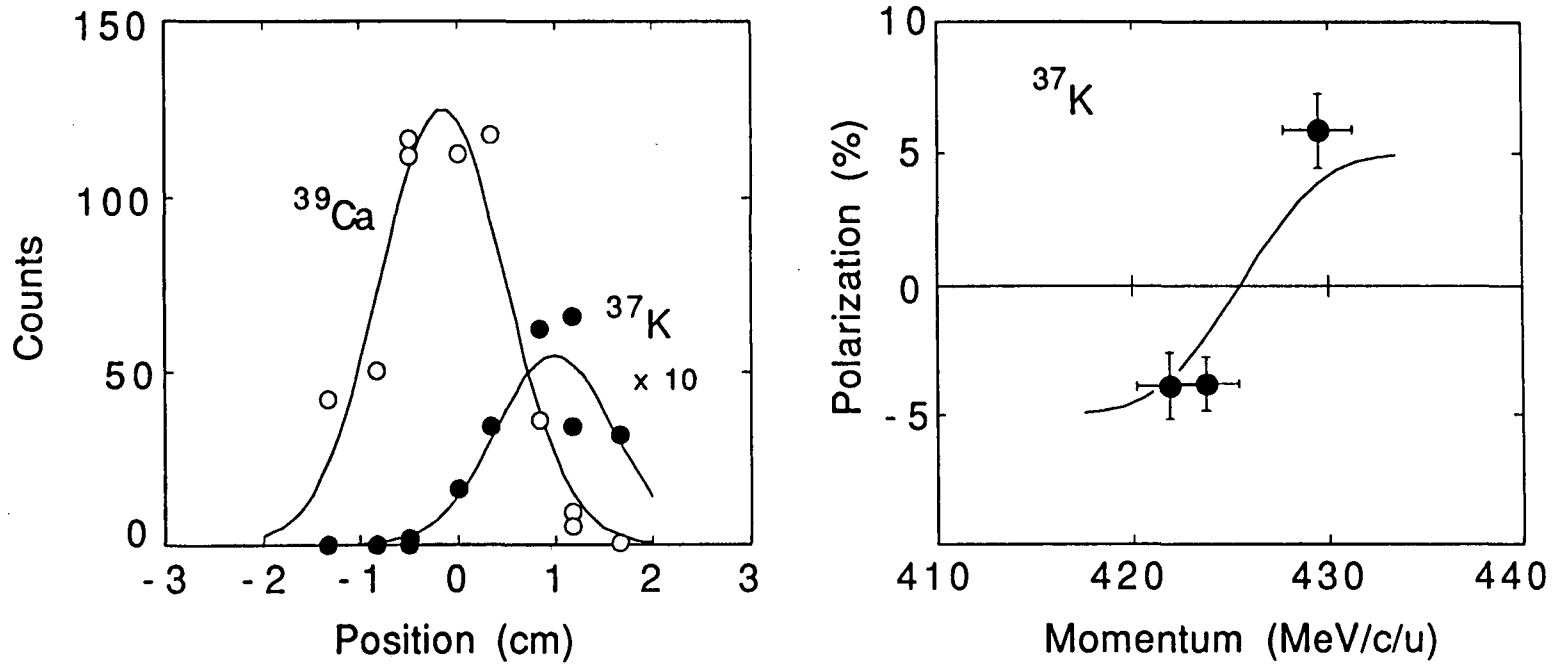


Fig. 5. Distribution at the final focus and typical fragment polarization.

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