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Imaging and Identification of Relativistic Projectile Fragments
with Lexan Spectrometry

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Abstract

We describe the method and some applications of Lexan spectrometry to the identification of nuclides produced in the fragmentation of relativistic heavy ions at the Lawrence Berkeley Laboratory Bevalac. Fragments emitted at 0° to the beam are deflected in a magnetic spectrometer and come to rest in a large stack of Lexan plastic detectors. Charge, mass, and energy are determined from measurements of range and lateral position in the stack and from etch pit lengths in two consecutive sheets. In favorable cases charge and mass can be determined from range and deflection alone without the necessity of etch pit measurements. The main advantage of the method is its large collecting power: fragments striking any portion of the 450 cm^2 detector surface are sufficiently focussed for their mass, charge, and energy to be identified. Unusual events such as the attachment of two electrons by a projectile nucleus can be observed.

1. Introduction

Fragmentation of relativistic heavy ions at large impact parameters

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leads to fragments in a narrow cone about the beam direction with approximately Gaussian distributions of longitudinal and traverse momenta in the projectile frame.¹ The widths of these Gaussians are typically $\sim 10^2$ MeV/c. We will describe a method for determining mass and charge of projectile fragments by measuring their range and lateral position in a stack of Lexan track detectors at the focal plane of a zero-degree magnetic spectrometer built by the Heckman/Greiner group.² Figure 1 is a sketch of the experimental setup. In analyzing the tracks in our first test of this method, using a 200 MeV/N ^{40}Ar beam on an Al target, we found that non-Gaussian tails of the momentum distributions often smeared the range peaks such that several isotones populated the same region of the detector stack. The charges of these isotones can be determined, and the ambiguity removed, by measuring etch pit lengths in two consecutive Lexan sheets.

The method has several features that make it potentially competitive with the sophisticated particle-telescope system being used by others^{3,4} to search for exotic nuclides using the same spectrometer:

1. The collecting power is $\sim 450 \text{ cm}^2$ instead of $\sim 20 \text{ cm}^2$.
2. There is no upper limit on the nuclear charges that can be studied.
3. Rare products close to the beam rigidity can be studied as well as rare products with much higher rigidity such as projectile nuclei with several electrons attached.

2. The Method

The principle is illustrated in Fig. 2, which shows the relationships between range and magnetic rigidity for a number of possible

proton-rich nuclides that might be produced in the fragmentation of ^{40}Ar projectiles. The calculations were done for a 205 MeV/N ^{40}Ar beam on a 0.2 g/cm² Al target assuming the production of projectile fragments with a most probable velocity equal to that of the ^{40}Ar at a point halfway through the target and a Gaussian distribution of $p_{\parallel}$ given by the empirical expression of Viyogi et al.⁴

$$\sigma(Z,A) = 94\sqrt{A(40-A)}/39 \text{ MeV/c} \quad (1)$$

The ordinate is mean range in a Lexan stack. Range straggling of a fragment of mass A is $A^{-1/2}$ times the range straggling of a proton (typically ~1%) and is thus $\leq 0.2\%$, so that it detracts negligibly from the resolution. The abscissa is deflection at the detector stack. In an experiment one Lexan stack at a time is positioned on a rail so as to intercept fragments in a 30-cm deflection interval; the spectrometer is focussed for fragments striking the center of the stack; an exposure is made at constant magnet current; and the operation is repeated with a new Lexan stack at a different 30-cm deflection interval and the spectrometer refocussed.

Unlike solid state detectors, Lexan records only at very high ionization rate, so that particles of low Z stopping in a given sheet, and particles of high Z that pass through a given sheet with considerable residual range, do not produce a signal in that sheet. The practical lower limit for an appreciable signal is $Z/\beta \geq 70$, if no ultraviolet sensitization is employed, and $Z/\beta \geq 40$ if the Lexan is strongly exposed to ultraviolet light before etching. In the interval of Z from ~10 to ~20 of interest here, the etch time of the Lexan

stack can be chosen so that a fragment produces a measurable signal only at a distance less than 0.1 cm from the end of its range.

The heavy points in Fig. 2, corresponding to mean range and most probable parallel momentum, show that in the absence of smearing effects the A and Z of a fragment would be uniquely determined by range and deflection. The most serious smearing effects are the following:

1. Dispersion in $p_{||}$. The lines on either side of the heavy points in Fig. 2 indicate the effect of a $\pm 1\sigma$ dispersion of $p_{||}$ calculated from eq. 1. This momentum dispersion leads to a set of well-defined, continuous bands of isotones running from large range and small deflection to short range and large deflection. Figure 3 is an ammonia print of a Lexan sheet showing sets of isotone bands for several neutron-rich nuclides. The print is made by taping an etched Lexan sheet over a piece of blueprint paper and passing ammonia gas over the sheet. The spots provide a map of etched-through tracks corresponding to highly ionizing particles near the ends of their ranges.

We find that in general the momentum smearing is worse than that calculated, because of long, asymmetric, non-gaussian tails extending to low momentum. (In his thesis, Frankel⁵ has reported measurements of asymmetric distributions of fragments with $5 \leq Z \leq 10$ from the reaction 100 MeV/nucleon $^{40}\text{Ar} + \text{U}$.) On the proton-rich side of stability the smearing is worse than on the neutron-rich side because the cross sections decrease very rapidly with increasing Z along a band of isotones. Thus, at the range and deflection expected for a

ISOTOPE : same Z
ISOTONE : same A

given nuclide, say ^{22}Al , the low-momentum tails of the much more copiously produced nuclides ^{21}Mg , ^{20}Na , and ^{19}Ne cause a very large background. Typically 3 to 5 isotones contribute comparably to the track density at a given range and deflection on the proton-rich side, only 1 isotone contributes along the stability line, and 2 to 3 isotones contribute on the neutron-rich side.

2. Sources of lateral broadening of the spots at the detector.

Dispersion of $p_{\perp}$ of the fragments, spectrometer optics, and finite beam width and angular dispersion contribute to a smearing of the images at the Lexan stack. As Figs. 3 and 4 show, none of these sources is serious enough to destroy the bunching into isotone bands. The reason for the vertical broadening at the edges of the Lexan sheet is that the focal plane of the spectrometer makes an angle of $\sim 87^\circ$ with the plane of the Lexan stack so that only the center of the stack passes exactly through the focal plane.

3. Dispersion due to finite target thickness. The contribution to overlapping within an isotone band and between adjacent bands due to differential slowing of fragments within a thick target is smaller than other sources of dispersion if a 0.2 g/cm^2 Al target is used, but becomes significant if a 1 g/cm^2 target is used. In experiments where exotic nuclides with extremely low production cross sections are being sought, it is advantageous to use a 1 g/cm^2 target now that the validity of the method has been established using a thinner target.

4. Dispersion due to nuclear reactions of the fragments slowing in the Lexan stack. About 20% of the fragments with $Z \geq 10$ from a $200 \text{ MeV/N } ^{40}\text{Ar}$ beam break up in the Lexan stack before coming to rest.

For the following reasons the interference of these secondaries at the range and deflection expected of primary fragments is small. Experiments in our group⁶ have shown that 600 MeV/N ^{56}Fe ions have a very sharp straggling curve even though more than half of the particles fragment before stopping. Interactions widen the straggling curve by a factor ~ 1.5 to a FWHM of $\sim 0.2\%$ and produce a low, continuous background of particles with lower Z or N extending mainly to greater range than that of the Fe. A loss of charge is easily detected by a decrease in etch pit diameter. A loss of only neutrons that occurs near the end of its range will result in the fragment falling within the straggling curve and being identified as the pre-interaction nuclide. A loss of neutrons that occurs near the beginning of its range will normally cause the particle to stop in a region populated by particles with higher Z, from which it can easily be distinguished. A study of Fig. 2 and similar graphs for other rigidity intervals shows that, in the usual situation, wherein a secondary fragment has a greater range than its parent because of loss of charge, it will stop at the range and deflection expected of a more common nuclide rather than a rarer nuclide. In Fig. 2 the only case where a heavier primary fragment might cause interference by fragmenting into a common isotope that could be mistaken for the exotic isotope is at ^{19}Na , which is known from experiment to be unbound. A ^{21}Mg or ^{23}Al could lose one or two protons respectively, have an increased range, and as a Na isotope be mistaken for ^{19}Na . By rejecting events with ranges corresponding to velocities differing more than $\sim 2\%$ from the beam velocity, we have found that interference due to secondary fragmentation

is diminished to an acceptably low level.

3. Fragments with Rigidity Similar to that of a 205 MeV/N ^{40}Ar Beam

The results of a short exposure (10 pulses of 205 MeV/N ^{40}Ar ions at $\sim 5 \times 10^5$ particles/pulse onto a 0.2 g/cm^2 Al target) with the spectrometer focussed at the beam rigidity illustrate a number of features of Lexan spectrometry. Figure (5) shows the distribution of ammonia spots as a function of deflection and of range, obtained by summing the number of spots in vertical strips two mm wide. Figure 4 is an ammonia print of a single Lexan sheet at approximately the mean range of the uninteracted ^{40}Ar beam. The region of Lexan at the $^{40}\text{Ar}^{+18}$ spot was so porous after etching that it had to be taped to prevent ammonia from flooding a large area of Lexan. The spot due to stopping ^{40}Ar ions labeled $^{40}\text{Ar}^{+17}$ on the figure is very clearly defined. They arise from attachment of a single K-electron by the stripped ^{40}Ar ions passing through the Al target. Their rigidity at the spectrometer is like that of a stripped ^{40}Cl nucleus, but after hitting the detector stack the K-electrons are stripped off and these nuclei have a range distribution identical to that of the main beam.

We call attention to several features in Fig. 5.

1. The monoenergetic ^{40}Ar beam is deflected by 200 cm and the peak in its straggling curve is in sheet 215. The high density of secondaries in the stack above and below sheet 215 makes rigidities corresponding to deflections of ~ 199 to ~ 201 cm inaccessible to study.

2. A continuum of degraded ^{40}Ar due to inelastic interactions in the target and in the beam transport line marches across the range-deflection space and joins the beam spot at sheet 215.

3. The number of events in the well-defined straggling curve for $^{40}\text{Ar}^{+17}$, relative to the number in the fully stripped beam, is 2.9×10^{-4} (to within a factor 2). Using the relation

$$N(^{40}\text{Ar}^{+17})/N(^{40}\text{Ar}^{+18}) = (\sigma_a/\sigma_s)(1-e^{-\sigma_s x}) \quad (2)$$

we estimate the ratio of attachment to stripping cross sections to be $\sigma_a/\sigma_s \approx 2.9 \times 10^{-4}$ in the limit $\sigma_s x \gg 1$, valid for a 0.2 gm/cm^2 Al target. This result is consistent with the value $\sigma_a/\sigma_s = 2.4 \times 10^{-4}$ obtained by interpolation of data by Crawford⁷ and Raisbeck et al.⁸

4. The etching time for this stack was chosen to discriminate against the production of ammonia spots for stopping particles lighter than argon. The efficiencies for ammonia spot production in this stack by various charges were determined by direct measurement to be 0.5 for Ar, 0.35 for Cl, 0.2 for S, 0.04 for P, and 0 for $Z < 15$. The rapid decrease in efficiency for $Z \lesssim 16$ explains why the sharp straggling curve at $^{40}\text{Ar}^{+17}$ is not seriously broadened by secondaries: most of them are too light to be detected by the ammonia process.

5. ^{39}Cl is separated from its two neighboring isotones, ^{40}Ar and ^{38}S .

6. ^{39}Ar and ^{38}Cl are roughly separated. The ^{39}Ar peak is in sheet 211 at the expected mean range; the ^{38}Cl peak, though obscured by the ^{40}Ar beam spot, appears to be near sheet 221, at its expected mean range; and there is a clear minimum in this isotone band at sheet 216. Of course, to determine cross sections accurately, one would have to make etch pit measurements and assign charges to each event.

7. Even with only 10 pulses there is some evidence for the pion

exchange product ^{40}Cl with a mean range at ~sheet 229, as well as a suggestion of the single neutron pickup reaction leading to ^{41}Ar . Further evidence for ^{40}Cl appears in Fig. 7.

It is clear that a single pulse through a detector stack centered on the beam rigidity would suffice to provide an accurate measure of the beam energy (through the range-energy relation), of the spectrometer setting, of the spot shape, and of the equilibrium ratio of attachment and stripping cross sections for the projectile, target, and energy employed.

4. Detection of Very Neutron-Rich Nuclides

With the spectrometer focussed for a mean rigidity of ~1200 MV we exposed a Lexan stack to fragments from reactions of $\sim 3 \times 10^9$ 205 MeV/nucleon ^{40}Ar on the 0.2 g/cm² Al target. The stack collected particles with a deflection of 155 to 184 cm; at the beam velocity such particles would have A/Z ranging from 2.42 to 2.87. Etching times and ammonia scanning were chosen to permit fragments with $10 \leq Z \leq 18$ to be located. Microscope measurements were made for ~3000 events. Momenta, charges, and masses were determined and events with velocities differing by more than 2% from the beam velocity were rejected.

Satisfactory isotope resolution was achieved for elements up to sulfur. Figure 6 shows histograms of the isotopes of Mg, Al, and Si for deflections between ~155 and ~177 cm. These histograms illustrate the quality of the mass separation but do not accurately reflect the relative production cross sections. They only show the relative yields in a narrow rigidity interval. Our analysis of the overall yields,

obtained by summing over all rigidities, is consistent with the results of Vinyo et al.⁴ and Symons et al.³ With a thicker target and longer running time it is clear that good statistics on the most neutron-rich nuclides could be obtained.

5. Production of Particles with High Magnetic Rigidity due to Attachment of one or More Electrons

At the same spectrometer focus and in the same Lexan stack discussed in the previous section, we have found a strong peak in the range-deflection plot corresponding to $^{40}\text{Ar}^{+16}$, and a possible peak due to $^{40}\text{Cl}^{+16}$. Figure 7 shows the ammonia spot distribution at shallow depths in the Lexan stack where high-Z particles come to rest. Microscope measurements confirm that the group of events labeled $^{40}\text{Ar}^{+16}$ have $Z = 18$ and that the group labeled $^{40}\text{Cl}^{+16}$ have $Z = 17$. The ranges and deflection are exactly as expected for these species.

The observed number of $^{40}\text{Ar}^{+16}$ relative to the number of fully stripped $^{40}\text{Ar}^{+18}$ beam particles is 1.7×10^{-8} to within a factor 2. The calculated equilibrium ratio for a thick target ($\sigma_s x \gg 1$) is given by

$$\begin{aligned} N(^{40}\text{Ar}^{+16})/N(^{40}\text{Ar}^{+18}) &= (\sigma_a/\sigma_s)^2/4 \\ &= 1.4 \times 10^{-8} \end{aligned} \quad (3)$$

using the ratio $\sigma_a/\sigma_s = 2.4 \times 10^{-4}$ from Crawford.⁷ The correctness of the charge, range, deflection, and production rate provides conclusive evidence for the detection of two-electron attachment by beam particles. The almost complete absence of background at the ^{40}Ar range and at deflections less than that of the $^{40}\text{Ar}^{+16}$ encourages us to believe that the three-electron attachment cross section could be

studied in an experiment at much higher beam fluence. Such a process is of considerable interest because L-shell attachment cross sections are likely to be quite different from K-shell attachment cross sections and are not easy to calculate. Some knowledge of cross sections for attachment into higher shells is needed in interpreting ionization rate measurements used to identify heavy, relativistic nuclei in cosmic radiation.

6. Current Application of Lexan Spectrometry

In April, 1979, several Lexan stacks were exposed to neutron-rich fragments produced in reactions of ~ 200 MeV/nucleon ^{48}Ca with a 0.89 g/cm^2 Be target. In a preliminary survey of ammonia spot distributions it appears that a number of new, neutron-rich nuclides were produced. A complete analysis of charges and masses will take several months.

Acknowledgments

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Figures

- Figure 1. Schematic diagram of spectrometer (not to scale), showing focusing and bending magnets and orientation of Lexan stack.
- Figure 2. Range vs deflection for some proton-rich nuclides, showing bands that must be separated by ionization rate measurements. Symbols enclosed in parentheses indicate nuclides not yet discovered.
- Figure 3. Ammonia print of a cut at constant range showing the bands for several moderately neutron-rich nuclides.
- Figure 4. Ammonia print showing $^{40}\text{Ar}^{+18}$, $^{40}\text{Ar}^{+17}$, $^{37}\text{Cl}^{+17}$, and $^{39}\text{Ar}^{+18}$.
- Figure 5. Distributions of ammonia spots as a function of deflection at ranges near the mean range of the uninteracted ^{40}Ar beam. The ordinate is sheet number, which increases with range. Data from sheet 217 are missing. Labeled curves give mean ranges with $\pm 1\sigma$ signifying ± 250 MeV/c spread in $p_{\parallel}$. The region between 199 and 201 cm is obscured by the ^{40}Ar beam and its interactions in the stack; the diagonal region along the curve labeled $^{40}\text{Ar}^{+18}$ has too high a density of ammonia spots to plot.
- Figure 6. Resolution of isotopes of Mg, Al, and Si produced in the rigidity interval ~ 1100 to ~ 1260 MV.
- Figure 7. Distributions of ammonia spots as a function of deflection at ranges near the mean range of the uninteracted ^{40}Ar beam and at much higher rigidities and fluence than in Fig. 5. The dot density increases logarithmically with

event density. The sheets were half as thick as those in Fig. 5; not all of the sheets were scanned.

XBL 799-2905

FIGURE 1

XBL 798-2906

FIGURE 2

XBB 790-15253

FIGURE 3

$^{40}\text{Ar}^{+17}$

$^{40}\text{Ar}^{+18}$

$^{39}\text{Ar}^{+18}$

$^{37}\text{Cl}^{+17}$

XBB 790-13255

FIGURE 4

XBL 798-2486

FIGURE 5

XBL 798-2487

FIGURE 6

XBL 798-2488

FIGURE 7