Nucl. Tracks, Vol. 9, Nos. 3/4, pp. 183–188, 1984
Printed in Great Britain

0191 – 278X/84 $3.00 + .00
Pergamon Press Ltd.

CALIBRATION OF TUFFAK POLYCARBONATE TRACK DETECTOR FOR IDENTIFICATION OF RELATIVISTIC NUCLEI

SHI-LUN GUO[†‡], J. DRACH*, P. B. PRICE*, M. H. SALAMON*, M. L. TINCKNELL[†]
Department of Physics, University of California, Berkeley, California 94720, U.S.A.
S. P. AHLEN
Department of Physics, Indiana University, Bloomington, Indiana 47405, U.S.A.
and
G. TARLÉ
Department of Physics, Randall Laboratory
University of Michigan, Ann Arbor, Michigan 48109, U.S.A.

(*Received* 8 *October* 1984)

Abstract—We discuss response of Tuffak polycarbonate to relativistic heavy nuclei using two methods, measurement of the minor axis diameter and of the length of the track cone, to determine charge resolution. At $Z = 92$ (0.95 GeV/u ^{238}U) both methods give about $0.9e$ charge resolution for a single cone measurement. Multiple cone measurements along the ion's trajectory have yielded a charge resolution $\sigma_z \leq 0.25e$ (16 cones) when stripping foils (Cu) are interleaved between plastic sheets to minimize sheet-to-sheet charge state correlations. As the charge of the incident ion decreases to $Z \approx 52$–57, the single-cone charge resolution improves ($\sigma_z \sim 0.29e$). The angular response of Tuffak is fairly constant for zenith angles of incidence from 0° to 48°. Range measurements of stopping relativistic ^{238}U in Tuffak deviate by ~5% from that predicted by the Bethe-Bloch formula, as expected from recent relativistic calculations. We conclude that Tuffak is an excellent track detector for identification of nuclear charges of relativistic heavy nuclei with $50 \leq Z \leq 92$.

1. INTRODUCTION

IN THE study of ultra-heavy cosmic rays and relativistic heavy ion nuclear interactions, one needs a series of nuclear track detectors with high charge resolution for relativistic heavy nuclei. In a previous study, Price *et al.* (1983) and Salamon *et al.* (1984) have shown that CR-39 is an excellent nuclear track detector with high charge resolution for relativistic nuclei of $10 \leq Z \leq 60$. The next important task is to find detector materials with high charge resolution for relativistic nuclei of $60 \leq Z \leq 92$ or even heavier. For this purpose, silica glass, Melinex, Lexan, CR-39, Tuffak and BPADC (bisphenol-A diallyl carbonate) (Ahlen *et al.*, 1984) have been tested. As a result of these tests, study has focussed on Tuffak polycarbonate plastic because of its superiority over others for identification of heavier relativistic nuclei (O'Sullivan and Thompson, 1981).

Since track length as well as cone diameter measurements are used in cosmic ray and relativistic nuclear physics studies employing plastic detectors, we examined the properties of Tuffak making use of both measurement techniques. In this study we examine the range-energy relation of relativistic uranium in Tuffak, the reduced etch rate versus Z^*/β, the reduced etch rate versus residual range, the charge resolution obtainable with track length and track diameter measurements, charge resolution improvement for actinide nuclei by using a stripping medium, and the angular response of Tuffak for different angles of incidence.

*Also Space Sciences Laboratory, University of California, Berkeley, CA 94720, U.S.A.
[†]Also Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, U.S.A.
[‡]Present address: Institute of Atomic Energy, Academia Sinica, P.O. Box 275(2), Beijing, China.

2. RANGE-ENERGY RELATION FOR RELATIVISTIC ^{238}U IONS IN TUFFAK

Ahlen and Tarlé have shown that 955 MeV/u ^{238}U in copper has an obvious range deficit (Ahlen and Tarlé, 1983) from the standard Bethe-Bloch formula (Ahlen, 1980). They showed that the discrepancy is of significance for high energy astrophysics experiments. In order to see if the range of relativistic ^{238}U ions in plastic track detectors has a range deficit, we started our study by measuring the range of relativistic ^{238}U ions in Tuffak.

A stack composed of 369 sheets of Tuffak was exposed to a ^{238}U beam of 955 MeV/u at a zenith angle of $\sim 10°$ at Lawrence Berkeley Laboratory's Bevalac. Each sheet of the stack had an area 7.2×7.2 cm^2 and a thickness ~ 0.265 mm. The Tuffak stack was thick enough to stop the ^{238}U ions.

One out of every ten sheets was first etched at 40°C in 6.25N NaOH and 0.05% Dowfax surfactant and saturated with Lexan etch products. The etching time was changed from sheet to sheet to ensure that the tracks in each sheet could be seen easily under the microscope. All sheets around the stopping point of the ^{238}U ions were then etched. The stopping points of about 120 ^{238}U ions were then measured with an optical microscope. Figure 1 shows the histogram of stopping points of ^{238}U ions

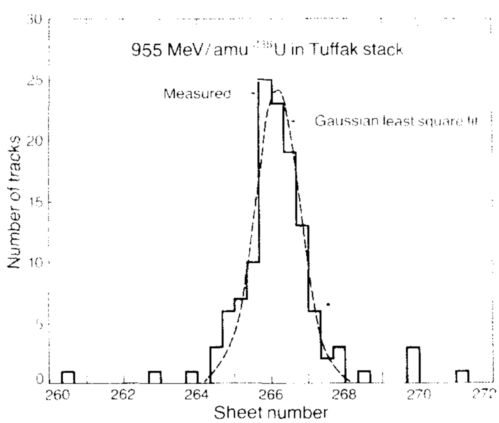

FIG. 1. Histogram of stopping points of ^{238}U ions in Tuffak stack. Standard deviation of range of 955 MeV/u ^{238}U in Tuffak stack is 0.60 sheets. The range of ^{238}U in Tuffak is 5% shorter than that calculated from standard Bethe-Bloch formula.

in the Tuffak stack. The standard deviation of the range histogram is 0.60 sheet of Tuffak. The range straggling was found to be 0.23%, which is consistent with that expected for very heavy projectiles.

The measured range of ^{238}U ions in Tuffak stack is about 5% shorter than that calculated by the Bethe-Bloch stopping power formula and is consistent with that calculated after inclusion of the Mott cross section and the relativistic Bloch correction (Ahlen, 1982) in the stopping power formula.

In the following analysis we use the result of the range measurements to calculate parameters such as ion velocity in our study of charge resolution.

3. REDUCED ETCH RATE VERSUS Z^*/β

The same Tuffak stack used for range measurements was used to get a relation between the reduced etch rate S and Z^*/β, where $S = V_T/V_G$, V_T is etch rate along particle track; V_G is bulk etch rate; Z^* is the effective charge of the incident heavy nuclei (Ahlen, 1980; Pierce and Blann, 1968):

$$Z^* = Z(1 - e^{-130\beta/Z^{2/3}}) \tag{1}$$

where Z is atomic number of the incident nucleus and β is its velocity (in units of speed of light) as determined by its residual range in the stack. In the interval of Z^*/β from ~ 105 to ~ 170, we selected 13 sheets of Tuffak for etch rate measurements. Etching was performed with the same conditions as those in the range measurements. The etching time varied from 12.6 to 84 h so that the total length of the two cones of each Tuffak sheet (one per side) equaled 90% of the path length of the ^{238}U ion in the sheet; this minimized relative track length errors.

The track length was measured under 53 (oil) $\times$ 10 magnification of a Leitz Largefield Metallographic Microscope (METALLOPLAN) with a linear displacement transducer for accurate depth measurement. The deviation of track length measurements was found to be less than 0.4 μm in the interval of track lengths from 20 to 70 μm.

The reduced etch rate S was calculated from the track geometry using the formula (Fleischer *et al.*, 1975)

$$S = [\sin\{\tfrac{1}{2}[-\arctan(\frac{Q}{a+p})+\arctan(\frac{Q}{p})]\}]^{-1} \quad (2)$$

where a, p and Q are shown in Fig. 2.

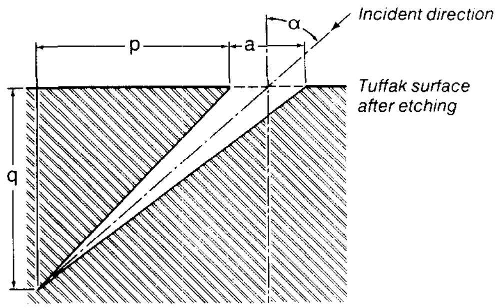

FIG. 2. Track geometry of a particle with incidence angle α.

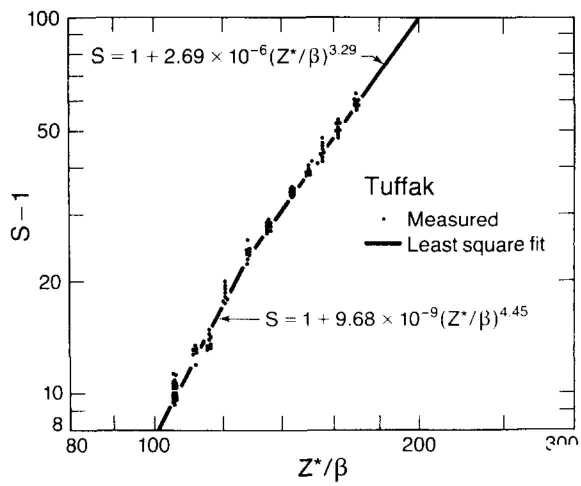

FIG. 3. Relation of reduced etch rate S to Z^*/β in Tuffak. Least square fit to two straight lines:

$S = 1 + 9.68 \times 10^{-9}(Z^*/\beta)^{4.45}$ $(105 \leq Z^*/\beta \leq 130)$

$S = 1 + 2.69 \times 10^{-6}(Z^*/\beta)^{3.29}$ $(130 \leq Z^*/\beta \leq 180)$.

A plot of reduced etch rate S versus Z^*/β is shown in Fig. 3. Here we use two straight lines in bi-logarithmic coordinates to fit the S data:

$$S = 1 + 9.68 \times 10^{-9}(Z^*/\beta)^{4.45} \quad 105 \leq Z^*/\beta \leq 130 \quad (3)$$

$$S = 1 + 2.69 \times 10^{-6}(Z^*/\beta)^{3.29} \quad 130 \leq Z^*/\beta \leq 180. \quad (4)$$

4. REDUCED ETCH RATE VERSUS RESIDUAL RANGE OF ^{238}U IN TUFFAK

From track length and residual measurements of ^{238}U tracks in Tuffak, the relation between reduced etch rate S and residual range R_0 of ^{238}U in Tuffak can be obtained. The relation is shown in Fig. 4. All ^{238}U data which are below 955 MeV/u fall approximately on a straight line in bi-logarithmic coordinates. This line can be expressed by the formula $S = 42.2\ R_0^{-0.63}$.

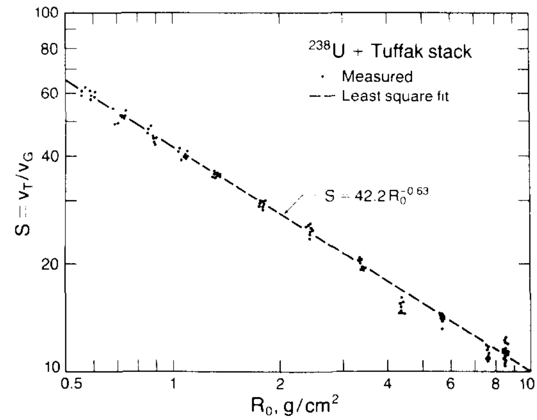

FIG. 4. Relations of reduced etch rate S to residual range R_0 of ^{238}U in Tuffak. Straight line is a least square fit to measured date.

5. CHARGE RESOLUTION OF TUFFAK FOR TRACK LENGTH MEASUREMENTS

In the track length measurements described in Section 3, nine tracks of nine ^{238}U ions were followed through the stack. One of them suffered a nuclear interaction midway through the stack. The other eight ions' values of reduced etch rate in each sheet were used to calculate the standard deviation σ_s of reduced etch rate for each sheet. The charge resolution σ_z follows from

$$\sigma_z = \sigma_s/(\partial S/\partial z) = \frac{\sigma_s\beta}{ab(Z^*/\beta)^{b-1}} \quad (5)$$

where

$a = 9.68 \times 10^{-9}$, $b = 4.45$ for $105 \leq Z^*/\beta \leq 130$;

$a = 2.69 \times 10^{-6}$, $b = 3.29$ for $130 \leq Z^*/\beta \leq 170$;

and $Z = 92$.

The calculated charge resolution of Tuffak for ^{238}U ions is shown in Fig. 5. The average value of charge resolution of Tuffak for ^{238}U in the energy region from 400 MeV/u to 955 MeV/u is about 0.89*e* for a single track length measurement. Below 400 MeV/u, the charge resolution has a larger fluctuation, but the average value is still below 0.9*e*.

6. CHARGE RESOLUTION OF TUFFAK FOR TRACK DIAMETER MEASUREMENTS

Another stack of Tuffak was perpendicularly exposed to ^{238}U ions of 962 MeV/u at the Bevalac. After etching in the same conditions as described in Section 2, track diameters in the top sheet were measured in reflected light with a Leitz Ortholux microscope coupled to a Compumetric AMS-100 system. The width of the track diameter distribution is a measure of σ_z, from which the charge resolution of 962 MeV/u ^{238}U in Tuffak is obtained, being $\sigma_z = 0.9e$ for single track diameter measurement, almost the same value as we obtained from single track length measurements. This datum is shown as a square in Fig. 5.

A third stack composed of Tuffak, polyethylene (to enhance nuclear interaction fragment production) and Pb (to increase ion slowing) was exposed to 1.25 GeV/u ^{139}La at the Bevalac. Several sheets of Tuffak were then etched in the same solution mentioned above for 239.8 h. The track diameters from midstack were measured with the Compumetric system. A histogram of the track diameter distribution is shown in Fig. 6. This distribution was obtained by selecting 525 cones for measurement on a single sheet surface, then following the tracks through 3 additional surfaces and averaging the diameters for each ion; the fragments' diameter widths diminish as $1/\sqrt{n}$, where n is the number of *independent* cone measurements for a given ion. The peak on the right side of the histogram corresponds to incident La ions. The others correspond to fragments of La produced from nuclear interactions with nuclei of the detector stack. The incident La peak in the histogram is reduced in height relative to the other peaks because a diameter cut was applied during cone selection in the first surface to favor selection of fragments (a total of 97). Tracks of particles which interacted in the region from the first to the last measured surfaces were eliminated using the criterion that the track diameter difference ΔD between two contiguous cones be less than 2.4 μm. Lowering ΔD

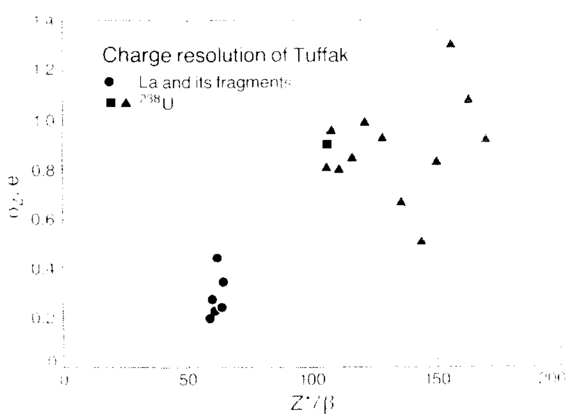

FIG. 5. Charge resolution of Tuffak as a function of Z^*/β of incident particles. ^{238}U tracks were measured by both track length method (▲) and track diameter method (■). La and its fragments were measured by track diameter method (●).

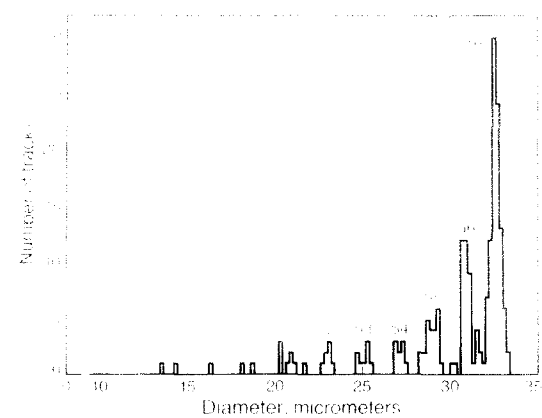

FIG. 6. Track diameter distribution of relativistic La and its fragments (4 track cone measurement). If $\Delta D \geq 2.4$ μm, the tracks were eliminated as interacted events. The meaning of ΔD is described in the text

improves charge resolution at the expense of statistics.

The charge resolution of La and its fragments was obtained from the peak widths and the separation between the individual peaks. The results are shown by solid circles in Fig. 5. The average value of charge resolution of Tuffak for $52 \leq Z \leq 57$ is about $\sigma_z \simeq 0.29e$ for a single track diameter measurement. Thus, Tuffak has a very good charge resolution for Z as low as 52, being much better in this region than CR-39.

7. CHARGE RESOLUTION OF TUFFAK INTERLEAVED WITH STRIPPING FOILS

As mentioned above, from a single track diameter measurement a charge resolution of $0.9e$ can be achieved for ~1 GeV/u ^{238}U. In order to get better charge resolution, many successive track cone diameters along the same ^{238}U trajectory were measured. (At relativistic energies, Z^*/β values for adjacent sheets are almost the same.) The charge resolution obtained as a function of the number n of successive track cone diameters measured is shown in Fig. 7. This particular work has been published previously, (Salamon *et al.*, 1984) so we restrict our discussion to a couple of salient features: as seen in the figure, although σ_z decreases as n increases for a pure Tuffak stack, it does not fall as rapidly as $1/\sqrt{n}$. Salamon *et al.* (1984) have explained this as being due to the statistics of electron capture and loss by the slowing uranium ion; charge state correlations from sheet to sheet destroy the statistical independence required for a $1/\sqrt{n}$ falloff in charge width. Introduction of Cu stripper foils between each Tuffak sheet restores statistical independence by 'reshuffling' the charge state distribution, and it is seen in Fig. 7 that a charge resolution $\sigma_z = 0.25e$ has been achieved for 1 GeV/u ^{238}U ions in Tuffak with $n = 16$ cone diameter measurements.

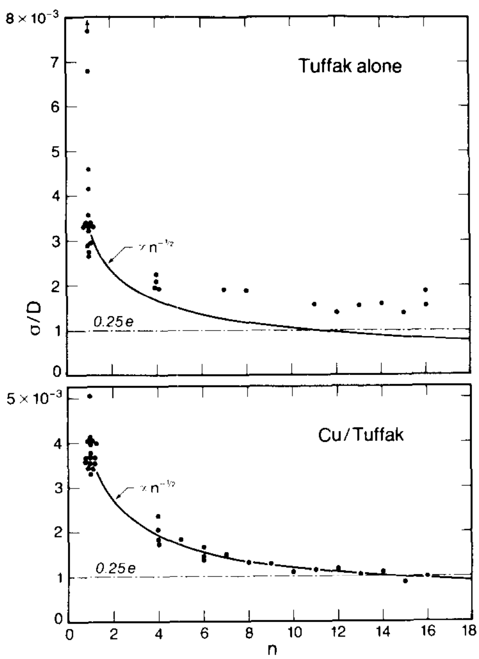

FIG. 7. Improvement of charge resolution of Tuffak as measuring n cones successively along the same trajectory of ^{238}U ions. For $n > 1$, the charge resolution of pure Tuffak stack (top figure) is poorer than that of Cu–Tuffak stack (bottom figure) which follows a factor of $1/\sqrt{n}$.

8. ANGULAR RESPONSE OF TUFFAK FOR DIFFERENT INCIDENT ANGLES

Knowing the angular response of nuclear detector is very important for detecting particle sources with varying incidence angles. A fifth stack of Tuffak was exposed to 955 MeV/u ^{238}U beam at four incident angles (α): ~0°, 15.6°, 31.9° and 48.0°. After etching, track lengths of 9 ions for each angle were measured, yielding an average reduced etch rate S value for each angle. The resulting angular

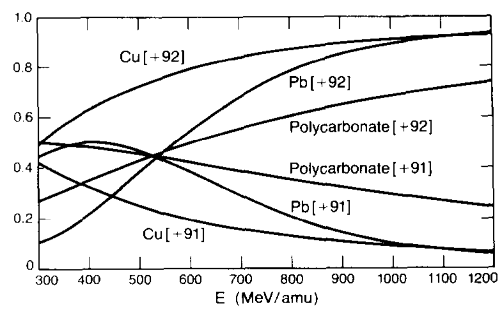

FIG. 8. Charge state fraction [$+92e$] and [$+91e$] of ^{238}U in Tuffak, Cu and Pb as a function of energy.

response of Tuffak is shown in Fig. 10, and is fairly isotropic from $\alpha \simeq 0°$ to at least $\alpha = 48.0°$. This property is important for studies of ultraheavy cosmic rays since angular correction factors are unnecessary.

9. SUMMARY

The study of charge resolution of Tuffak polycarbonate plastic shows that it is an excellent detector for identification of relativistic nuclei of $50 \leq Z \leq 92$. When identifying very heavy nuclei the Mott cross section and relativistic Bloch correction

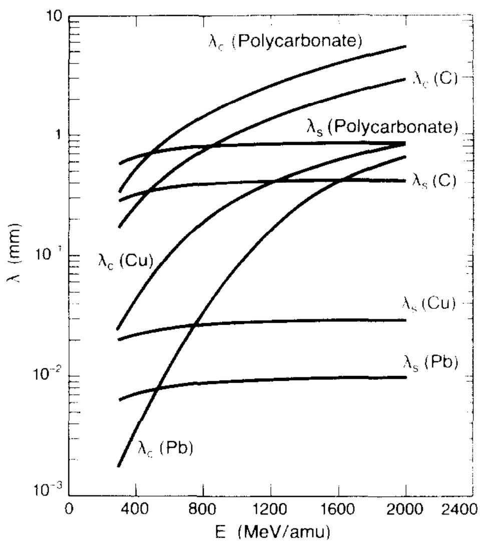

FIG. 9. Electron capture and stripping interaction lengths (in mm) of ^{238}U in Tuffak, C, Cu, and Pb as a function of energy.

must be employed in range and energy calculations. Either track lengths or track diameters can be used to scan heavy nuclear tracks; both methods can achieve a charge resolution $\sigma_z \simeq 0.9e$ for relativistic ^{238}U for a single track cone measurement. For lighter nuclei around La, the charge resolution can reach $\sigma_z \simeq 0.29e$ for a single track diameter measurement. Stripping materials (Cu foils) interleaved with Tuffak can improve the charge resolution by removing sheet to sheet charge stack correlations, validating the $1/\sqrt{n}$ law for relativistic actinides. A charge resolution $\sigma_z \leq 0.25e$ for

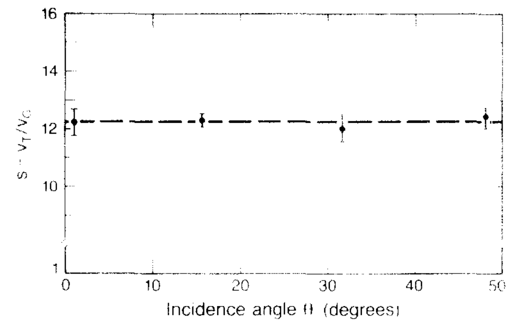

FIG. 10. Angular response of Tuffak at different incident angles to 940 MeV/u ^{238}U ions.

relativistic ^{238}U has thus been obtained. We are sure that $\sigma_z \leq 0.1e$ is easy to reach in the region of $50 \leq Z \leq 60$.

Acknowledgements—We are indebted to M. Solarz for his technical assistance in part of this work. Thanks are due to the staff at the Bevalac, LBL, especially Hank Crawford, for their help in exposure of the samples. Shi-Lun Guo thanks Prof. P. B. Price and all members of this group, especially Judy Blair, for hospitality and friendly help at Berkeley.

This work was supported by NASA Grant NGR 05-003-376.

REFERENCES

Ahlen S. P. (1980) *Rev. Mod. Phys.* **52**, 121.
Ahlen S. P. (1982) *Phys. Rev. A* **25**, 1856.
Ahlen S. P. and Tarlé G. (1983) *Phys. Rev. Lett.* **50**, 1110.
Ahlen S. P., Coan T. E., Drach J., Shi-Lun Guo, Price P. B., Salamon M. H., Tarlé G. and Tincknell M. L. (1984) *Nucl. Tracks Rad. Meas.* **8**, 571.
Fleischer R. L., Price P. B. and Walker R. M. (1975) *Nuclear Tracks in Solids: Principles and Applications*, University of California Press, Berkeley.
O'Sullivan D. and Thompson A. (1981) *Proc. 11th Inter. Conf. on Solid State Nuclear Track Detectors*, Bristol, England, p. 85.
Pierce T. E. and Blann M. (1968) *Phys. Rev.* **173**, 390.
Price P. B., Tincknell M. L., Tarlé G., Ahlen S. P., Frankel K. A. and Perlmutter S. (1983) *Phys. Rev. Lett.* **50**, 566.
Salamon M. H., Drach J., Shi-Lun Guo, Price P. B., Tarlé G. and Ahlen S. P. (1984) *Nucl. Instrum. Meth.* **224**, 217.
Salamon M. H., Price P. B., Tincknell M. L., Shi-Lun Guo and Tarlé G. (1984) *Nucl. Instrum. Meth.* in press.