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CHARGED PARTICLE TRACKS IN POLYMERS NO. 6: A Method For Charge Determination Of Heavy, Multicharged Cosmic Ray Particles

by

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ABSTRACT

A simple, direct and accurate method for charge determination of heavy, multicharged cosmic ray particles is presented. The method is based on the measurement of the portion of the particle range over which a track can be produced by a heavy particle in plastics. Accuracy in Z of ± 1 appears easily attainable. The results of a cellulose nitrate nuclear emulsion stack flown aboard a high altitude balloon are discussed.

SUMMARY

The Problem

Conventional passive dosimeters do not accurately measure the dose from the multicharged component of the primary cosmic radiation. Since the contribution of such radiation to the total dose received will be considerable during the long range manned space flights, it is important to develop a heavy ion dosimeter for this purpose.

The Findings

A simple, direct and accurate method for charge determination of heavy, multicharged cosmic ray particles in dielectric nuclear track detectors has been found. The method is based on the measurement of the extent of the particle range over which the energy loss rate is sufficiently high to allow track production through etching.

I. INTRODUCTION

Dielectric, charged particle track detectors have a number of characteristics that make them particularly well suited for the study of heavy, multicharged cosmic ray particles. Some of these are: small weight, simplicity, mechanical ruggedness, high latent image stability, freedom from distortion, and simple and direct processing. Their chief merit, however, lies in their ability to selectively measure the highly ionizing charged particles in the presence of high backgrounds of electrons, protons, neutrons and gamma radiation. Recent satellite and high-altitude balloon exposures suggest that these detectors will be useful in the study of both solar and galactic cosmic radiation,[1,2] where measurements of particle charge, velocity and mass are required. The purpose of this paper is to present a preliminary report on a simple and direct method for charge determination of the high Z ions.

a. "Development" of Cosmic Rays by Etching

Charged particles produce developable tracks in dielectric nuclear track detectors by producing ionization and excitation along their paths. Tracks are "developed" by immersing the irradiated samples into a suitable chemical reagent such as a strong hydroxide solution. The particle damage trails are attacked faster than the undamaged bulk material. Under ideal etching conditions, this produces a conical etch pit with a cone angle $\theta\left(\theta/2 = \sin^{-1}(r_B/r_T)\right)$, where r_B is the rate of attack of the bulk material, and r_T is the rate of attack along the particle trajectory. The vertex of the cone remains sharp until it reaches the point where the particle came to rest; subsequent etching causes the apex to become rounded off. In the case where the particle penetrates the entire thickness of a plastic sheet, etching proceeds from both sides, resulting in two collinear cones. If etching is allowed to proceed long enough, the two cones merge, resulting in a hole penetrating the thickness of the plastic (see Fig. 1).

b. The Restricted Energy Loss Rate Criterion for Particle Registration

Recently it was shown[3] that in order to produce an etchable track a charged particle must have a restricted energy loss rate[4,5,6] (REL) above some certain critical value, $\mathrm{REL}_{\mathrm{crit.}}$, characteristics of that particular recording medium. It was found that $\mathrm{REL}_{\mathrm{crit.}} = 1.1 \times 10^3$ and 3.7×10^3 MeV cm^2/g for cellulose nitrate and Lexan polycarbonate resin respectively, which at present are the two most useful track recording media. REL is a quantity closely related to the total rate of energy loss of a charged particle and is calculated in a similar manner.[3]

In the calculation of REL, the occasional large transfers of energy $> w$ to electrons are neglected. For cellulose nitrate and

Lexan $w = 10^3$ eV was found to be consistent with the available experimental data on track registration.

c. Charge Determination

The residual range, R, of a charged particle with a charge Z and a kinetic energy E is given by

$$R = \int_E^0 \frac{dE'}{\left(\frac{dE'}{dx}\right)}, \tag{1}$$

where E is the kinetic energy at that point corresponding to a velocity $v = \beta c$. The rate of energy loss, dE/dx, as well as the restricted rate of energy loss, REL, are functions of the particle charge and velocity. Inversely, the particle charge may be determined by measuring two quantities such as E (or R) and dE/dx (or REL); the variation in dE/dx (or REL) over an interval of range may also be used. If the particle's velocity is known, Z may be determined by a single measurement of dE/dx.

In this paper we are concerned with two categories of particles:

(a) Those that stop in the dielectric track detector cosmic ray stack, where the range and REL can be used to determine Z.

(b) Those that show appreciable slowing down, but do not stop the stack. Here REL and its variation over the available portion of the trajectory can be used. Very fast particles whose velocity remains essentially constant during traversal of the stack or particles that undergo significant nuclear interactions are not considered.

d. Dielectric Track Detector Stack for Cosmic Ray Flux Measurement

A charged particle penetrating a stack of dielectric track detectors produces a series of collinear, etchable track segments over the part of its range where REL of the particle is above the critical value required by the material. A subsequent partial etching for a time, t, reveals a series of etched tracks, each of length ℓ and having a cone angle θ. The entire information content of such a track ensemble resides in the following track parameters: the length of each track segment, ℓ, the variation of ℓ as a function of R, the cone angle, θ, of each track segment, and the variation of θ as a function of R, where R is the residual range of the particle at the point where ℓ or θ are measured. The cone angle is a function of REL of the particle, decreasing with increasing REL, and quickly becoming large when REL approaches the critical value of the material. The track length of an individual segment of the entire track is defined for specific etch conditions. For an etch time, t, ℓ is given by

$$\ell = \overline{r_T}\, t \; . \tag{2}$$

The quantity ℓ will approach zero where β is sufficiently high (β_c) such that REL drops below $\mathrm{REL}_{crit.}$. Each stopping particle of sufficient initial energy (corresponding to $\beta > \beta_c$) traversing a stack of sufficient dimensions (to bring it to rest) will produce etchable tracks at every plastic surface between the point where REL = $\mathrm{REL}_{\mathrm{crit.}}$ and the point where the particle stops. The length of this region of the particle trajectory is R_{reg}, the registration range. In Fig. 2 the predicted R_{reg} (according to the REL criterion)[3] is given as a function of Z for the most abundant isotope of each element. By measuring R_{reg} of every track, a charge number, Z, can then be assigned to each particle. It is observed that R_{reg} is a rather sensitive function of Z.

II. THE EXPERIMENT

In order to investigate the various possible techniques for charge determination, a cosmic ray stack was assembled and exposed for approximately 11 hours at an altitude of 144,000 ft over Manitoba, Canada. The stack consisted of 12, 1 x 3 in., 500 micron thick sheets of cellulose nitrate plastic and 18, Ilford K.5, 1 x 3 in., 600 micron thick emulsion pellicles. Upon recovery, the nuclear emulsions were mounted on glass and processed in a standard manner. The cellulose nitrate sheets were etched together in a 10 M NaOH solution for a period of 15 hours at 23°C. The etch time was short enough that for more than one-half of the particles that traverse the entire thickness of a single cellulose nitrate sheet and where etching proceeds from both sides (see Fig. 1) the tracks did not etch completely through.

The entire stack was scanned at 50X magnification and measurements were performed at 500X magnification using a digitized microscope. For each track the parameters measured in each layer of the stack included the intersection of the trajectory with the surface, the azimuthal and dip angles of the trajectory, and the length and the cone angle of the etched tracks.

III. RESULTS

Sixty different cosmic ray particles were recorded. Thirty of these produced tracks in more than one plastic layer and were followed to find the locations of the stopping end and the points on the trajectory where REL dropped below $\mathrm{REL}_{\mathrm{crit.}}$. For the particles registering at the exterior surface of the stack one or both of these points could not be observed. Only two particles produced tracks in all 12 layers of plastic, but 15 particles registered in more than 3 layers.

a. Evaluation of Z for Particles Whose Entire Registration Range is Contained Within the Stack

For 33 of the 60 particles found both the $\mathrm{REL} = \mathrm{REL}_{\mathrm{crit.}}$ point and the stopping point were contained within the stack. For these Z was determined according to Fig. 2. For the 6 layers of emulsion which were located between the layers of plastic, an approximate plastic equivalent thickness of 0.15 g/cm^2 was used.

The precision of the Z determination (aside from any uncertainty in value of $REL_{crit.}$) is governed by the ability to locate both ends of of the registration range. In some cases the stopping end of the particle trajectory could only be determined to approximately ± one-half of the distance from the point where the particle last registered to its expected, but undetected registration point on the next plastic surface. However if a particle stopped in a layer of emulsion or if the track in the stopping layer of plastic was etched to the stopping end (indicated by rounding off of the track) this end of the registration range was quite precisely determined. This condition was observed for 31 of the 60 different particles detected.

The point where REL equals $REL_{crit.}$ can also be determined to within ± one-half of the distance between surfaces along the trajectory. This is demonstrated by the fact that all of the particles seen to pass through the $REL = REL_{crit.}$ point were consistent in registering at all points where $REL > REL_{crit.}$ and in failing to register where $REL < REL_{crit.}$. The uniqueness of the $REL = REL_{crit.}$ point is the key to the accurate determination of Z by the measurement of the registration range. Thus the very critical dependence of the registration range on Z indicates that Z can be determined to ± 1 or possibly with complete confidence if the range of the particle through each layer of the stack is less than about 20% of the registration range, i.e., if the particle registers in more than 5 layers of the stack. For stacks composed of much thinner layers, the layer in which REL = $\mathrm{REL}_{\mathrm{crit.}}$ would not be as well defined and more than 5 layers would be required for a positive identification of Z.

The Z distribution determined by using the R_{reg} criterion is shown as the grey area in Fig. 3. Since the Z determination was not restricted to integral values, the peaks observed in the figure indicate that charge discrimination is being achieved. The precision in the Z determination varied from approximately ± 0.3 for Z = 18 to ± 3 for some of the particles measured as Z = 7.

b. Evaluation of Z for Particles Whose Entire Registration Range is Not Contained Within the Stack

If the entire registration range is not contained within the stack, Z cannot be determined by the method designated above. However, if a sufficient fraction of the registration range can be observed, Z identification can be achieved by determining the change in REL (or dE/dx) as a function of distance along with particle trajectory. The problem then is to find a measurable track parameter which is a sensitive function of the REL.

Assume that a parameter P is only a function of REL, i.e.,

$$P = P(\mathrm{REL}). \qquad (3)$$

Then the rate of change of P with respect to the distance along the trajectory, $\frac{dP}{dR}$, is a constant times a function of Z determined from the range energy relationship of the ion, i.e.,

$$\left(\frac{dP}{dR}\right)_{REL} = \left(\frac{dP}{d(REL)}\right)_{REL} \left(\frac{d(REL)}{dR}\right)_{REL} . \tag{4}$$

If dP/dR is measured at a particular value of P a particular value of REL is implied and dP/d(REL) evaluated at this point is a constant for all of the particles measured. For a given value of REL, d(REL)/dR is only a function of Z. In our stopping material at REL = 1.5×10^3 $\frac{\text{MeV cm}^2}{\text{g}}$, d(REL)/dR can be given approximately by

$$\frac{d(REL)}{dR} = 4.76 \times 10^7 \ Z^{-2.59} \left(\frac{\text{MeV cm}^4}{\text{g}^2}\right) \text{ for } 5 < Z < 23. \tag{5}$$

Therefore,

$$\frac{dP}{dR} = C \ Z^{-2.59} \text{ for } 5 < Z < 23, \tag{6}$$

where C is a function of the chemistry of the stopping material and the etching conditions. From Eq. (6) it is observed that as in the case of the registration range, R_{reg}, the rate of change of P with R is quite a sensitive function of Z.

Of the two parameters which gave the most promise for Z identification, the track length, ℓ, was the only one with satisfactory consistency. Plots of cone angles (governed by the ratio of the bulk to preferential etch rates) for consecutive plastic surfaces showed a large spread about the regression line, making the uncertainty in the slope of this line prohibitively large for accurate Z determination. It should be mentioned that tracks are not strictly cones due to diffusion effects during etching and deviations of the plastic from isotropy. Plots of the etched track length, ℓ, for consecutive surfaces as a function of the distance along the trajectory did not show a large spread. A contributing factor here is the fact that the track length is governed not only by the preferential etch rate but also by a delay in time from the initiation of etching of the sample to the time at which a particular track actually begins to etch. This time delay increases with decreasing REL.

Of the particles with Z's determined by the registration range, 7 had sufficient range to permit a good determination of $d\ell/dR$, the slope of the plot of track length, ℓ, vs. distance along the trajectory, R. The 7 values of $d\ell/dR$ are plotted in Fig. 4. The solid line is given by

$$\frac{d\ell}{dR} = 36.3\ Z^{-2.59} \text{ for } 5 < Z < 23, \qquad (7)$$

or

$$Z = 4.00 \left(\frac{d\ell}{dR}\right)^{-0.386}, \qquad (8)$$

showing that the data are well represented by the $Z^{-2.59}$ dependence as given by Eq. (6). For values of Z which are not within the range of validity of Eq. (7), d(REL)/dR is scaled by the factor 7.63×10^{-7}. This is represented by the dashed line in Fig. 4.

It is found that the plot of ℓ vs. R can in most cases be represented by a straight line, indicating that the coefficient, $(dP/d(\mathrm{REL}))_{\mathrm{REL}}$ is fairly insensitive to the value of REL at which it is evaluated. For some tracks, however, there is some curvature in the ℓ vs. R plot. This is the reason for the choice of REL = 1.5×10^3 $\frac{\mathrm{MeV\ cm}^2}{\mathrm{g}}$, a value not far above the critical value. For this value of REL, the slopes of the ℓ vs. R plots are measured in the region of the shortest track lengths which are usually less than 100 or 200 microns.

Nine values of Z which could not be determined by using the registration range have been determined by measuring $d\ell/dR$. These are included in Fig. 3 as black areas. For the remaining 18 particles Z could not be determined; here the portion of R_{reg} within the stack was simply too short for an accurate determination of $d\ell/dR$.

IV. DISCUSSION

The distribution given in Fig. 3 is in general agreement with the measurement of cosmic ray abundances by others. In particular the peaks at Z = 10, 12, 14, 16, and 18 are typical of other measurements. While the apparent peaks at Z = 21, 23, and 26 are not truly statistically significant they are in agreement with Neelakantan and Shukla.[7] Others[8] do not find peaks at Z = 21 and 23. An anomalous feature of Fig. 3 is the peak at Z = 7. There should be two well-defined peaks at Z = 6 and 8, however these appear to be absent. Here, there is a strong possibility of systematic errors in the measurement of R_{reg} which arise as a result of the relatively thick plastic layers used (500 μ) which tend to throw the Z = 6 and 8 particles into Z = 7 group. This occurs because only about one plastic thickness is traversed by the R_{reg} for each of these particles, a situation which can be avoided by using thinner plastics.

In comparing the flux values of particles recorded here with those measured by others, the bias of the detector as well as that of the stack must be taken into account. The nature of this detector is such that the registration efficiency is much higher for the higher Z particles as compared with the lighter ions. This is due to the much larger registration range of the heavy particles (see Fig. 2). Thus while the fluxes of alpha particles in cosmic radiation are fairly high, the number of tracks registered in the stack will be very low. Again, this response can be altered by varying the thickness of individual plastic layers. Charge identification of very heavy particles such as iron was not satisfactorily achieved simply because of the small size of this stack. For charge identification of Z = 26 ions using the R_{reg} method, a minimum stack thickness of 10 g/cm^2 is required. Even when using the somewhat less accurate $d\ell/dR$ method a larger stack is desirable. It is likely that a sizable fraction of the unidentified 18 particles belongs to the iron group. Having taken the above biases into account (as well as the somewhat uncertain amount of shielding experienced during the balloon flight), our measurements of the differential energy spectrum [particles/m^2 sec(MeV/nuc)sterad.] at the top of the atmosphere compare favorably with the measurements of Amand, et al.[9] However the small stack volume and the short exposure time result in rather poor statistics which severely limit the usefulness of this comparison.

This work clearly demonstrates the great potential of dielectric track detectors in measurements of high Z cosmic ray particles. The sensitivity of the R_{reg} method is embodied in the fact that R_{reg} varies approximately as Z^3 for carbon and as $Z^{4.8}$ for iron. Thus the accuracy of R_{reg} measurement need not be great in order to discriminate between the adjacent Z's. Furthermore the nature of the detector is such that it discriminates against the low Z particles, as seen from the relative abundances of Z = 7 and Z = 12 particles in Fig. 3. This method should work well in measurements of fluxes of ultra-high Z particles (Z > 26) whose knowledge is currently of great interest to cosmic ray physicists. Since R_{reg} for these particles in cellulose nitrate is prohibitively large, a material of lower sensitivity (such as Lexan polycarbonate resin) could be used.

In conclusion it should be mentioned that a determination of mass is also possible. It is expected that isotropic separation can be achieved for large values of Z if larger stacks of fairly thin layers of plastic are used. For mass discrimination it will probably be necessary to prepare the stack very carefully to insure uniformity of the layers. This will be required for an accurate determination of the $REL = REL_{crit.}$ points.

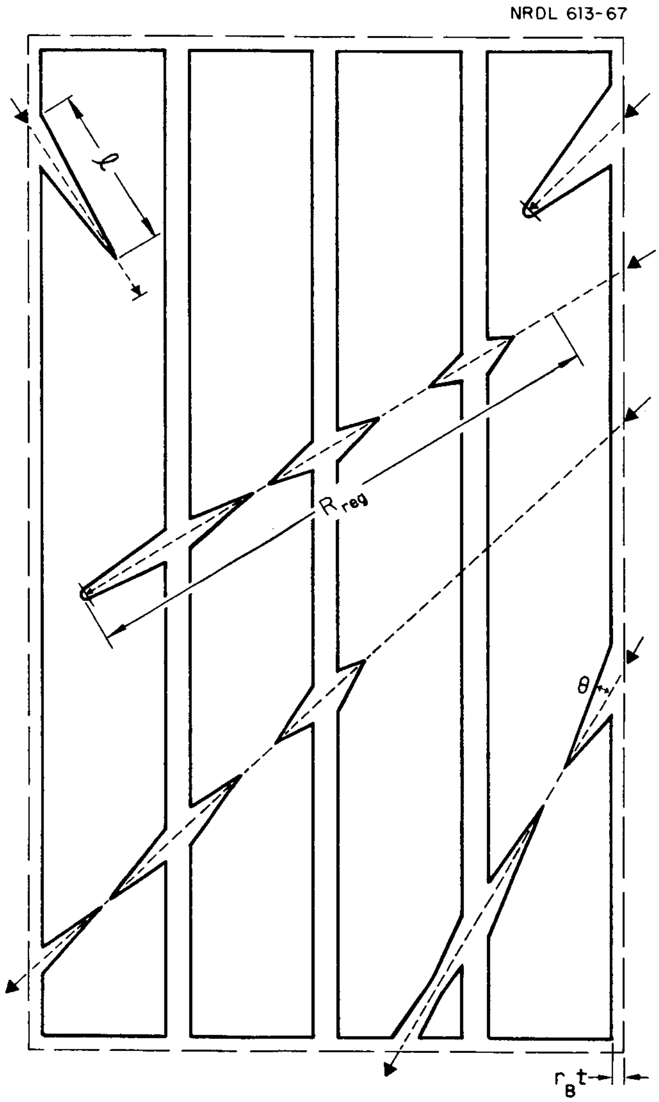

Fig. 1 The various observed categories of etch tracks.

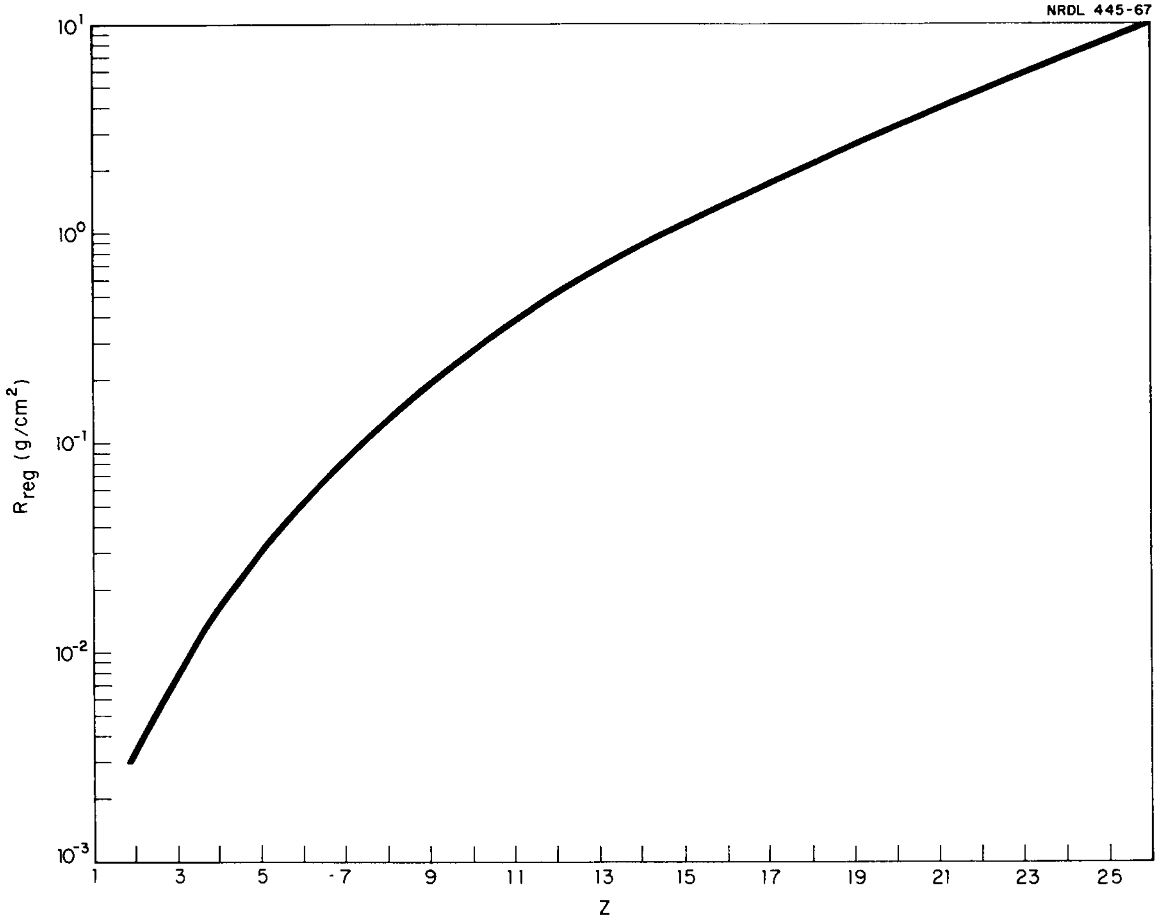

Fig. 2 The predicted maximum registration range, R_{reg}, for the most abundant isotope of each element.

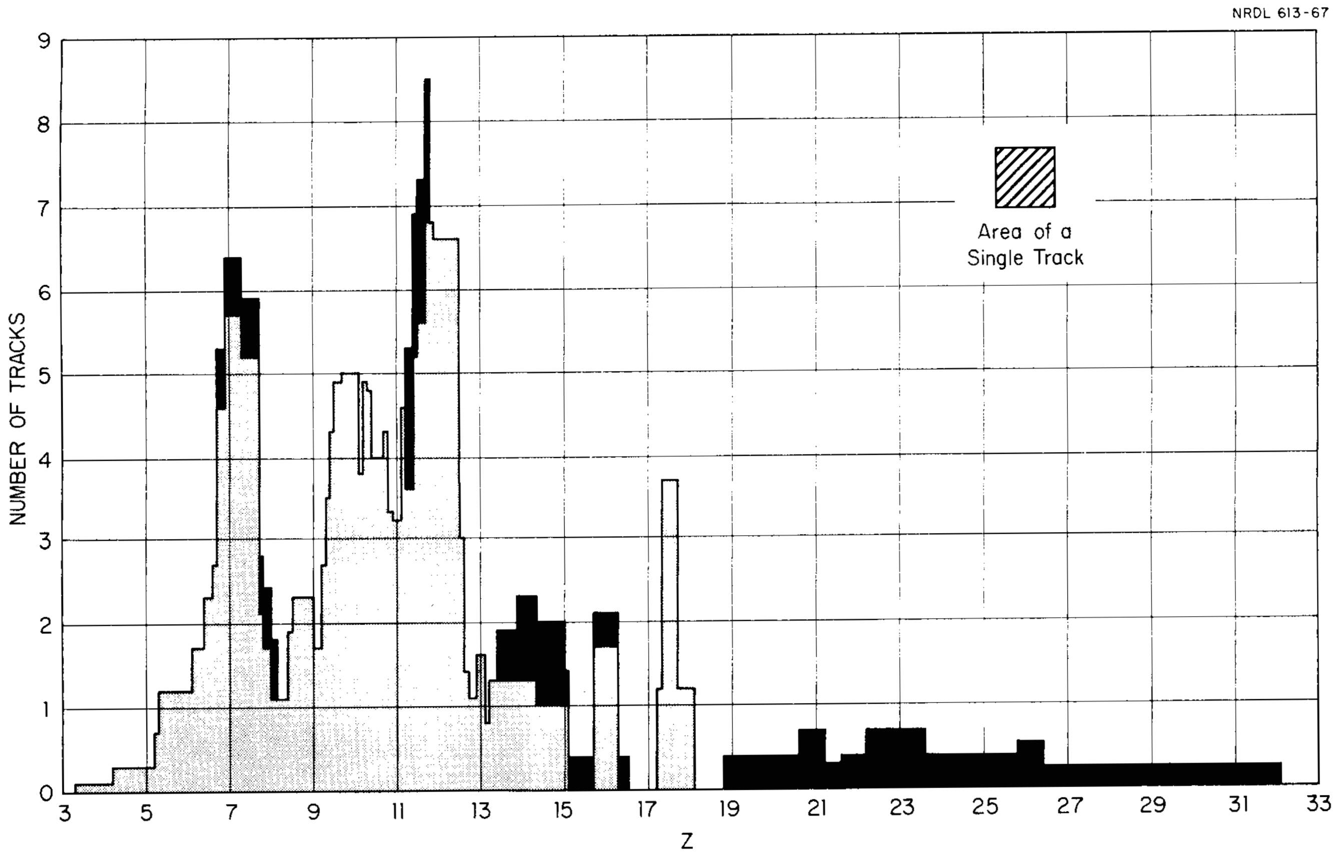

Fig. 3 The measured charge distribution; grey area represents tracks measured by the R_{reg} method; black area shows tracks measured by the $d\ell/dR$ method.

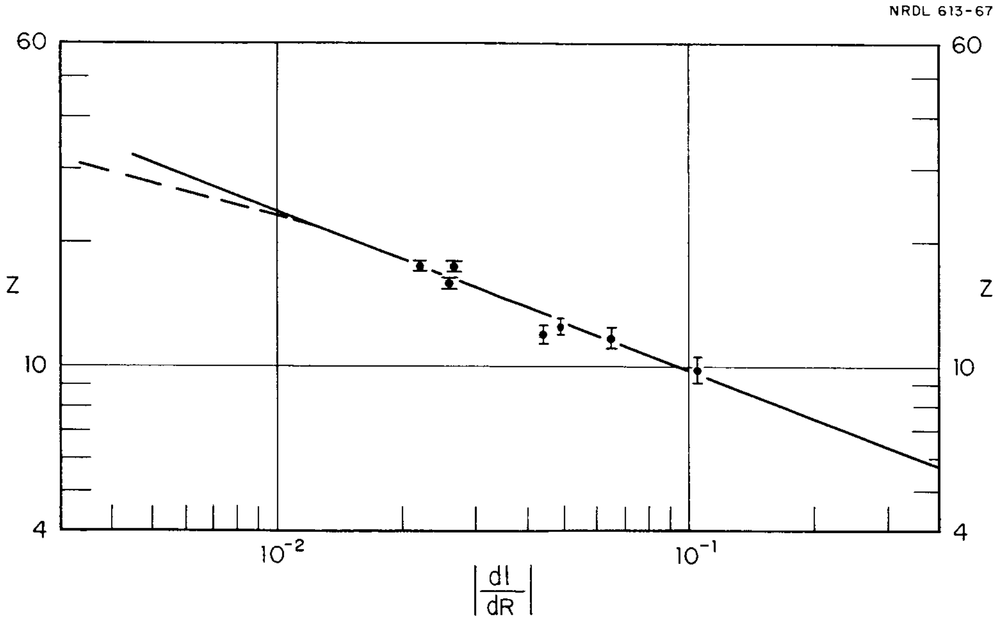

Fig. 4 The rate of change of etched track length with respect to particle range (measured from the stopping end) vs. Z (Z determined by the R_{reg} method.

REFERENCES

1. R. L. Fleischer, et al., Science 155, 187 (1967).
2. E. V. Benton and M. M. Collver, Health Phys. 13, 495 (1966).
3. E. V. Benton, "Charged Particle Tracks in Polymers No. 4: Criterion for Track Registration," USNRDL-TR-67-80 (1967).
4. B. Rossi, High Energy Particles, Prentice-Hall, New York (1961).
5. W. H. Barkas, Nuclear Research Emulsions, Academic Press, New York and London (1963).
6. National Academy of Sciences - National Research Council Publication-1133 (1964).
7. K. A. Neelakantan and P. G. Shukla, Phys. Rev. 130, 362 (1963).
8. O. Mathiesen, et al., University of Minnesota School of Physics and Astronomy, Technical Report CR-100.
9. K. C. Amand, et al., J. Geophys. Res. 71, 4687 (1966).

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13. ABSTRACT

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