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CHARGE MEASUREMENTS OF STOPPING HIGH-Z NUCLEI ( $6 < Z < 92$ ) IN NUCLEAR EMULSION

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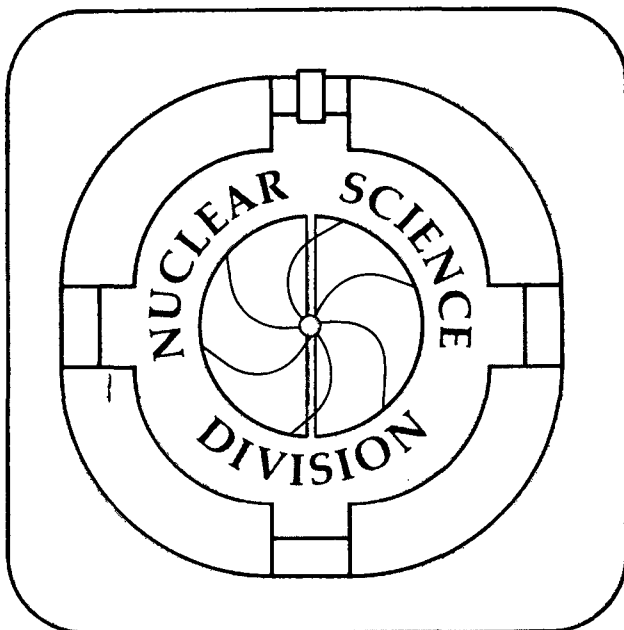
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ABSTRACT

The technique of charge determination by measurements of track-width of stopping tracks in nuclear emulsion has been extended to uranium nuclei. The method utilizes the last 1 mm of residual range to estimate mean-track-widths, and has been applied to nuclear beams of  $Z = 6, 26, 57$  and  $92$ . A resolution in charge of  $\sigma(Z) = \pm 1-2$  units was obtained over the entire interval of charges  $6 \leq Z \leq 92$ .

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

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## 1. Introduction

Measurements of the nuclear charges of heavy nuclei based on the linear structure of their ionization tracks in nuclear research emulsion (e.g., grain (blob) densities, gap-length distributions and lacunarity<sup>1</sup>) are no longer applicable. This is because the tracks of high-Z nuclei, in all but the most insensitive emulsions, are completely saturated, thereby eliminating the feasibility of extracting charge information from them by these means. Furthermore, because of the very high  $\delta$ -ray densities produced by such nuclei, the counting of individual  $\delta$ -rays to determine the linear density of  $\delta$ -rays becomes an impractical method for the estimation of charge. One is thus led to the track-width technique.<sup>2-4</sup> In this work we report on measurements of the mean track widths (MTW  $\equiv$  w) of stopping nuclei in electron-sensitive nuclear emulsion over residual ranges of 1.0 mm, and we assess the accuracy to which the charges of stopping nuclei can be determined by this technique for charges in the interval  $6 \leq Z \leq 92$ .

The ionization and  $\delta$ -ray densities produced by a charged particle in matter is directly related to the particle's rate of ionization  $dE/dx = \frac{Z^2}{\beta^2} L(\beta)$ , where the stopping number  $L(\beta)$  is a function of velocity  $\beta$  for a given projectile nucleus and target material. Hence, as a charged particle loses energy in matter by ionization in coming to rest, its rate of energy loss increases with decreasing velocity (range) until charge neutralization begins to occur at velocities comparable to the velocity of the K-electron of the ion and  $dE/dx \rightarrow 0$ . In nuclear emulsion, this stopping process is visually characterized by rising grain and  $\delta$ -ray densities as the ion approaches its end point and charge neutralization occurs. Prominent

features of stopping tracks of ions in emulsion, particularly those of multi-charged ions, are their increased widths with decreasing residual range and, after attaining a maximum width, their monotonically decreasing widths as they come to rest. The latter is the well-known thin-down effect. The thin-down phenomenon is attributed to two effects: i) the diminution of the  $\delta$ -ray energies ( $E_{\delta}(\text{max}) = 1.022 (\beta\gamma)_{\text{ion}}^2$ ), and, hence, the transverse range of diffusion of the  $\delta$ -rays as the velocity of the ion decreases, and ii) the capture of orbital electrons by the ion as its velocity decreases. Electron capture becomes important for ion velocities  $\beta \lesssim \frac{2Z}{137}$  i.e. twice the ion's K-electron velocity.<sup>5</sup> For light nuclei, the  $\delta$ -ray effect is the dominant factor in establishing track-widths, hence, thin-down, whereas electron capture becomes an increasingly important contribution to the thin-down of tracks of high-Z nuclei.

The "thin-down length" of a stopping ion is defined to be the residual range at which the opaque core of the track has a maximum width. Early work using cosmic-ray nuclei indicated a linear relation between Z and thin-down length.<sup>6</sup> However, we found that measurements of the thin-down lengths of stopping nuclei were not accurately defined operationally, so we have chosen the mean-track width method as most applicable in the present measurements.

## 2. Measurements

In this work two stacks of 600  $\mu\text{m}$ -thick Ilford G-5 emulsion pellicles were exposed at the Bevalac to beams of  $^{12}_6\text{C}$ ,  $^{56}_{26}\text{Fe}$ ,  $^{139}_{57}\text{La}$  and  $^{238}_{92}\text{U}$  at energies  $< 1.0$  AGeV. The energies were selected so that all ions would be brought to rest in the  $7.4 \times 12.5 \times 1.8$  cm<sup>3</sup> emulsion stacks. The beam nuclei traveled parallel to the surfaces of the pellicles in each case. One of the

stacks (#1) was exposed to Fe and U while the other (#2) was exposed to C, Fe and La. By having Fe beams common to both stacks, the track-width data from both stacks can be normalized, enabling us to present MTW measurements over a wide range of charges,  $6 \leq Z \leq 92$ .

For our measurements we used optical microscopes equipped with 100X oil objectives and a 15X filar micrometer, giving a total magnification of 1500X. The stopping beam nuclei were aligned with the x-axis of the microscope stage, while the motion of the filar micrometer was aligned with the y-axis of the stage. Track widths were measured within the field-of-view of the filar micrometer, the boundaries of the track segment being recorded to a precision of 0.04  $\mu\text{m}$ . In these measurements we defined the track width to be the minimum projected diameter of the completely saturated core of the track, observed over a track segment of 15  $\mu\text{m}$ . The intent of this definition of track width was to quantify this parameter as much as possible, and to limit large systematic differences between different observers. Although we found individuals could reproduce their MTW measurements to  $\frac{dw}{w} \approx \pm 1\%$ , subjective systematic differences still persisted among different observers as to the value of the MTW for a given track. For this reason the data presented here were obtained by one observer (MTG).

We selected for measurements 10 to 20 stopping tracks of each beam particle that were distributed uniformly (approximately) in depth in an emulsion pellicle. The MTW of each track was measured over the last 1 mm of residual range. This was done by measuring the "core" widths of the track at 50  $\mu\text{m}$  intervals, over residual ranges from 50 to 1000  $\mu\text{m}$ . Only one measurement of the MTW was made for each track in order to evaluate the adopted technique as an operational method of charge measurement. A measure



of the MTW of the track was taken to be the average of the individual track-width measurements  $w \equiv \frac{1}{n} \sum_{i=1}^n w_i$ , with  $n = 20$ . Because of gradients in the sensitivity of the processed emulsions with depth, and for purposes of charge estimation, as described below, all values of measured MTWs are extrapolated to their corresponding values at the bottom (i.e. emulsion/glass interface) of the pellicle.

### 3. Results

Figure 1ab shows the measured MTWs of C, Fe, La and U ions versus  $D$ , the fractional height of the track in the emulsion pellicle,  $D = z/z_0$  where  $z$  is the distance of the event from the emulsion/glass interface and  $z_0$  is the thickness of the processed emulsion. The data for Fe and U from stack 1 are shown in Fig. 1a, and for C, Fe and La from stack 2, in Fig. 1b. The data are plotted as exponential functions to illustrate that i) the emulsion-depth gradients in the MTW are significant, and ii) the (fractional) gradients tend to be independent of the charge  $Z$  of the ion, but with clear evidence that the value of the gradient is different in each stack. (The stacks were neither exposed nor processed simultaneously.) The data were fitted by least squares to exponential functions of the form  $w = w_0 \exp w_1 D$ , shown as straight lines in Fig. 1ab.

Table I presents the results of the least squares fits to the data, part A giving the coefficients  $w_0$  and  $w_1$  for the exponential fits illustrated in Fig. 1ab and the rms deviation of the data points from the fitted curves. Similarly in part B, the values of these quantities are tabulated assuming the linear relationship  $w = w_0 + w_1 D$ . Although the fits to the MTWs of individual ions do not enable one to differentiate between the assumptions of linear

or exponential gradients, the gradient coefficients  $w_1$  for the exponential fits are, within their errors, independent of the species of ion, under the reasonable assumption that the gradients in stacks 1 and 2 are, and are expected to be, different. Figure 2 presents the results shown in Fig. 1ab after the  $w$  versus  $D$  data from stack 2 are transformed to their equivalent values in stack 1. Specifically, the transformation  $W(\text{stack \#2}) \rightarrow W(\text{stack \#1})$  is given by the expression

$$w[\#1] = (w_{01}/w_{02})w[\#2]\exp(w_{12} - \langle w_{11} \rangle)D$$

where  $w_{01}/w_{02}$  is the ratio of the intercepts of  $w$  for Fe ions at  $D = 0$  in stacks 1 and 2 ( $=1.264$ ),  $w_{12}$  is the exponential slope of the l.s. fitted curve for each ion in stack 2 and  $\langle w_{11} \rangle = 0.325$  is the mean value of the exponential slopes of Fe and U ions in stack 1. Figure 3a exhibits the data (Fig. 2) as  $w$  versus  $D$ . When presented in this linear form data points appear to radiate from a "focal" point at  $(0, Z_0)$ . Although of no physical significance, the focal point  $(0, Z_0)$ , as illustrated in Fig. 3b, is exact when the (linear) slope is taken to be  $w_0(e^{w_1} - 1)$ , where  $w_0$  and  $w_1$  are the l.s. coefficients for the exponential fit to the data. The relation  $w/w_0 = 1 - (1 - e^{w_1})Z$  follows, for which  $w = 0$  when  $Z = Z_0 = (1 - e^{w_1})^{-1}$ . Given  $w_1 = \langle w_1 \rangle = 0.325$ , the "focal" point  $(0, Z)$  is  $(0, 3.60)$ , as indicated in Fig. 3b.

The quantity we adopted to correlate with the charge  $Z$  of the  $j^{\text{th}}$  stopping nuclear species is the value of the intercept of the least-squares curve at  $D = 0$ , i.e.  $w_0$ , Table IA. Alternatively, given the slope  $w_1$  for the  $j^{\text{th}}$  set of  $w$  versus  $D$  data, Table I, each measured value of  $w(D)$  can be extrapolated to its equivalent value at  $D = 0$  by the expression

$w(0) = w \exp(-w_1 D)$ , or when using the "focal" point approximation, by  $w(0) = 3.6 w(3.6 - D)^{-1}$ . The average value  $\langle w(0) \rangle = \frac{1}{n} \sum_{i=1}^n w_i(0)$  is equivalent to  $w_0$ .

The values of  $w_0$  from stack 2 were normalized to those from stack 1 via the factor  $1.264 \pm 0.072$ , the ratio of the intercepts for Fe in stack 1 relative to stack 2. The resultant normalized values of  $w_0$  versus  $Z$  are given in Table II and are plotted in Fig. 4. The curve drawn through the data points is a least-squares polynomial given by

$$\ln w_0 = (3.65 \pm 0.29) - (0.400 \pm 0.162) \ln Z + (0.213 \pm 0.022) (\ln Z)^2 \quad \text{Eq. 1}$$

From Eq. 1 we have

$$\ln Z = 0.938 [1 + (5.33 \ln w_0 - 18.44)^{1/2}] \quad \text{Eq. 2a}$$

and

$$\frac{dZ}{Z} = (0.427 \ln Z - 0.400)^{-1} dw_0/w_0 \quad \text{Eq. 2b}$$

Whereas the reproducibility of an observer for measuring the quantity  $w_0$  is typically  $dw_0/w_0 \approx 0.01$  for a given track, the rms deviation of  $w_0$  for a sample of stopping tracks of the same charge was found to be  $dw_0/w_0 = 0.05 \pm 0.04$  (Table I). For this value of  $dw_0/w_0$ , the error in measurements of  $Z$  on a track-to-track basis, evaluated from Eq. 2b, vary from  $\sigma(Z) = \pm 0.82$  for  $Z = 6$  to  $\pm 3.0$  for  $Z = 92$ . However, the observations, Table I, indicate that the dispersion of the MTW measurements tend, in fact, to decrease systematically

with increasing charge, the actual rms deviation in  $Z$  being  $\sigma(Z) = 1.7, 1.0$  and  $1.4$  units of charge for  $Z = 6, 26$  and  $92$  respectively. Such errors are intrinsically related to the shapes of the  $w_0$  versus  $Z$  curve, Fig. 4, and can be reduced only by decreasing the dispersion of the MTWs.

Possible methods for decreasing the dispersion of the measurements are to increase the sampling rate of the track-width measurements, and to reduce both vertical and lateral gradients in the sensitivity of the processed emulsion. The suggestion that increased sampling of track widths would be an effective means for reducing the observed dispersion of the MTWs stems from the fact that the fractional dispersion of the measured MTWs for carbon ions is significantly larger than that for uranium, Table I. The reason for this is that, in contrast to the well-defined profile of the highly saturated tapered tracks of stopping high- $Z$  nuclei, the profile of a light ion, e.g.  $Z = 6$  (over the  $1 \text{ mm}$  residual range used here) exhibits significant deviations in the width of the core of the track, attributable to local fluctuations in the (lower) production rate of  $\delta$ -rays along the track. Thus, by taking track-width measurements over range intervals as small as  $5 \text{ }\mu\text{m}$  and by repeating MTW measurements on individual tracks up to four times, Jönssen<sup>3</sup> was able to obtain charge resolutions for stopping cosmic ray nuclei (for residual ranges up to  $400 \text{ }\mu\text{m}$ ) of  $\sigma(Z) = 0.24$  to  $0.83$  units of charge for  $Z = 6$  to  $26$  respectively. Comparing the results of Jönssen with those in the present work indicates that repetitive measurements of track widths do improve the charge resolution for low- $Z$  ions, but give less improvement for ions of  $Z \approx 26$ , where the estimates for  $\sigma(Z)$  given by Jönssen and observed here agree to within 20%.

#### 4. Conclusions

We have investigated an operational technique of charge measurement of stopping nuclei  $6 \leq Z \leq 92$  in nuclear emulsion by the conventional method of track-width measurements. The method utilizes the last 1 mm of the ionization track of the stopping ions. The track widths  $w_i$  were measured by use of a filar micrometer at each 50  $\mu\text{m}$  interval of range  $R$ ,  $50 \leq R \leq 1000 \mu\text{m}$ . The  $\text{MTW} \equiv w = \frac{1}{n} \sum_i w_i$  constitutes a quantity we adopt as a measure of charge. The method requires calibration of the MTW versus depth in the emulsion pellicle owing to optical and processing gradients. All measurements of the MTW are therefore extrapolated to zero height in the emulsion to give a normalized value  $w_0$  for the MTW.

We find that the reproducibility of the MTW by an observer is typically  $dw/w \approx 1\%$ , whereas the intrinsic rms distribution of a sample of stopping ion tracks of the same charge varied from  $\pm 10\%$  for  $Z = 6$  ions to  $\pm 2.4\%$  for  $Z = 92$  ions. With these fractional rms values of the MTW, a charge resolution  $\sigma(Z)$  of the  $\pm 1$  to 2 units of charge can be operationally obtained in a single measurement over the entire charge interval  $6 \leq Z \leq 92$ . When coupled with the capability of emulsions for measuring charges of relativistic ions  $1 \leq Z \leq 5$  to high precision,<sup>7</sup> we have in nuclear emulsion a detector of large dynamic range for charge measurement.

Although a charge resolution of  $\sim \pm 1-2$  is satisfactory for many classes of experiments the need for improved charge resolution of stopping ions is evident. Based on our observations, reduced values of  $\sigma(Z)$  can be obtained by extending the present method of MTW measurements to involve increased, even continuous, sampling of the track width versus residual range; and, where visual observers are concerned, repetitive measurements of the MTW of track

segments can be effective in improving charge resolution. Although the use of the filar micrometer by an observer to measure track widths is a method having nearly maximal resolution in track-width measurements, the time required for an accurate charge measurement of a stopping ion may limit the total number of such measurements in a practical experiment. In such cases, current state-of-the-art optical-electrical techniques and methods of pattern recognition and analysis can be invoked to increase significantly the rate, and, conceivably, the accuracy of charge measurements derived from measurements of the MTW of stopping nuclei.

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Table I Least-Squares coefficients of measured MTW,  $w$ , versus fractional height  $D$  of track in emulsion pellicle. The rms deviations of the data from the l.s. fits are also tabulated.

A.  $w = w_0 \exp w_1 D$

Stack	Z	$w_0$	$w_1$	rms
1	26	$99.8 \pm 2.8$	$- 0.36 \pm 0.05$	3.3%
	92	$492.3 \pm 6.3$	$- 0.32 \pm 0.02$	2.4
		ave =	$- 0.32_5 \pm 0.020$	
2	6	$29.6 \pm 2.8$	$- 0.60 \pm 0.16$	10.7
	26	$79.0 \pm 3.9$	$- 0.55 \pm 0.05$	3.9
	57	$208 \pm 11$	$- 0.48 \pm 0.10$	7.0
		ave =	$- 0.54 \pm 0.04$	

B.  $w = w_0 + w_1 D$

Stack	Z	$w_0$	$w_1$	rms
1	26	$99.1 \pm 2.4$	$- 30.6 \pm 4.2$	2.8 $\mu\text{m}$
	92	$487.4 \pm 5.6$	$-132.2 \pm 9.4$	10.3
2	6	$29.2 \pm 2.2$	$- 13.6 \pm 3.8$	2.5
	26	$77.4 \pm 2.0$	$- 33.3 \pm 3.4$	2.7
	57	$204.6 \pm 10.0$	$- 78.8 \pm 16.5$	12.0



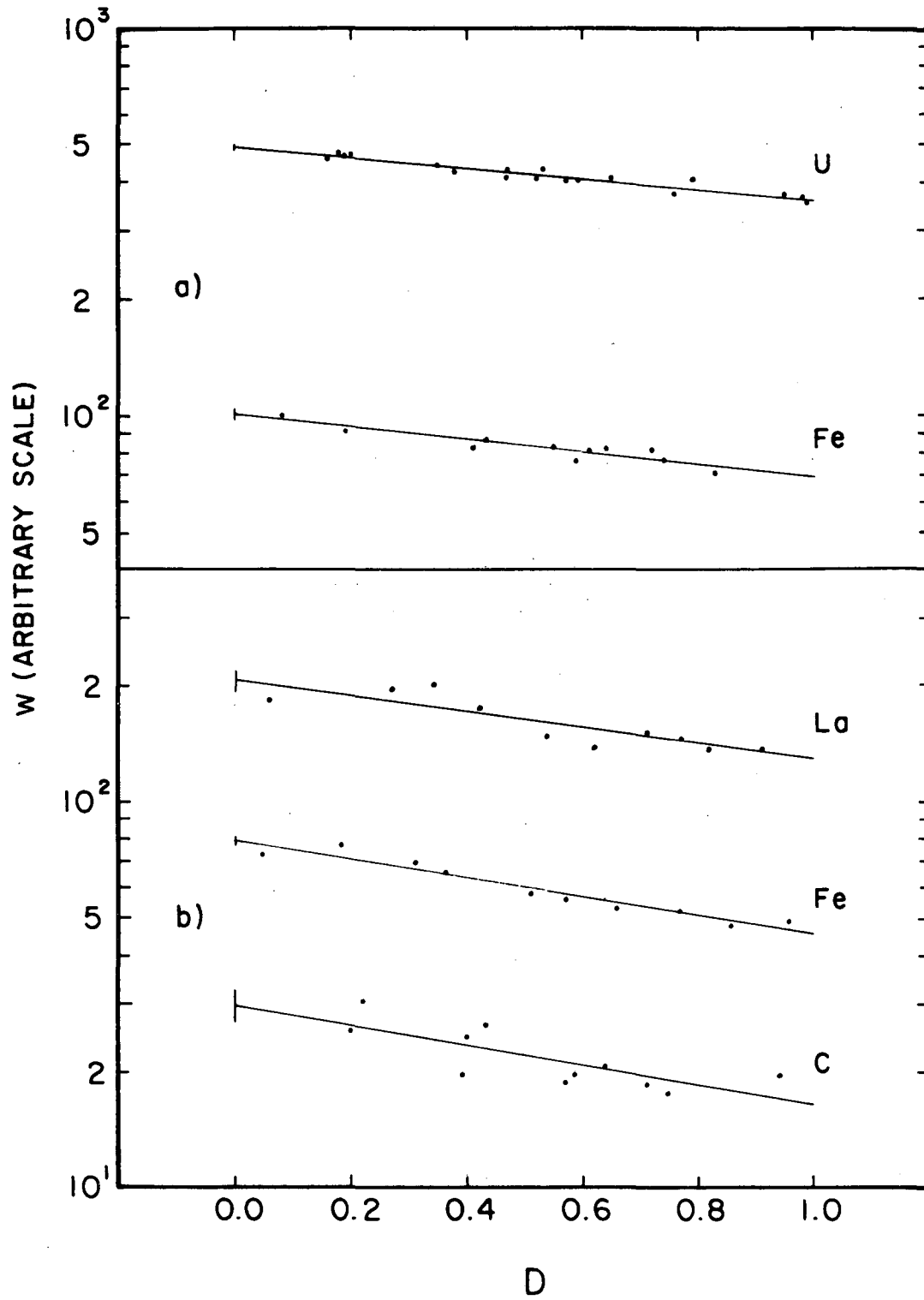
Table II Values of MTW ( $w_0$ ) versus Z, normalized via common Fe data in stacks 1 and 2.

Z	$w_0$	$w_0(\text{calc, Eq. 1})$
6	$37.5 \pm 4.1^*$	37.2
26	$99.8 \pm 2.8$	100.3
57	$263. \pm 21. ^*$	248.3
92	$492.3 \pm 6.3$	491.0

\*Error includes error of normalization (5.7%)

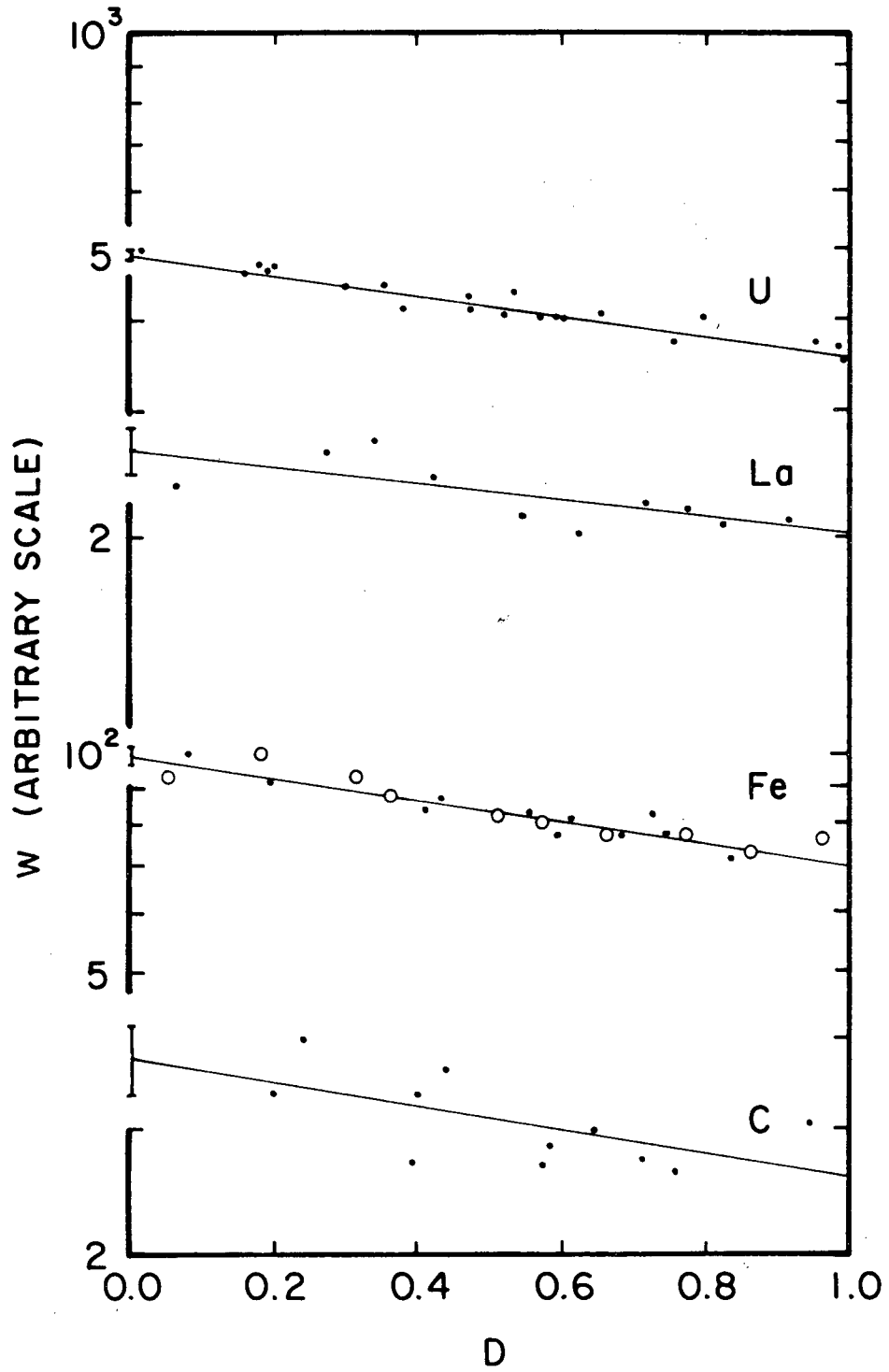
## Figure Captions

- Fig. 1) Mean width of stopping tracks of 1 mm residual range  $w$  versus fractional height of track in emulsion pellicle  $D$ . a) U and Fe in stack #1, b) La, Fe and C in stack #2. Straight lines are least-squares fit to data,  $w = w_0 \exp w_1 D$ . Errors in the intercept  $w_0$  are indicated at  $D = 0$ .
- Fig. 2) Data shown in Fig. 1ab after measurements in stack #2 are transformed to equivalent values in stack #1. Normalization errors are included in the indicated error bars for the intercept  $w_0$  at  $D = 0$ . The Fe data from stack #1 are indicated by closed circles, from stack #2 by open circles.
- Fig. 3) a) Linear plot of mean track widths  $w$  versus  $D$ . Straight lines connect values of  $w(0) = w_0$  and  $w(1) = w_0 \exp w_1$ . b) Straight line fits defined in a) converge at  $Z = Z_0 = (1 - e^{w_1})^{-1}$ ; with  $Z_0(w_1 = -0.325) = 3.60$ .
- Fig. 4) Mean track width  $w_0$  versus nuclear charge  $Z$ . Curve is a least-squares polynomial fit to data.



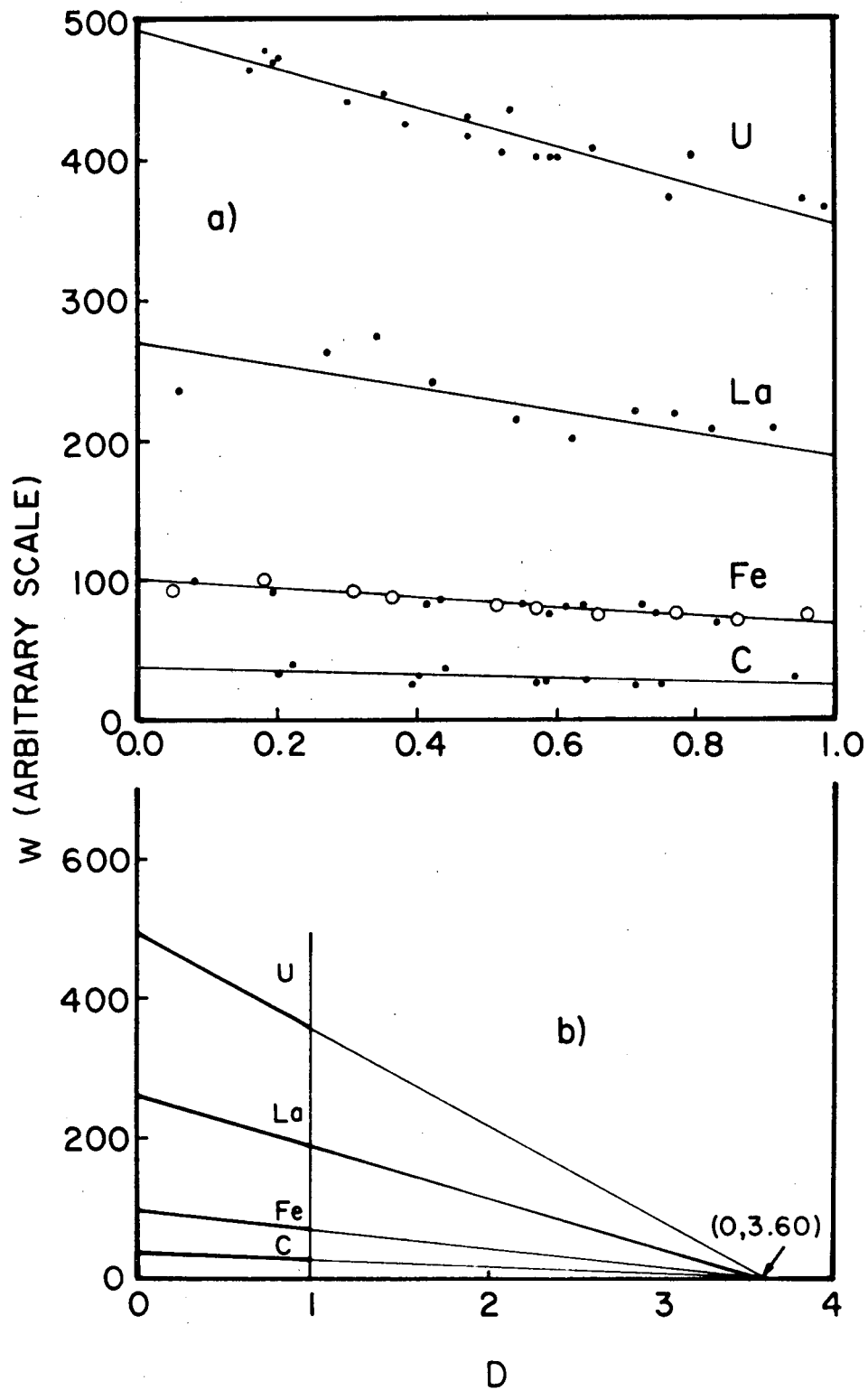
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Fig.1



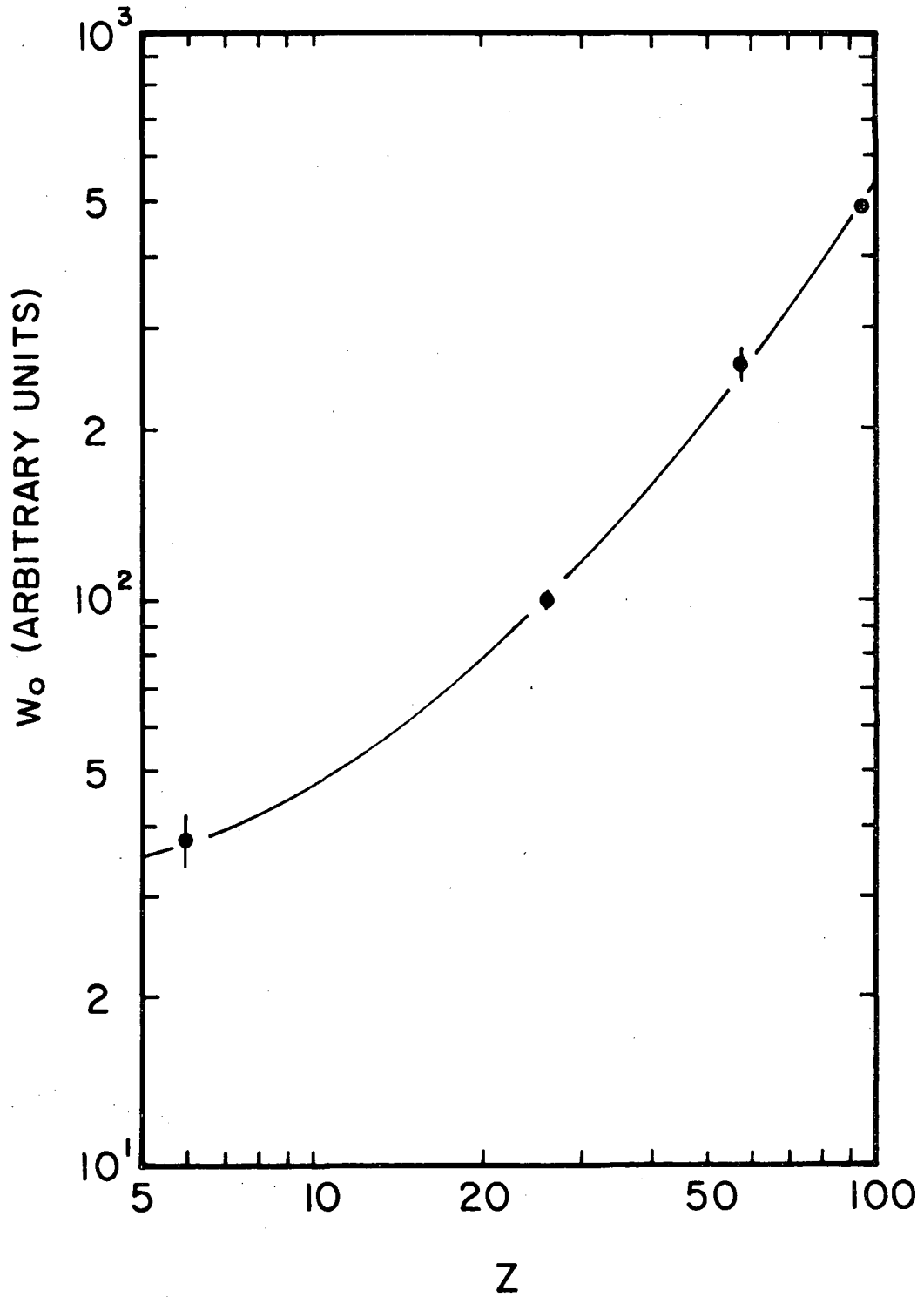
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Fig.2



XBL 8512-5013

Fig. 3



XBL 8512-5011

Fig.4

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