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CR-39 (DOP): ITS RESPONSE AND CHARGE RESOLUTION FOR THE DETECTION OF HEAVY IONS

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The response and charge resolution for the detection of near relativistic heavy ions have been investigated using the fragmented beam of 1.88 A GeV ^{56}Fe nuclei from LBL Bevalac. The average experimental charge resolution has been found to be 0.37e for $22 < Z < 28$ in place of average intrinsic charge resolution which is $\approx 0.19e$ for single etch pit diameter measurement. Our observations are in accord with those obtained by other workers.

1. *Introduction*

Introduced by Price and his collaborators[1] the plastic allyl diglycol carbonate commonly known as CR-39 has been found to have unique detection characteristics[2]. It is a detector with the widest possible dynamic range responding and detecting charged particles with all possible Z values in almost all possible energy ranges covering from very low energy U ions to near relativistic protons ($Z/\beta \approx 5$).

Furthermore Tarle et al.[3)] had demonstrated that CR-39(DOP) has a charge resolution for the detection of charged particles which is superior to scintillation detectors, Cerenkov detectors, nuclear emulsion, ionization chambers and even semiconductor detectors having equivalent detector thickness. This important attribute of CR-39(DOP) has become possible due to the fact that in (dielectric) track detector experimental observations with electron microscopy show that the damaged region around the path of the charged particle traversing through the detector medium is confined to a region of diameter of about 10 nm only. It is therefore aparent that only the low energy portion with an upper cut off energy of w_0 of the spectrum of electrons and not the entire spectrum of electrons released in the interaction of the charged particle during its passage through the detector medium is responsible for the production of the damage trail. For CR-39 the values of w_0 has been experimentally found to be 200 eV[4)]. The variance of the total energy loss is therefore smaller in track detectors compared to other types of detectors for the same amount of total energy loss. This means that particle track detectors like CH-39(DOP) will have better intrinsic charge resolution compared to other detectors of equivalent detector thickness especially in the near relativistic region.

The desirable features of wide dynamic range of detection improved charge resolution, low cost, large detection area, retention of latent damage trail images for an almost indefinite time period and the possibility of achieving any geometry of detection make the passive plastic track detectors especially CR-39 — ideal detector for cosmic ray studies. CR-39(DOP) has been extensively studied for its properties and characteristics in order to standardise it and perfect it for long duration cosmic ray flights especially as medium to heavy cosmic ray collector and detector. Accurate measurement of the composition and elemental abundances of heavy to ultra heavy cosmic rays may become a key factor in the understanding of the explosive nucleosynthesis, the origin, acceleration mechanism and propagation of cosmic rays, the nature of the interstellar medium and the chemical evolution of the Galaxy.

In our attempt to study the response as well as the charge resolution of CR-39 (DOP) (Pershore, U. K.; 32 hour curing cycle) for near relativistic charged particles near about the charge number $Z = 25$ we used the 1.88 A GeV ^{56}Fe beam of LBL Bevalac. The 1.88 A GeV ^{56}Fe beam was allowed to be incident on a wedge shaped Al target having a base width of 1 cm. The wedge shape allowed us to study the effect of the target thickness at the same time in one exposure. The maximum target thickness of about 2.7 gcm^{-2} at the base (bottom) end which is about 1/2 of the thickness of the equivalent interstellar matter ensured small but finite amout of fragmented nuclei with ΔZ up to -5 as well as a very small but also finite amount of trans-iron nuclei through pick up or charge exchange processes. These species of nuclei are emitted in the forward direction with $\Theta_{lab} \approx \approx 0°$ with practically no change in velocity (Heckman et al.[5)]). A stack of CR-39 (DOP) sheets of nominal thickness 300 μm and lexan polycarbonate sheets of thickness 130 μm were placed at a zenith angle of 30° to the beam to detect the different species of ions emergent from the target with unchanged velocity equal to the original velocity of the incident ^{56}Fe ions. The detector stack was placed at an inclined position so as to sort out the relevant ions with proper selection criteria. The incident particle flux was 960 cm^{-2}. Fig. 1 indicates the experimental arrangement. From the first stack of CR-39(DOP) sheets (the stack B) a plate was taken and etched at 70 °C in 6.25 N NaOH solution for 24 hours. The plate

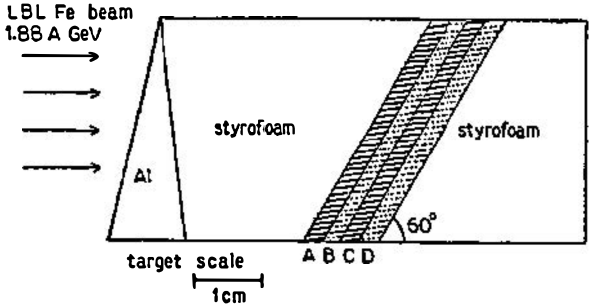

Fig. 1. Schematic diagram of the experimental set up.

was then ultrasonically washed in warm distilled water for 2 hours. It was wiped with tissue paper and was allowed to dry under atmospheric conditions. The thickness of the sheet was measured at various places by a dial gauge before and after the etching and thus the average amount of material lost due to etching was estimated and was found to be 65 μm. Therefore the average bulk etching rate was seen to be $V_g = 1.36\ \mu\mathrm{mh}^{-1}$. The etched detector foil was then scanned by a Leitz Ortholux microscope with a dry air objective X40 and a filar micrometer eye piece having a magnification X15. The least count of the micrometer eyepiece scale was 0.192 μm. While scanning for the measurement of the minor axis those elliptic etch pits were selected who had a corresponding etch pit at the other surface of the detector and where the dip angle was around 60°. Minor variation to the tune of ±3° was allowed in the fip angle as it was thought that individual particles in the incident beam may have a divergence of ±3° with respect to the beam direction. Divergences in the dip angle greater than this was rejected as it was felt that in such cases there will be a change in the velocity due to kinematical considerations.

2. *Results and discussion*

The minor axes of 4331 such etch pits (elliptic) were measured by Leitz Ortholux microscope having a filar micrometer eyepiece as stated above. The minor axes distribution is presented in Fig. 2 in the form of a histogram having a class interval of 0.2 μm. From the nature of the distribution it is apparent that the data cannot be fitted by a single gaussian distribution. It is in fact a superposition of several gaussian distributions of suitable intensities or amplitudes with the mean values of each distribution located at different diameter values. The full width at half maximum is related to the standard deviation of the distribution through the relation $\sigma = FWHM/2.35$. Therefore the measurement of *FWHM* allows us to determine σ. Furthermore it is also known that for a Gaussian distribution about 95% of events lie within a region of $\pm 2\sigma$ about the mean value. Therefore with a maximum error of 5% it can be assumed that a particular species of ion is confined to a region of $\pm 2\sigma$ about the mean value of its distribution. This criteria enables us to sort out the locations and intensities of each species of ions through the minor axis measurement of the single etch pit only. Experimental results from

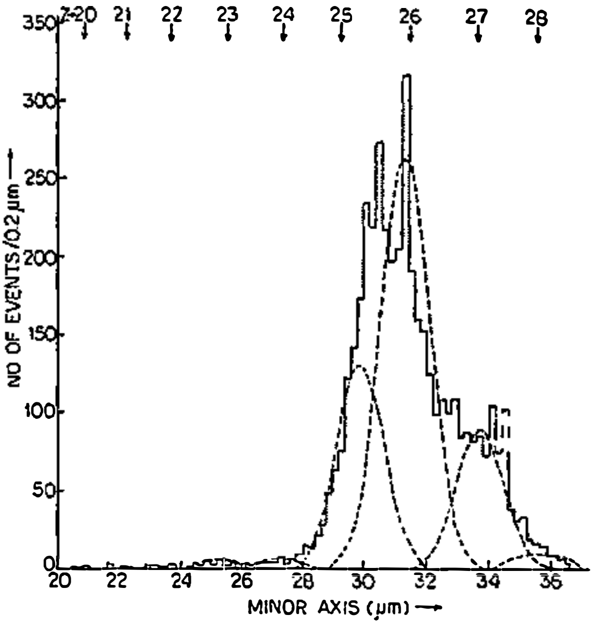

Fig. 2. Histogram of minor axes of elliptic etch pits in CR-39(DOP) obtained from the interaction of 1.88 A GeV ^{56}Fe nuclei with ^{27}Al target as detected in a single plate of CR-39(DOP), (B4).

TABLE 1.

Z	D μm	σ_D (i)	σ_D (ii)	σ_D (iii)	$\Delta D/\Delta Z$ μm/e	σ_Z	$\bar{\sigma}_Z$ (assuming no Z dependence)
20	20.7	—	—	—	—	—	0.37e
21	22.0	—	—	—	1.3	—	
22	23.3	—	—	—	1.3	—	
23	25.2	0.79	0.60	0.70	1.8	0.39e	
24	27.3	0.79	0.70	0.75	2.0	0.37e	
25	29.9	0.75	0.75	0.75	2.5	0.30e	
26	31.3	0.79	0.75	0.77	1.7	0.45e	
27	33.8	0.78	0.76	0.77	2.2	0.35e	
28	35.7	0.77	0.76	0.76	2.1	0.36e	

The charge number Z; mean minor axis D μm; the standard deviation of the diameter distribution of each species σ_D from (i) FWHM measured, (ii) from the spread of the distribution and (iii) the average of the above two values (i) and (ii) $\bar{\sigma}_D$; the dispersion in mean diameter values with unit change in charge number $\Delta D/\Delta Z$ and $(\sigma_Z)_{exp.} = \bar{\sigma}_D/(\Delta D/\Delta Z)$ the experimental charge resolution along with $\bar{\sigma}_Z$ the average charge resolution assuming no Z dependence are given in the table.

the measurement of 4331 etch pits are presented in tabular form in Table 1. Fig. 3 is a plot of the Z and D as obtained from Fig. 2 and presented in column 1 and 2 of Table 1. When fitted in the form of a power relation one obtains

$$D = \alpha Z^{\beta} \ \mu\text{m} \tag{1}$$

where $\alpha = 0.17$ and $\beta = 1.59$.

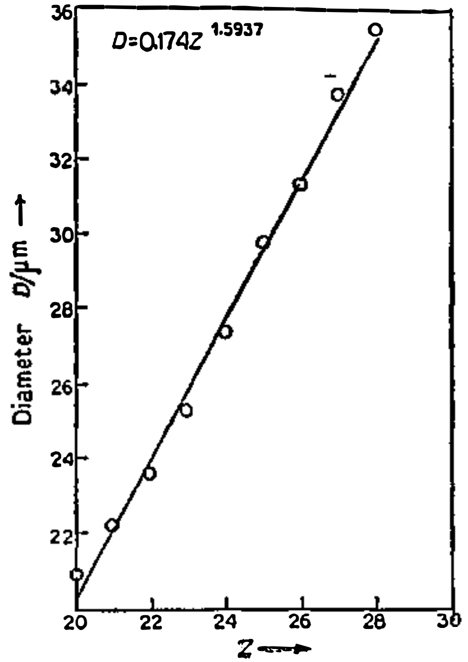

Fig. 3. The minor axis diameter plotted as a function of charge number Z. o represents our predicted Z from Fig. 2. Full line is the fit to our result from relation (1).

Furthermore the formation of the etch pit or the track profile in a track detector is due to the combined action of the general or bulk etch rate and the track etch rate. During etching for a time t the surface of the track detector is eroded at a bulk etch rate V_g while the latent track which is only ≈ 10 nm wide is eroded at a faster rate V_t. In our case both V_g and V_t are constants. If Θ be the half angle of the cone produced in etching then in this bow wave model $\Theta = \sin^{-1}(V_g/V_t)$. For a charged particle incident with a dip angle δ the minor axis of the elliptical etch pit at the etched surface of the detector is given by the relation

$$D = 2V_g t \sqrt{\left(\frac{s \sin \delta - 1}{s \sin \delta + 1}\right)} \tag{2}$$

where $s = V_t/V_g$ is reduced etch rate.

The etch pit profile at the surface is completely determined by the track etch rate within the depth x of the detector ($x < (h = V_g t)$). x is known as the effective detector thickness and is given by the relation

$$x = \left(\frac{s}{(s+1)\sin \delta}\right) h \tag{3}$$

where the reduced etch rate is

$$s = \frac{V_t}{V_g} = \frac{1 + (D/2h)^2}{[1 - (D/2h)^2] \sin \delta} \tag{4}$$

and $h = V_g t$ is the thickness of the material removed from one surface of the detector material during etching for a time t

$$h = 32.5\ \mu\mathrm{m}$$

and δ dip angle = 60° (in our case).

It should be remembered that the track etch rate within the depth x of the track detector (effective detector thickness) coupled with the general or bulk etch rate completely determines the etch pit profile at the surface and changes in the etch rate or otherwise below this effective detector thickness will only modify the etch pit profile below the surface keeping the profile at the surface unaffected. Therefore for measurements based on surface diameters the effective detector thickness is given by Eq. (3) by Fleischer et al.[6]. The ratio of the energy loss ΔE within the effective thickness of the detector x and the variance of the energy loss σ_E given by Ahlen[7] follows the form

$$\frac{\sigma_E}{\Delta E} = \frac{0.0015}{Z\,(x \text{ in cm})^{1/2}} \frac{[w_0\,(\mathrm{eV}) + 2640 + 656 \ln \beta]^{1/2}}{4.06 + \ln (\beta\gamma)} \tag{5}$$

where

x = effective detector thickness (given by Eq (3)),

Z = charge number of the incident charged particle,

w_0 = the upper cutoff energy of the spectrum of electrons released during the interaction of the charged particle during its passage through the detector medium responsible for the production of the damage trail as per the Restricted Energy Loss model after Benton and Henke[8] = 200 eV for CR-39 (DOP),

β = v/c, where v is the velocity of the particle and

$$\gamma = \frac{1}{(1 - \beta^2)^{1/2}}.$$

Ignoring other factors such as measurement error, inhomogeneities in composition etc, $\sigma_E/\Delta E = 2\sigma_Z/Z$ to a first order of approximation where σ_Z is the charge resolution, since ΔE is proportional to Z^2, following Salamon et al.[9] one can obtain

$$\sigma_Z = \frac{Z}{2} (\sigma_E/\Delta E). \tag{6}$$

In Table 2 the Z values, Z/β, the reduced etch rate is estimated through Eq. (4), the effective detector thickness x estimated through Eq. (3), $\sigma_E/\Delta E$ estimated through Eq. (5), σ_Z estimated through Eq. (6) and $\sigma_{Z\,expt.}$ taken from column 5 of Table 1 are presented in a tabular form. The reduced etch rate are usually parametrised by quantities such as restricted energy loss (REL_{200}) or Z/β over a limited dynamic range. When the values of Z/β and A from column 2 and 3 of Table 2 are fitted in a power law one obtains a relation of the type,

TABLE 2.

Z	$s = V_T/V_g$	x (cm)	$\sigma_E/\Delta E$	σ_Z derived from REL	σ_Z observed
20	1.3768	0.0022	0.0200	0.200e	—
21	1.4577	0.0022	0.0191	0.201e	—
22	1.5392	0.0023	0.0178	0.196e	—
23	1.6214	0.0023	0.0170	0.196e	0.39e
24	1.7041	0.0024	0.0160	0.192e	0.37e
25	1.7875	0.0024	0.0153	0.192e	0.30e
26	1.8715	0.0025	0.0144	0.187e	0.45e
27	1.9559	0.0025	0.0139	0.188e	0.35e
28	2.0410	0.0025	0.0134	0.188e	0.36e

The Z values, Z/β where $\beta = 0.943$ for 1.88 A GeV ^{56}Fe ions and its fragments emitted at forward angles ≈0°, the reduced etch rate s estimated through Eq. (4), the effective detector thickness x estimated through Eq. (3), $\sigma_E/\Delta E$ estimated through Eq. (5), σ_Z estimated through Eq. (6) and $(\sigma_Z)_{exp.}$ taken from column 5 of Table 1 are presented in the table.

$$s = V_T/V_g = A\,(Z/\beta) \tag{7}$$

where $A = 0.038$ and $n = 1.17$.

Fig. 4 shows the response of CR-39(DOP) as obtained in the present work. In reduced etch rate data of Tarle et al.$^{3)}$ and that of Atwater et al.$^{10)}$ are also displayed in the same figure. Our present results are in accord with the data of Atwater et al. who used 1.75 A GeV Mn beam for the estimation of response of CR-39. Our data have a similar but somewhat different values when compared to the data of Tarle et al.$^{3)}$. This may arise due to the different and possibly better etching conditions (etching for longer hours at 40° instead of at 70 °C) used by them. We also notice in Fig. 5 that $(\sigma_Z)_{expt.}$ as obtained by us from the minor axes measurements of single etch pits compare very well with those obtained by Salamon et al.$^{9)}$. We also notice further that $(\sigma_Z)_{expt.}$ (average value is about 0.37e) is somewhat greater than $(\sigma_Z)_{theory}$ (average value ≈ 0.19e). This is probably an indication that some errors due to uncertainties in the measurement have crept in. This sort of measurement errors are always present and are unavoidable. As suggested by Salamon et al.$^{9)}$ this can be reduced or minimised by simultaneous measurement over a number of etch pits say n by which the errors are reduced by a factor of $n^{1/2}$. In our observation we find an indication that $(\sigma_Z)_{expt.}$ is practically independent of Z instead of a weak Z/β dependence i. e. a weak Z dependence since β is constant in our case.

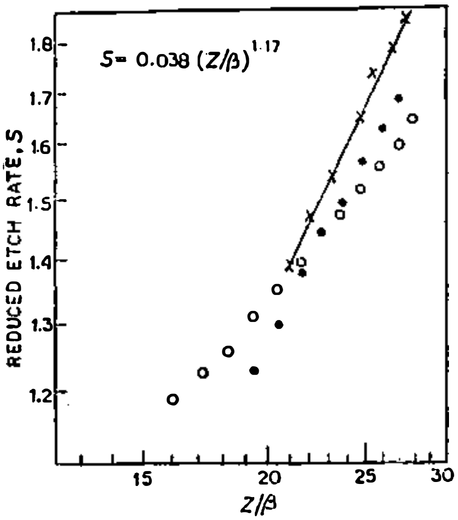

Fig. 4. Response of CR-39(DOP) to the fragmented 1.88 A GeV ^{56}Fe LBL beam. Data: o — Tarle et al.[3], ● — Atwater et al.[10], X — present work. Full line is the fit to our result from relation (1).

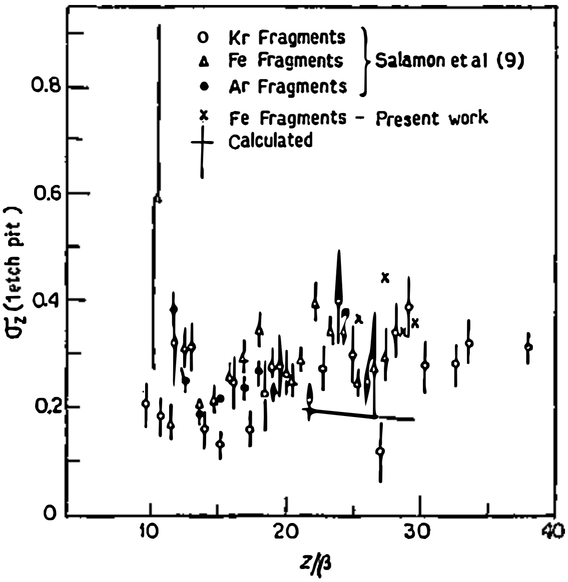

Fig. 5. The estimated charge resolution σ_Z for a single etch pit as a function of Z/β in CR-39(DOP), obtained from the charge peak widths of the fragment distribution of Fe (Fig. 2) ions that have interacted with the solid state track detector. Full line represents the derived result obtained from restricted energy loss model (Ahlen[7]). Experimental data: X — Fe fragments, present work, O Kr, Δ Fe and ● Ar fragments from Salamon et al.[9].

Moreover Drach[11)] has developed the heavy nuclei collector (HNC), an instrument to study elemental abundances of ultraheavy ($Z \geqslant 30$) cosmic ray nuclei and found that the charge resolution of CR-39 in the mid-Z stack (which is designed to detect charges in the range $30 < Z < 70$) depends on the energy of the charged nuclei becoming worse as the energy increases. The charge resolution is $\approx 0.25e$ at energies 1.0 A GeV rising to about $0.6e$ at about 4 A GeV and coming down again to about $0.25e$ at about 8 A GeV. The peak in the σ_Z vs energy curve occurs in the region 2 to 4 GeV. At about this energy range (our energy is 1.88 A GeV) the response curve becomes flatter and the charge resolution starts to become worse. Our average experimental charge resolution of about $0.37e$ is in accord with their measurements[9)].

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CR-39 (DOP): NJEGOV RESPONS I NABOJNA REZOLUCIJA PRI DETEKCIJI TEŠKIH IONA

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Istraživan je respons i nabojna rezolucija pri detekciji gotovo relativističkih teških iona koristeći fragmentiran snop od 1,88 A GeV jezgre ^{56}Fe iz LBL Bevalaca. Nađena je prosječna eksperimentalna nabojna rezolucija od 0,37e za $22 < Z < 28$ umjesto prosječne stvarne nabojne rezolucije od 0,19e po mjerenju dijametra jednog ureza. Naša opažanja se slažu s rezultatima drugih radova.