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Measurement of heavy ion range in a complex medium using a solid state nuclear track detector

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Abstract. A simple method has been described for measuring the range and energy loss of a heavy ion (^{238}U) in a complex medium (Hostaphan§, ~168 μm) with the help of CR-39 solid-state nuclear track detectors. In this work, we present the results obtained from our measurements of range, energy loss of 16.34 MeV/u ^{238}U ions in Hostaphan, and other related track parameters such as the bulk etch rate, the track etch rate, the sensitivity of the track detector V_T/V_G, the critical angle $\sin^{-1}(V_G/V_T)$ etc. The experimental range is compared with the corresponding theoretical value. The critical energy loss rate $(dE/dX)_c$ has been found to be 5 MeV mg^{-1} cm^{-2} for this detector material.

1. Introduction

The detection and measurement of ranges of heavy ions using solid-state nuclear track detectors (SSNTDs) have been found to be very useful because of their simplicity and high efficiency (Fleischer *et al* 1975, Benton and Henke 1968, Dwivedi and Mukherji 1979, Bimbot *et al* and Jain *et al* 1988). The development of the newer detector materials and also the availability of energetic heavy ion beams have aroused a greater awareness in recent years amongst scientists (Book of Abstracts, 14th International Conference on Solid State Nuclear Track Detectors, Lahore, Pakistan, April 1988).

In the last few years, thin sheets of polycarbonates have been used for detecting heavy ions of energy above 10 MeV/u (Saxena *et al* 1987). The motivation of the present work on Hostaphan plastic detector is the relevance to its use in the production of microfilters and single pore membranes. The present work deals with measurement of the range of ^{238}U ions of energy 16.34 MeV/u in Hostaphan plastics arranged in the form of a stack consisting of 14 of such thin sheets lying one over the other, using CR-39 as a track detector. In addition, other useful related etching parameters such as the bulk etch rate V_G, the track etch rate V_T, the activation energies E_a and E_b and the critical energy loss rate $(dE/dX)_c$ have also been measured. An attempt is also made to compare some of our measured data such as range, dE/dX etc with the theoretical values obtained from the computer code DEDX based on the stopping power calculation of Mukherji *et al* (1979).

§ Bayer Co., Federal Republic of Germany.

2. Experimental details

The stacks of Hostaphan (composition $C_{10}H_8O_4$ and density 1.41 g ml^{-1}) targets were made by cutting several 10 × 20 mm^2 rectangular foils from 12 μm thin sheets of Hostaphan. The stacks of varying thickness (12–168 μm) were prepared by mounting 1 to 14 foils successively on CR-39 detectors. These stacks were then fixed with a slide-glass backing for irradiation. The stacks of Hostaphan foils with a CR-39 detector were then exposed to a well collimated beam of 16.34 MeV/u ^{238}U ions in the XO channel of UNILAC, GSI, Darmstadt. All irradiation was performed at an incident angle of 45° to the detector surface, as shown in figure 1. An optimum flux of ~3 × 10^4 ions/cm^2 was used. A number of CR-39 detectors (without target foils) were also irradiated under similar conditions with

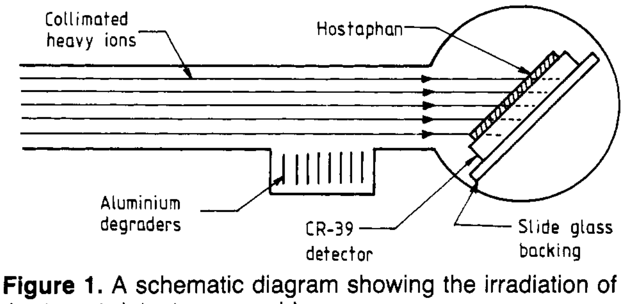

Figure 1. A schematic diagram showing the irradiation of the target detector assembly.

different ^{238}U energies to obtain a calibration curve as shown in figure 2.

After irradiation, the target foils of Hostaphan were removed from the CR-39 detectors and kept in a dust-free box in a cool, dry atmosphere. The chemical etching was carried out at the Nuclear Research Laboratory, Banaras Hindu University. The target foils were etched in 6.25N NaOH at 40, 50, 60 and 70 °C, in a temperature-controlled oven. The etching time lasted from 5 to 60 min to develop narrow conical tracks. The etching was continued till the tracks formed on the upper and lower surfaces nearly joined together, i.e. in the 11th foil, and in the 12th foil till the track tip assumed a round shape. Figure 3 shows the final profile of the tracks formed by ^{238}U ions in a Hostaphan stack. After complete etching and thorough washing the foils were dried under vacuum. The energy loss curve for ^{238}U ion in Hostaphan was plotted against target thickness using the relation $\Delta E = (E_i - E_x)$ (Saxena *et al* 1987) as shown in figure 4.

All measurements were made with an Olympus microscope (model BH-2) using a 40× objective and ×15 occulars. One of the eyepieces was fitted with a standard glass graticule.

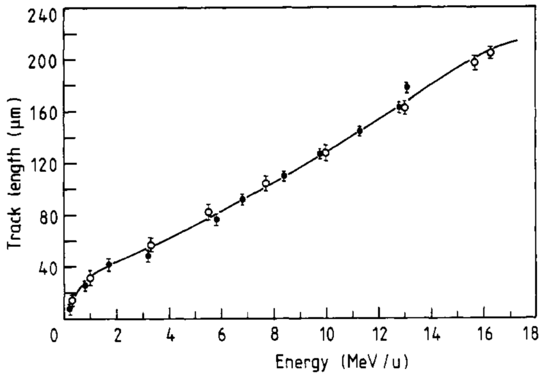

Figure 2. A plot showing the calibration curve between the energy of ^{238}U and the measured track length in CR-39. ○, Saxena *et al* (1987); ●, present work.

Table 1. The bulk-etch rates and the track-etch rates of Hostaphan plastic at different temperatures. Etchant: 6.25N NaOH.

Temperature (°C)	V_G (μm h^{-1})	V_T (μm h^{-1})
40	0.479	16.090
50	1.202	41.680
60	2.290	79.430
70	5.012	165.780

Table 2. The activation energies and the value of the constants *A* and *B* for Hostaphan plastic. Etchant: 6.25 N NaOH.

E_a (eV)	E_b (eV)	A (μm h^{-1})	B (μm h^{-1})
0.73 ± 0.02	0.71 ± 0.03	2.64×10^{11}	4.23×10^{12}

Table 3. The sensitivity and the critical angles at different temperatures. Plastic: Hostaphan; etchant: 6.25N NaOH.

Temperature (°C)	Sensitivity (V_T/V_G)	Critical angle $\sin^{-1}(V_G/V_T)$
40	33.60	1.70
50	34.67	1.65
60	34.68	1.65
70	33.07	1.73

3. Results and discussion

The details of the measurement of V_G, V_T and track length can be found in our earlier work (Jain *et al* 1988, Dwivedi *et al* 1979). Table 1 gives the bulk etch rate V_G and the track etch rate V_T at various temperatures at 16.34 MeV/u ion energy. Table 2 gives the constants *A* and *B* and the activation energies E_a and E_b, defined

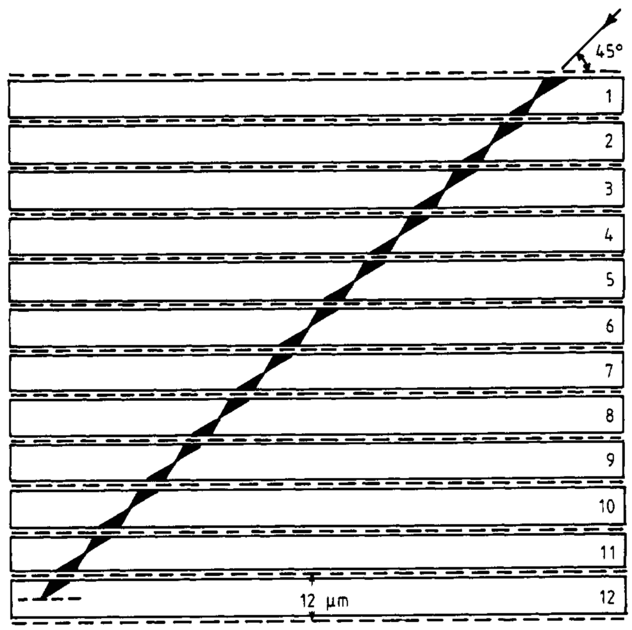

Figure 3. Track etch profile for ^{238}U in a Hostaphan stack.

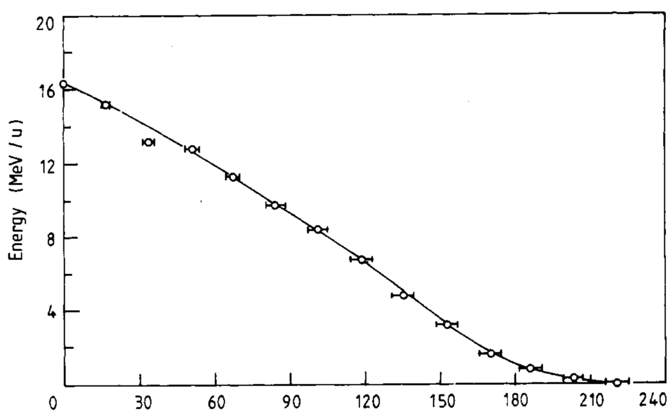

Figure 4. The energy loss curve for ^{238}U in Hostaphan. The initial energy (E_i) of the ^{238}U is 16.34 MeV/u.

Table 4. Values of Hostaphan thickness, maximum etchable track length of ^{238}U ions in the CR-39 detector, energy of the transmitted ^{238}U ion, total energy lost by the ions and the ranges obtained in Hostaphan.

Target thickness Δx (μm)	Track length L (μm)	Ion energy E_x (MeV/u)	Total energy lost ΔE (MeV/u)	^{238}U range in Hostaphan (μm)	
				Experimental	Theoretical
Without target	204 ± 2	16.34	0.0	206 ± 1.2	202.5
16.97 ± 0.03	195 ± 2	15.18 ± 0.24	1.16 ± 0.24	197 ± 1.8	194.02
33.93 ± 0.02	178 ± 2	13.17 ± 0.23	3.17 ± 0.23	175 ± 2.4	177.05
50.90 ± 1.0	161 ± 3	12.86 ± 0.25	3.48 ± 0.25	163 ± 2.8	160.08
67.87 ± 1.8	144 ± 3	11.38 ± 0.26	4.96 ± 0.26	145 ± 3.2	143.12
84.84 ± 2.2	127 ± 3	9.85 ± 0.25	6.49 ± 0.25	125 ± 3.4	126.15
101.81 ± 2.8	110 ± 3	8.46 ± 0.28	7.88 ± 0.28	108 ± 3.6	109.18
118.78 ± 3.2	93 ± 3	6.87 ± 0.24	9.47 ± 0.24	90 ± 3.8	92.21
135.74 ± 3.5	76 ± 3	4.85 ± 0.21	11.49 ± 0.21	73 ± 4.0	75.24
152.71 ± 3.8	59 ± 3	3.19 ± 0.19	13.15 ± 0.19	56 ± 4.3	58.27
169.68 ± 4.1	42 ± 3	1.77 ± 0.17	14.57 ± 0.17	48 ± 4.5	41.30
186.65 ± 4.3	25 ± 3	0.86 ± 0.15	15.48 ± 0.15	23 ± 4.8	24.34
203.62 ± 4.5	8 ± 3	0.27 ± 0.11	16.07 ± 0.11	7 ± 5.0	7.37
220.58 ± 4.8	No track	—	—	—	—

Table 5. The value of V_T at various depths of penetration (thickness) 'x' along with the corresponding values of energies and dE/dX.

E (MeV/u)	Thickness x (μm)	V_T (μm h^{-1})	dE/dX (MeV mg^{-1} cm^{-2})
16.34	16.97	15.1	134.43
15.18	33.93	14.5	138.22
13.17	50.90	17.0	146.14
12.86	67.87	16.0	148.23
11.38	84.84	15.5	138.50
9.85	101.81	16.75	150.23
8.46	118.78	17.5	155.62
6.87	135.74	19.5	179.13
4.85	152.71	20.25	180.00
3.19	169.68	17.25	159.33
1.77	186.65	13.0	121.00
0.86	203.62	9.75	82.13

in the following way:

$$V_G = A\exp(-E_a/KT) \quad (1)$$

$$V_T = B\exp(-E_b/KT). \quad (2)$$

Table 3 gives the sensitivity and critical angle of the plastic target at various etching temperatures. Figure 5 shows the variation in $\log_{10}V_G$ and $\log_{10}V_T$, respectively, with the inverse of the temperature. Table 4 lists the values of target thickness (Δx), maximum etchable track lengths (L) of ^{238}U ions emerging out of the Hostaphan targets, corresponding ion energies (E_x) obtained from calibration curve (figure 2), total energy lost (ΔE) by the ions in targets of different thicknesses and experimental ranges along with theoretical values obtained from the stopping power calculation of Mukherji *et al* (1979). An energy-loss curve is drawn between target thickness and ion energy (E_x) and is shown in figure 4. Table 5 lists the values of V_T at various depths of penetration (thickness) 'x' along the corresponding values of energies and energy loss rate calculated from the computer code DEDX (Mukherji *et al* 1979). A plot

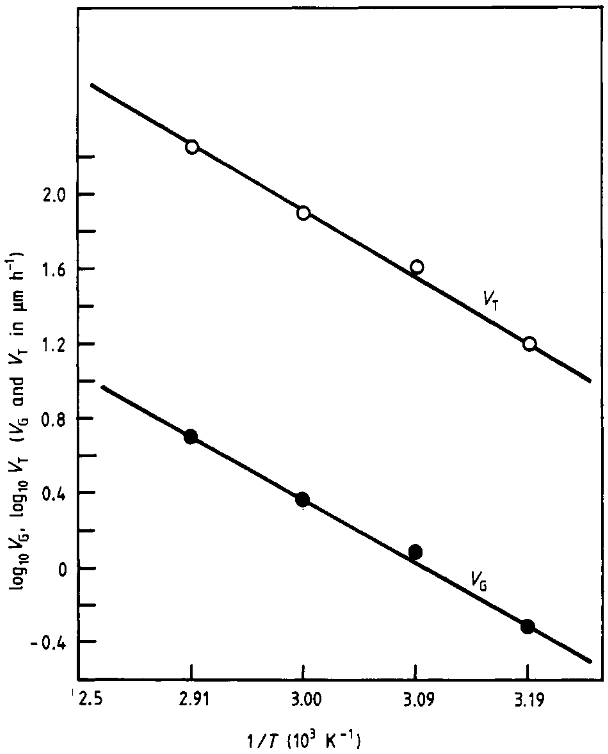

Figure 5. Variation of bulk etch rate (V_G) and track etch rate (V_T) with etching temperature for Hostaphan. E = 16.34 MeV/u; exposure: 45°; etchant: 6.25N NaOH.

of V_T and dE/dX as a function of ^{238}U energy in Hostaphan is shown in figure 6. From this figure a fairly good correlation of V_T and dE/dX has been observed. This represents a linear dependence of the energy-loss rate with the experimental values of the track etch rate. The following quantitative correlation between V_T and dE/dX has been obtained:

$$V_T = 0.1125\,\mathrm{d}E/\mathrm{d}X - 0.5000. \quad (3)$$

It has been observed from figure 6 that the critical energy loss rate $(\mathrm{d}E/\mathrm{d}X)_c$ for Hostaphan is nearly

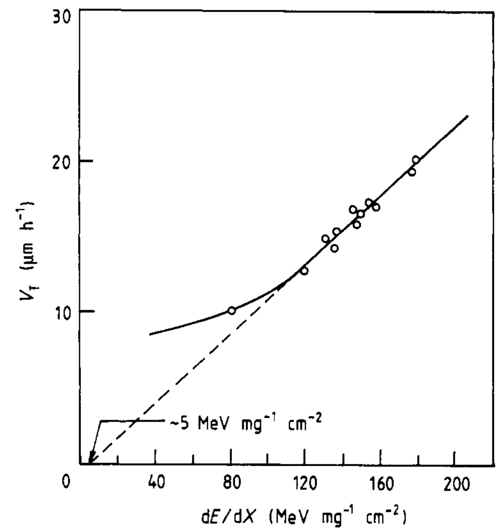

Figure 6. A plot showing the curve between V_T and dE/dX for ^{238}U in Hostaphan.

$5.0\,MeV\,mg^{-1}\,cm^{-2}$, corresponding to the point at which $V_T = V_G$. The maximum etchable track lengths of ^{238}U ions as a function of energy has been listed in table 4 and are shown in figure 7 along with corresponding theoretical values. In the present work the maximum etchable track length (i.e. range) of $16.34\,MeV\,u^{-1}$ ^{238}U ions was found to be $206 \pm 1.2\,\mu m$, which is comparable to the value of $202.5\,\mu m$ obtained from the stopping-power equations of Mukherji *et al* (1979). Taking $(dE/dX)_c = 5.0\,MeV\,mg^{-1}\,cm^2$, we obtained a range deficit nearly equal to $4\,\mu m$, which is within the error limits. Thus, in the present work we have calibrated Hostaphan plastic with CR-39 SSNTDs using a simple and fairly accurate method. From these results it is observed that ^{238}U ions with energies above $10\,MeV\,u^{-1}$ are suitable to produce microfilters and single pore membrane using Hostaphan foils.

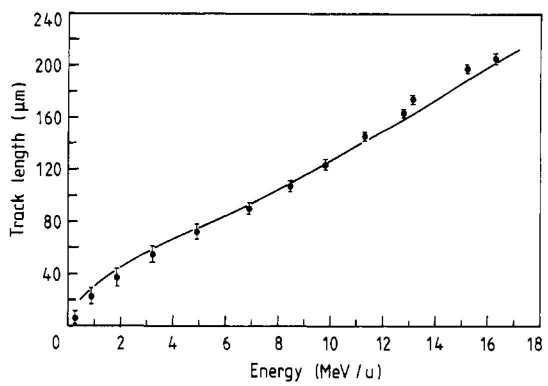

Figure 7. Measured range energy data (●) shown along with the theoretical values (full curve).

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