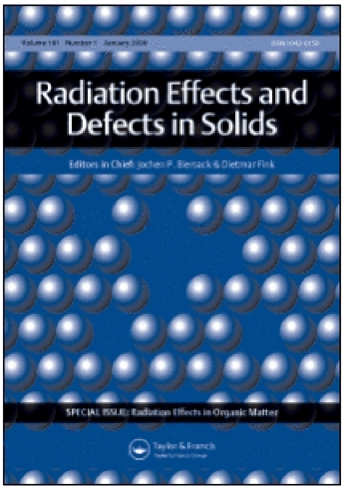

Radiation Effects and Defects in Solids
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713648881

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Online Publication Date: 01 January 1999

Radiation Effects & Defects in Solids, Vol. 147, pp. 151–164
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ENERGY-LOSS AND MEAN RANGES OF ^{129}Xe IONS IN MICA AND MAKROFOL-KG

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(Received in final form 15 December 1997)

Calibrated Polyallyldiglycol Carbonate (PADC) detectors have been used to determine energy-loss and mean ranges of 13.04 MeV/u ^{129}Xe ion in mica and Makrofol-KG using the nuclear track technique. The energy-loss rates (dE/dx) of the ion as a function of energy and depth of penetration in mica and Makrofol-KG have been derived from the respective energy-loss curves. Experimental data are compared with theoretical values obtained from four different sources. The significance and scope of the work is discussed.

Keywords: Energy loss; Ranges; Xenon; Mica; Makrofol-KG

1 INTRODUCTION

The nuclear track technique has established its reliability and diversified its applications in diverse fields from nuclear physics to biology, from the depths of the earth to distant space, from small to large and from ancient to recent in just three decades after its discovery [1,2]. The technique has found applications in many diverse fields like fusion–fission and particle evaporation [3–5], nuclear reaction studies [6,7], and the detection and identification of synthesised transuranic ($Z = 104$) element [2]. In medical sciences, it has been used in filtering cancer cells from normal blood cells [8,9].

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The measurement of mean ranges and the energy-loss rate of different heavy ions in various elemental and complex media is of great importance due to the practical applications mentioned above. The experimental measurement of range and energy-loss of energetic heavy ions in different media using the track technique requires a heavy ion source, uniform targets and a sensitive track detector. A number of experimental techniques have been employed for this study. A track detector for which some experimental range–energy calibration data are already available can be best utilised for measuring the range and energy-loss of any heavy ion in any elemental or complex medium with a simple experimental arrangement [10,11]. Polyallyldiglycol carbonate (PADC, also known as CR-39) is one of the most sensitive detectors which is widely used in charged particle detection and measurement since the last two decades [12].

The present work comprises the measurements of mean ranges and energy-loss of 13.04 MeV/u ^{129}Xe in mica and Makrofol-KG by a nuclear track technique using a calibrated PADC track detector. From these data also the energy-loss rate (dE/dx) of the ions in mica and Makrofol-KG have been determined as a function of mean ion energy and target thickness. Mica is a silicate with a layer or sheet-like structure [13]. Makrofol-KG is a polycarbonate which belongs to a class of detectors widely used to produce microfilters and single-pore membranes for their remarkable applications in environmental [14] and biomedical [15] sciences and in studying superfluidity [16].

The experimental data obtained are discussed and compared with theoretical values derived from four different computer codes, viz. (a) RANGE [17], (b) TRIM [18], (c) code HB of Henke and Benton [19], and (d) code HUBERT developed from the work of Hubert *et al.* [20] to check the accuracy and reliability of the data.

2 EXPERIMENTAL PROCEDURE

In the present experiment mica and Makrofol-KG have been used as target materials. The energy degraders are prepared using aluminium foils of known thickness to obtain different ion energies for calibration purposes. The following experimental procedure has been used in the present work.

2.1 Preparation of Targets Assembly

Thin sheets of Muscovite mica ($KAl_3Si_3H_2O_{12}$, density 2.81 g/ml, thickness 9.4 μm) and Makrofol-KG ($C_{16}H_{14}O_3$ manufactured by Bayer A.G., Leverkusen, Germany, density 1.18 g/ml, thickness 9.5 μm) were used. The targets were prepared in the form of stacks of both of these materials. The effective thickness of these targets ranges from 13.3 to 106.3 μm for mica and from 26.86 to 214.9 μm for Makrofol-KG, respectively. The target thickness was measured by the weighing method as well as by a depth measuring device (Heidenhain Ltd). The targets were mounted on the PADC detector surface as shown in Fig. 1(a).

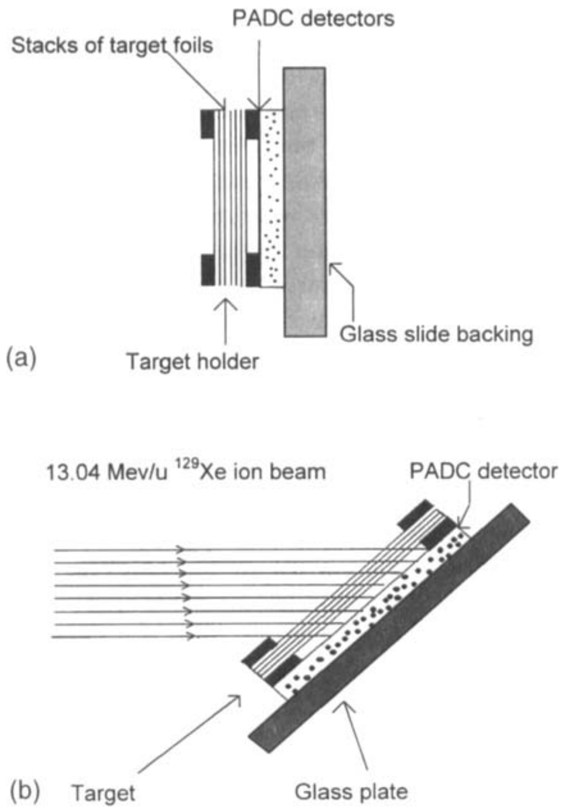

FIGURE 1 (a) Target assembly, (b) irradiation geometry.

2.2 Heavy Ion Irradiation

A well collimated beam of 13.04 MeV/u $^{129}Xe^{21+}$ ions was used for irradiation at the UNILAC accelerator of the GSI at Darmstadt. The optimum fluence of ions was $5 \times 10^4\,cm^{-2}$. The angle of irradiation was 45° with respect to the detector surface. The ion energies were measured by the Time-of-Flight (TOF) system at UNILAC and are found to be accurate within 0.1%. The irradiation geometry is shown in Fig. 1(b).

2.3 Development and Measurement of Nuclear Tracks

The latent ion trails formed after irradiation in PADC track detectors need to be developed so as to be optically visible. This was done by a chemical etching process which provides the best results in this regard. PADC was etched in 6 N NaOH solution at 55°C. The total time of etching varies from 85 to 110 min depending on the length of the tracks to be etched. The completion of the track etching is indicated by the formation of rounded tips at the end of the tracks.

The measurement of the ion tracks in the PADC detector was performed with a Leitz optical microscope at a magnification of 625×. The projected track lengths (l) were measured throughout the irradiated surface for a better representation and also to minimise the errors. The track diameters were also measured to obtain the surface etching corrections. The true track lengths were derived using the formula given by Dwivedi and Mukherji [21].

2.4 Calibration of the Detector

The calibration of the PADC detector for the measurement of the energy of the transmitted ^{129}Xe ions was carried out in terms of the maximum etchable track length. Several detectors were exposed to ^{129}Xe ions of varying energies ranging from 0.4 to 13.04 MeV/u. The maximum etchable track lengths were accurately measured after complete etching. A range–energy calibration curve was then constructed by fitting a suitable polynomial function to the experimental data. Figure 2 represents the calibration curve for ^{129}Xe in the PADC track detector.

2.5 Determination of Mean Ranges and Energy-loss Rate

The maximum etchable track lengths in PADC were measured for ^{129}Xe ions transmitted through different stacks of mica and Makrofol-KG

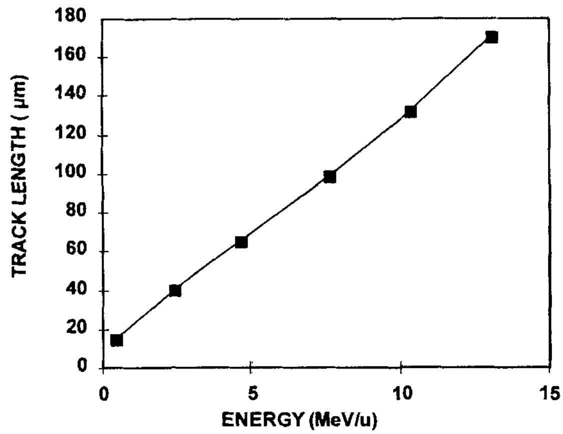

FIGURE 2 A plot showing the calibration curve for the energy of ^{129}Xe in PADC in terms of measured track lengths.

foils. From the track length data, the energies of degraded ions were obtained from the calibration curve (Fig. 2). The target thickness is plotted against the ion energy in order to obtain the energy-loss curve. An extrapolation of the fitted curve by an appropriate polynomial down to zero energy provides the mean range of the ions in the target material. The energy-loss rate (dE/dx) data of ^{129}Xe in mica and Makrofol-KG have been derived from the respective energy-loss curves (Figs. 3 and 5) as a function of mean ion energy and mean target thickness.

2.6 Experimental Errors

The uncertainties in determining the beam energies are small ($\sim 0.1\%$). The uniformity of degrader foils and targets was found to be accurate within ± 1 μm. The error in measuring the energy of degraded ions varies between 0.1 and 0.3 MeV/u. The experimental errors in the track length measurement vary within ± 2.5 μm. Hence the overall uncertainty in the mean ranges varies between 2 and 4 μm.

3 RESULTS AND DISCUSSION

The most probable track lengths of ^{129}Xe in PADC have been determined from the distribution curves obtained by plotting the maximum etchable track lengths against the number of events for different ion energies. Figure 2 shows the calibration curve of ^{129}Xe in PADC which gives a relation between the ion energy and the corresponding etched track length.

The energies (E_x) from the corresponding most probable track lengths of ^{129}Xe in PADC of particles having passed through different sheets of mica were obtained with the help of the calibration curve (Fig. 2). Table I shows the data obtained for the effective target thickness x (μm), maximum etchable track length L (μm), energy of the transmitted ion E_x (MeV/u), energy (MeV/u) lost by the ions in traversing through the target with thickness x, and the experimental and theoretical mean ranges (μm). Figure 3 shows the energy-loss curve obtained by plotting the ion energy against the effective target thickness. The mean range (R_i) of 13.04 MeV/u ^{129}Xe ions in mica which is obtained by fitting and extrapolating the energy-loss curve down to zero energy is found to be 98 ± 2 μm. The mean range of ^{129}Xe at different energies has been obtained from this value using the energy-loss curve. Figure 4 shows a plot of the experimental mean range of ^{129}Xe in mica against ion energy along with the values obtained from four different computer codes RANGE [18], TRIM [19], HB [20] and HUBERT [21]. The experimental values obtained were compared with these theoretical values and were found to be quite comparable within the error limits.

For Makrofol-KG targets with different thicknesses on PADC in different thickness, the most probable track lengths were measured for each target thickness and the corresponding ion energies were obtained again from these track lengths using the calibration curve. Table II contains the corresponding values of the same physical quantities as in Table I. The corresponding energy-loss curve is shown in Fig. 5, and the mean range (R_i) of 13.04 MeV/u ^{129}Xe ions in Makrofol-KG is determined by extrapolating this curve to be 200 ± 4 μm. The mean ranges of ^{129}Xe in Makrofol-KG at several other energies were obtained from this energy-loss curve. As in Fig. 4, the experimental mean ranges and the corresponding ion energies were plotted in Fig. 6 along with the corresponding theoretical values for Makrofol-KG targets. It is found that code HB underestimates the ranges by about 10% above the energy of 5.0 MeV/u, whereas the codes TRIM, RANGE and HUBERT predict reliable ranges for ^{129}Xe in Makrofol-KG.

The energy-loss rate data of ^{129}Xe in mica and Makrofol-KG are listed in Table III and Table IV and plotted as a function of mean ion energy E

TABLE I Values of target thickness, maximum etchable track length of ^{129}Xe in the PADC detector, energy of transmitted ions, total energy lost by the ion, and mean ranges in mica along with the theoretical values

Effective target thickness x (μm)	*Maximum etchable track length L* (μm)	*Energy of the ion E_x* (MeV/u)	*Energy loss* (MeV/u)	*Mean ranges in mica* (μm)				
				Present work	*Theoretical*			
					RANGE	*TRIM*	*HB*	*HUBERT*
No target	164.4	13.04	0.00	98	101.5	94.5	96.9	97.1
13.3	141.9	11.10	1.90	85	85.8	83.0	82.2	81.3
26.6	119.1	9.20	3.84	71	71.0	67.7	68.1	66.7
39.9	92.9	7.10	5.94	58	54.8	53.0	52.6	51.2
53.2	72.0	5.20	7.84	45	42.7	38.3	40.6	39.6
66.5	45.7	2.80	10.24	31	29.0	23.7	26.3	26.6
79.8	22.6	0.95	12.09	18	17.6	12.9	15.1	15.6
93.1	10.6	0.50	12.54	5	6.6	5.1	6.8	7.9
106.3	No tracks	—	—	—	—	—	—	—

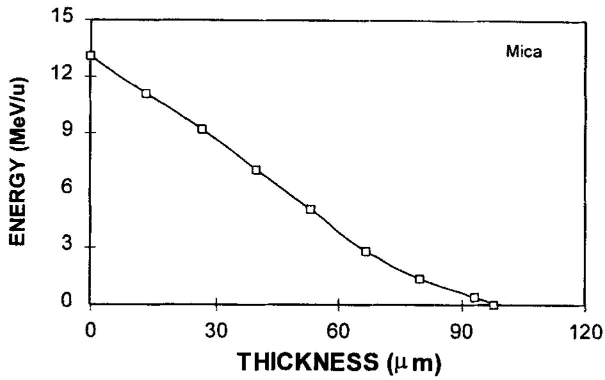

FIGURE 3 The energy-loss curve for 13.04 MeV/u ^{129}Xe ion in mica.

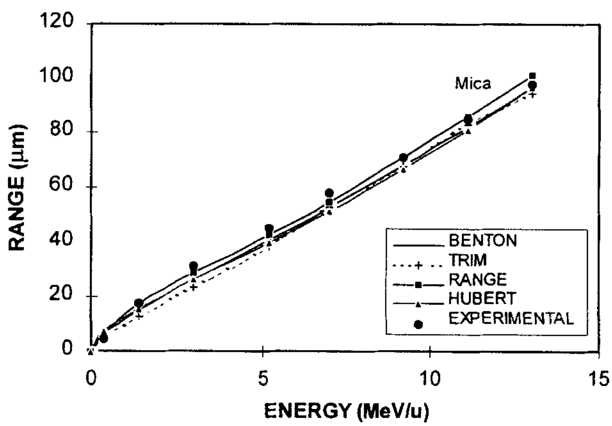

FIGURE 4 Mean ranges as a function of ion energy for ^{129}Xe in mica along with the theoretical values.

(MeV) in Figs. 7 and 8, respectively. Theoretical data on the energy-loss rate from the four different computer codes (viz. RANGE, TRIM, HB, HUBERT) are also plotted in these figures. It may be observed that the values obtained from the code TRIM are underestimated for mica whereas the values from the code HUBERT are too high upto 1000 MeV in case of mica and between 400–650 MeV and 1300–1700 MeV for Makrofol-KG. For mica the theoretical values of dE/dx from the codes

TABLE II Values of target thickness, maximum etchable track length of ^{129}Xe in the PADC detector, energy of transmitted ions, total energy lost by the ion, and mean ranges in Makrofol-KG along with the theoretical values

Effective target thicknessx (μm)	*Maximum etchable track length L* (μm)	*Energy of the ion E_x* (MeV/u)	*Energy loss* (MeV/u)	*Mean ranges in Makrofol-KG* (μm)				
				Present work	*Theoretical*			
					RANGE	*TRIM*	*HB*	*HUBERT*
No target	166.6	13.04	0.00	200	189.8	193.2	177.4	191.0
26.9	148.7	11.50	1.54	177	166.4	167.5	155.1	164.8
53.7	129.2	10.00	3.04	150	144.4	144.2	133.4	140.8
80.6	108.6	8.40	4.64	123	122.0	118.0	114.3	117.3
107.5	86.7	6.50	6.54	96	96.6	90.1	87.3	92.0
134.3	64.6	4.60	8.44	70	71.4	70.0	64.5	69.5
161.2	47.0	3.00	10.04	44	52.9	44.9	45.9	52.6
188.1	23.1	0.90	12.14	16	24.4	16.6	18.4	22.8
214.9	No tracks	—	—	—	—	—	—	—

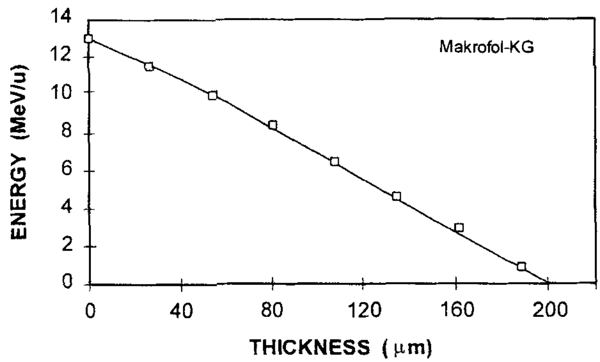

FIGURE 5 The energy-loss curve for 13.04 MeV/u ^{129}Xe ion in Makrofol-KG.

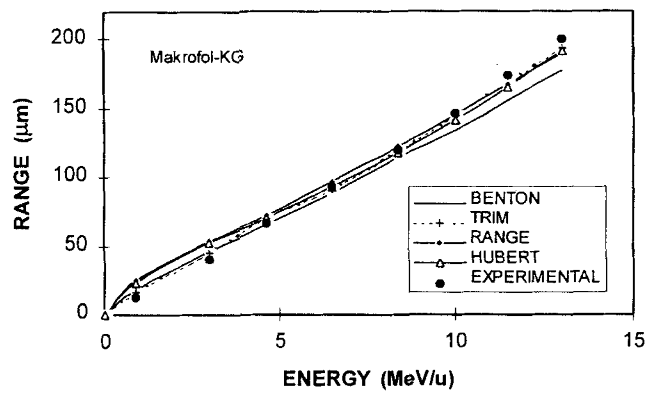

FIGURE 6 Mean ranges as a function of ion energy for ^{129}Xe in Makrofol-KG along with theoretical values.

RANGE and HB are in fairly good agreement with the experimental data whereas in case of Makrofol-KG these codes give comparable values for energies around 500–1000 MeV. Above this energy the values are overestimated by about 12%.

4 CONCLUSION

The following conclusions can be made from the present experimental results. The track technique is promising for determining the heavy ion

TABLE III Experimental and theoretical values of dE/dx for ^{129}Xe ion in mica along with mean ion energy and mean target thickness

Mean ion energy E (MeV)	*Experimental* dE/dx ($MeV\,mg^{-1}\,cm^2$)	*Theoretical* dE/dx ($MeV\,mg^{-1}\,cm^2$)				*Mean target thickness* (x) ($mg\,cm^{-2}$)
		TRIM	*RANGE*	*HB*	*HUBERT*	
129	32.8	60.6	44.5	58.1	—	24.2
258	63.3	67.7	64.2	65.3	—	20.4
387	76.5	69.7	72.9	69.7	85.9	18.6
516	78.1	69.1	74.2	70.9	83.3	16.9
645	73.5	67.4	73.2	70.5	79.7	15.0
774	70.6	64.3	70.6	69.5	76.0	13.1
903	68.0	63.1	68.0	68.1	72.6	11.2
1032	68.0	60.8	65.5	66.4	69.4	9.3
1161	68.0	59.0	62.4	64.6	66.4	7.5
1290	68.0	57.1	60.2	62.7	63.7	5.8
1419	66.8	55.7	58.0	61.8	61.3	3.7
1548	66.8	53.9	55.8	59.0	59.0	2.0
1677	—	52.5	53.8	57.4	57.0	0.6

TABLE IV Experimental and theoretical values of d*E*/d*x* for ^{129}Xe ion in Makrofol-KG along with mean ion energy and mean target thickness

Mean ion energy *E* (MeV)	*Experimental* d*E*/d*x* ($MeV\,mg^{-1}\,cm^{2}$)	*Theoretical* d*E*/d*x* ($MeV\,mg^{-1}\,cm^{2}$)				*Mean target thickness* (*x*) ($mg\,cm^{-2}$)
		TRIM	*RANGE*	*HB*	*HUBERT*	
129	68.3	78.0	62.6	79.2	—	21.8
258	76.7	84.9	87.3	88.3	—	20.0
387	82.5	86.5	97.2	93.3	108.3	18.3
516	89.2	84.9	97.4	94.1	102.6	16.7
645	93.0	82.1	93.2	92.7	95.8	15.3
774	87.5	79.4	89.1	90.3	89.7	13.8
903	81.0	75.8	85.4	87.7	84.1	12.3
1032	75.4	72.9	82.1	84.9	79.3	10.7
1161	68.3	70.3	78.6	82.0	75.1	8.9
1290	59.1	68.1	76.7	79.2	71.3	6.8
1419	57.5	66.6	73.6	75.2	67.9	4.8
1548	56.1	64.3	70.7	73.1	64.8	2.3
1677	—	61.8	68.0	71.5	62.0	0.9

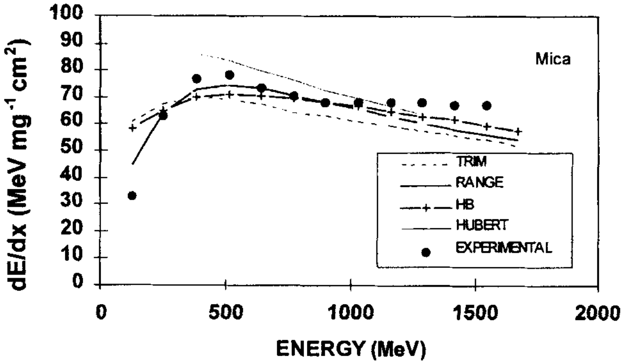

FIGURE 7 Experimental energy-loss rate of 13.04 MeV/u ^{129}Xe in mica, along with theoretical values as a function of mean ion energy E.

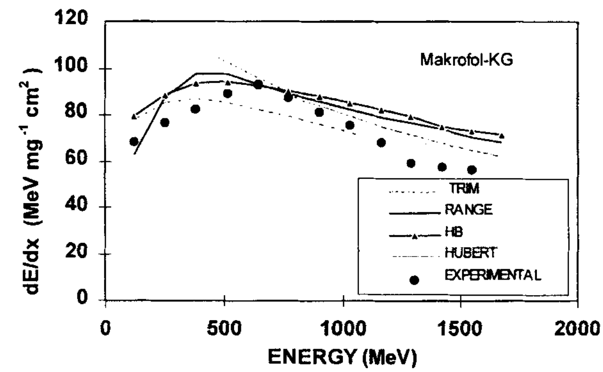

FIGURE 8 Experimental energy-loss rate of 13.04 MeV/u ^{129}Xe in Makrofol-KG, along with theoretical values as a function of mean ion energy E.

range and energy-loss in complex media. This provides useful data for designing several nuclear physics experiments where mica and Makrofol-KG find their use as absorber, in chamber windows and target backings. Further, this work has provided a possibility to verify the validity of a few commonly used computer codes of range and energy-loss determination. It may be noted that the computer codes RANGE, TRIM, HB and HUBERT reveal quite comparable range values within the experimental errors only in the case of Makrofol-KG, the code HB underestimated the ranges by about 8–10%.

Acknowledgements

We wish to thank the staff of UNILAC, G.S.I. Darmstadt, for providing the irradiation facilities. One of the authors (A.K.) is grateful to CSIR, New Delhi for providing financial support in the form of research associateship.

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