

# Measurements of range and energy loss of $^{208}\text{Pb}$ in Makrofol-G

A Kulshreshtha, S Ghosh and K K Dwivedi

Department of Chemistry, North Eastern Hill University, Shillong -793 003, India

Received 1 August 1997, in final form 24 October 1997

**Abstract.** Ranges and energy loss of  $17.1 \text{ MeV u}^{-1} \text{ }^{208}\text{Pb}$  ions in Makrofol-G polymer have been determined using a nuclear track technique. Calibrated polyallyldiglycol carbonate (PADC) detectors were used to determine the degraded energy of  $^{208}\text{Pb}$  ions after they had passed through the various stacks of Makrofol-G. The energy-loss rates as a function of the depth of penetration and ion energy have been determined. The mean ranges of  $^{208}\text{Pb}$  in Makrofol-G have also been measured at various energies up to  $17.1 \text{ MeV u}^{-1}$ . The experimental results are discussed and compared with the theoretical values obtained from four different computer codes.

## 1. Introduction

The importance of solid state nuclear track detectors (SSNTDs) in studying the interaction of heavy ions with matter is quite well established. During the last few years lots of work has been done to characterize and improve track detectors for better detection sensitivity and charge and energy resolutions. Because of the simple methodology involved in the preparation and diversity in their usefulness, SSNTDs have found many applications. The wide variety of applications of SSNTDs in various fields includes particle identification [1,2], measuring lifetimes of heavy unstable nuclear particles [3], development of microfilters [4,5], single-pore membranes [6] and uses in multifragmentation reactions [7,8], biomedical sciences [9,10] and environmental science [11,12].

Owing to the wide applications of SSNTDs and also due to the availability of energetic heavy-ion beams, more experimental data on the interaction of the heavy ions with new detector materials are needed in order to extend our search for newer SSNTDs. Since the maximum etchable track length and the rate of loss of energy to the material provide vital information about the detector material, it is desirable to have reliable and accurate data on heavy-ion ranges and energy loss in various complex materials for the characterization of any track detector.

The polycarbonates have found their use in producing microfilters and single-pore membranes which further have their applications in the fields of biomedical sciences [9], environmental sciences [13], health physics [14] and superfluidity [15]. The production of microfilters and single-pore membranes requires irradiation of polymer foils with highly ionizing ions. Since experimental range and energy-loss data for Makrofol-G are scanty in the literature, the measurement of the energy loss and range of  $^{208}\text{Pb}$  ions in Makrofol-G will provide useful information regarding the

track formation response and application of this polymer in numerous fields.

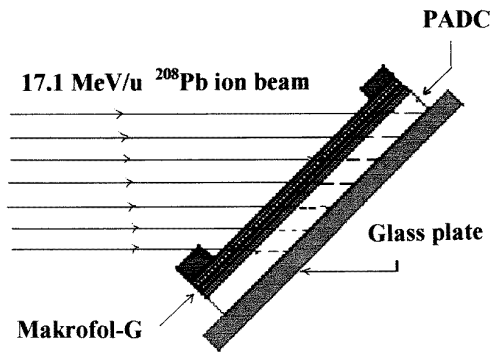
In view of these facts, the range and energy loss of  $17.1 \text{ MeV u}^{-1} \text{ }^{208}\text{Pb}$  ions in Makrofol-G have been determined by the nuclear track technique [16]. The nuclear track technique is quite versatile and accurate. It does not require costly equipment, such as time of flight (TOF) [17], double time of flight (DTOF) [18], magnetic or recoil proton spectrometers [19]. For measurement of range and energy loss a sensitive track detector is calibrated for a desired heavy ion in terms of the maximum etchable track length as a function of ion energy.

The target materials with precisely known thickness are placed before the same type of detectors and exposed to the same heavy ion of a given energy. The calibration curve and the measured track length in detectors give the energy of transmitted ions. An energy-loss curve may be plotted for transmitted energies as a function of target thickness [16]. In the present study, polyallyldiglycol carbonate (PADC) track detectors have been calibrated for energy measurement of  $^{208}\text{Pb}$  ions in terms of the maximum etchable track length. The range and energy loss of  $^{208}\text{Pb}$  ion in Makrofol-G foils are determined up to an energy of  $17.1 \text{ MeV u}^{-1}$ . The experimental data are compared with theoretical values computed from codes (i) RANGE [20] and (ii) TRIM [21] and the programs of (iii) Henke and Benton (HB) [22] and (iv) Hubert *et al* (HUBERT) [23] in order to assess their validity.

## 2. Experimental details

### 2.1. Target preparation

Several rectangular pieces of size  $20 \text{ mm} \times 15 \text{ mm}$  were cut from  $15 \mu\text{m}$  thin sheets of Makrofol-G (chemical composition  $\text{C}_{16}\text{H}_{14}\text{O}_3$ , density 1.2). The stacks of



**Figure 1.** A diagram showing the irradiation geometry used in the experiment.

varied thickness (15–180  $\mu\text{m}$ ) were prepared by mounting different number of foils on different pieces of PADC detectors. These stacks were then fixed on slide glass backing for irradiation.

## 2.2. Irradiation of Makrofol-G

The stacks of Makrofol-G on PADC were irradiated with a well collimated beam of 17.1  $\text{MeV u}^{-1}$   $^{208}\text{Pb}$  ions at UNILAC, GSI, Darmstadt. All irradiations were performed at an angle of incidence of  $45^\circ$  with respect to the detector's surface, using an optimum fluence of  $2 \times 10^4$  ions  $\text{cm}^{-2}$ . Figure 1 shows the irradiation geometry.

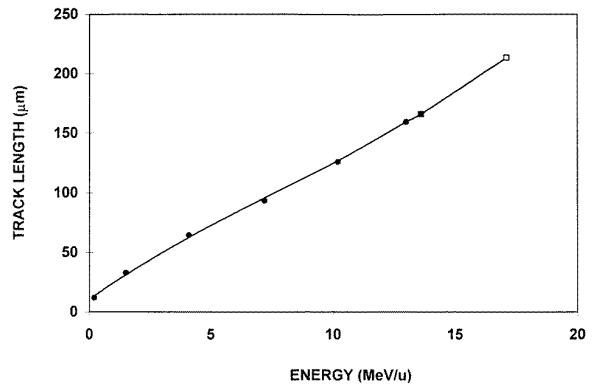
## 2.3. Etching and measurement of tracks

After irradiation, the Makrofol-G foils were removed from PADC detectors. The detectors were washed thoroughly and etched in 6 N NaOH at  $55^\circ\text{C}$  for a period of more than 2 h for all energies of the incident ions. After etching the detectors were washed in running water and dried. Etchable track lengths were then measured at a magnification of  $\times 625$  at random all over the detector surface. The true track lengths were then obtained from the measured projected track lengths using the relation given by Dwivedi and Mukherji [24].

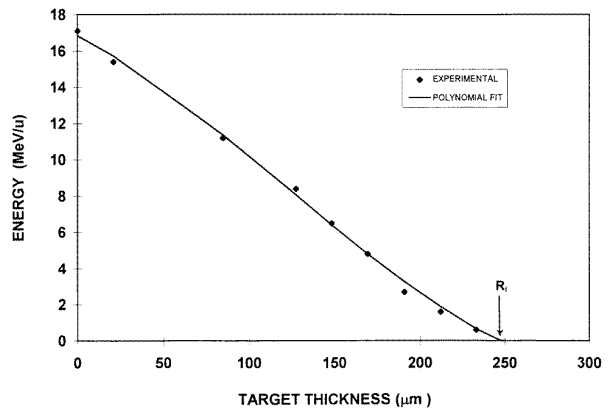
## 2.4. Energy calibration of the PADC detector

To measure the range and energy loss of  $^{208}\text{Pb}$  ions in Makrofol-G using PADC as the track detector, a range–energy calibration curve of the PADC detectors with  $^{208}\text{Pb}$  ions of various energies ( $E$ ) in terms of the maximum etchable track length ( $L$ ) has been prepared. Several detectors were exposed to  $^{208}\text{Pb}$  ions of various energies in the range 0.15–13.0  $\text{MeV u}^{-1}$  (obtained by using Al-degrader foils) under similar conditions. The tracks were fully etched and maximum etchable track lengths were measured. The experimental track lengths and the energies of  $^{208}\text{Pb}$  ions are plotted in figure 2. Two experimental points at energies 13.6  $\text{MeV u}^{-1}$  [25] and 17.1  $\text{MeV u}^{-1}$  [26] were taken from earlier works. The experimental data are fitted by a third-order polynomial of the type [16]

$$E = \sum_{\mu=0}^{\mu=3} a_{\mu} L^{\mu}$$



**Figure 2.** A plot showing the calibration curve for the relationship between the energy of  $^{208}\text{Pb}$  and the measured track length in PADC: (●), present work; (■), [25]; and (□) [26].



**Figure 3.** The energy-loss curve for 17.1  $\text{MeV u}^{-1}$   $^{208}\text{Pb}$  in Makrofol-G.

**Table 1.** Range–energy calibration of the PADC detector for 17.1  $\text{MeV u}^{-1}$   $^{208}\text{Pb}$  ions.

Energy of the ion ( $\text{MeV u}^{-1}$ )	Maximum etchable track length ( $\mu\text{m}$ )
17.1	$213.2 \pm 2.4$
13.6	166.2 <sup>a</sup>
13.0	$159.6 \pm 1.7$
10.2	$126.0 \pm 1.9$
7.2	$93.4 \pm 2.4$
4.1	$64.6 \pm 2.9$
1.5	$33.0 \pm 3.1$
0.2	$11.9 \pm 3.3$

<sup>a</sup> Error not quoted.

where  $a_{\mu}$  represents a set of coefficients giving the best polynomial fit,  $E$  is the energy of the ion and  $L$  is the maximum etchable track length.

## 2.5. Determination of mean ranges and the energy-loss rate

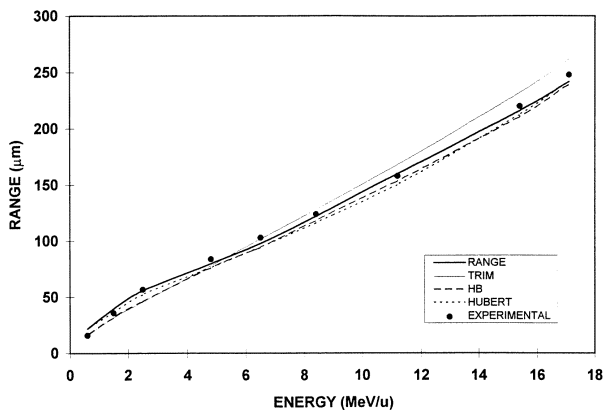
The maximum etchable track lengths in PADC detectors were measured for  $^{208}\text{Pb}$  ions being transmitted through

**Table 2.** Values of Makrofol-G target thickness, maximum etchable track length of  $^{208}\text{Pb}$  in PADC, energy of the transmitted ions and total energy lost by the ions after passing through Makrofol-G foils.

Effective target thickness $X$ ( $\mu\text{m}$ )	Maximum etchable track length $L$ ( $\mu\text{m}$ )	Ion energy ( $\text{MeV u}^{-1}$ )	Total energy lost ( $\text{MeV u}^{-1}$ )
No target	$213.2 \pm 3$	17.1	0.0
21.2	$191.4 \pm 3$	15.4	1.7
84.8	$138.4 \pm 3$	11.2	5.9
127.2	$108.9 \pm 2$	8.4	8.7
148.4	$88.9 \pm 4$	6.5	10.7
169.6	$74.5 \pm 3$	4.8	12.3
190.8	$46.2 \pm 4$	2.5	14.6
212.0	$32.8 \pm 3$	1.5	15.6
233.2	$18.7 \pm 3$	0.6	16.5
254.4	No tracks	0.0	17.1

**Table 3.** Values of experimental and theoretical mean ranges of  $^{208}\text{Pb}$  in Makrofol-G.

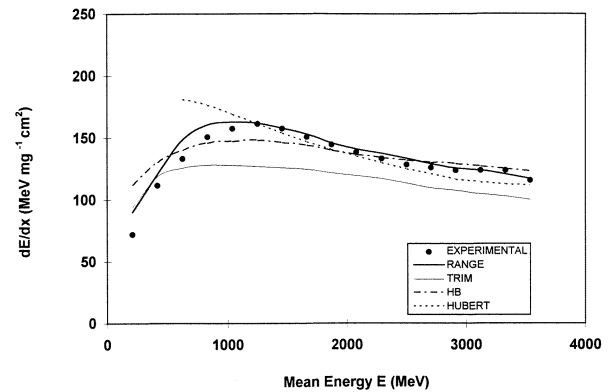
Energy of the ion ( $\text{MeV u}^{-1}$ )	Experimental range ( $\mu\text{m}$ )	Theoretical range ( $\mu\text{m}$ )			
		RANGE [20]	TRIM [21]	HB [22]	HUBERT [23]
17.1	$248 \pm 3$	241.0	264	234	241
15.4	$224 \pm 3$	218.0	236	210	213
11.2	$162 \pm 4$	159.3	168	153	150
8.4	$124 \pm 4$	122.0	128	118	116
6.5	$100 \pm 3$	98.3	100	95	94
4.8	$80 \pm 4$	80.3	78	76	76
2.5	$52 \pm 5$	55.5	46	46	53
1.5	$36 \pm 4$	40.3	32	32	37
0.6	$15 \pm 3$	23.0	16	18	22



**Figure 4.** Mean ranges as a function of ion energy for  $^{208}\text{Pb}$  in Makrofol-G, together with theoretical values.

various stacks of Makrofol-G. The energies of the degraded ions were obtained from the calibration curve (figure 2) using these values of track lengths. An energy-loss curve (figure 3) of the ion has been constructed from the data of target thicknesses and the ion energies. The experimental data were fitted by a third-order polynomial of the type

$$x(E) = \sum_{\mu=0}^{\mu=3} b_{\mu} E_x^{\mu}$$



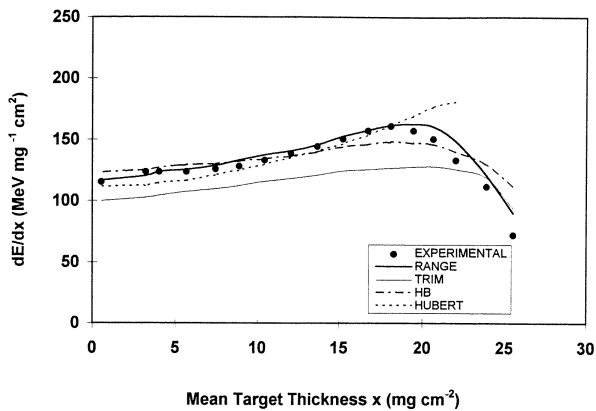
**Figure 5.** The experimental energy-loss rate of  $17.1 \text{ MeV u}^{-1}$   $^{208}\text{Pb}$  in Makrofol-G, together with theoretical values as a function of the mean ion energy  $E$ .

where  $x(E)$  is the range of the ion corresponding to the transmitted energy  $E_x$  and  $b_{\mu}$  is the best set of coefficients obtained from the polynomial fit.

By extrapolating the energy-loss curve down to energy  $E = 0$ , one may easily obtain the mean range of  $17.1 \text{ MeV u}^{-1}$   $^{208}\text{Pb}$  ions in Makrofol-G. The energy-loss rate ( $dE/dx$ ) data of  $^{208}\text{Pb}$  in Makrofol-G have been obtained by differentiating the energy-loss curve as a function of the mean ion energy and mean target thickness.

**Table 4.** Values of experimental and theoretical energy-loss rates ( $dE/dx$ ) of  $^{208}\text{Pb}$  ions in Makrofol-G at various mean ion energies and target thicknesses.

Energy (MeV)	Experimental ( $dE/dx$ ) ( $\text{MeV mg}^{-1} \text{cm}^2$ )	Theoretical ( $dE/dx$ ) ( $\text{MeV mg}^{-1} \text{cm}^2$ )				Mean target thickness ( $\text{mg cm}^{-2}$ )
		RANGE [20]	TRIM [21]	HB [22]	HUBERT [23]	
208	72.2	90.2	94.1	112.0		25.53
416	111.8	121.0	119.0	130.2		23.89
624	133.3	148.7	124.5	139.1	181.0	22.03
832	150.7	160.7	128.1	146.2	176.5	20.66
1040	157.6	163.0	127.9	146.5	169.1	19.45
1248	161.3	161.9	125.9	148.0	161.3	18.09
1456	157.6	158.1	125.2	145.5	153.9	16.72
1664	150.7	153.1	124.6	144.0	147.1	15.23
1872	144.4	146.8	119.1	139.1	140.6	13.67
2080	138.7	141.1	117.0	135.0	134.8	12.06
2288	133.3	137.5	115.8	136.1	129.5	10.43
2496	128.4	133.5	112.3	132.2	124.6	8.89
2704	126.0	129.2	109.6	129.9	121.0	7.45
2912	123.8	125.6	107.5	128.0	116.4	5.68
3120	123.8	124.0	104.6	126.9	114.3	4.01
3328	123.8	120.8	102.9	125.0	112.4	3.20
3536	115.6	117.1	100.1	123.1	111.5	0.53

**Figure 6.** Experimental energy-loss rates of  $17.1 \text{ MeV u}^{-1}$   $^{208}\text{Pb}$  in Makrofol-G, together with theoretical values as a function of the mean target thickness  $x$ .

## 2.6. Experimental errors

The error involved in the determination of initial energy was within 0.1% as obtained by the time-of-flight method and noted from the UNILAC beam protocol. The error in the measurement of thicknesses of the foils is of the order of  $2 \mu\text{m}$ . The standard deviations obtained from the track length distribution curves vary in the range  $1.7\text{--}3.5 \mu\text{m}$ . The variations in the mean ranges on account of the above-mentioned uncertainties were found to vary in the range  $2\text{--}4 \mu\text{m}$ .

## 3. Results and discussion

The experimental data for the maximum etchable track length ( $L$ ) corresponding to various energies of  $^{208}\text{Pb}$  ions

in PADC are given in table 1. Figure 2 shows the track length–energy calibration curve for the  $^{208}\text{Pb}$  ions in PADC. Two data points at energies  $13.6 \text{ MeV u}^{-1}$  [25] and  $17.1 \text{ MeV u}^{-1}$  [26] have been taken from earlier works.

With the help of this calibration curve and the values of maximum etchable track lengths of  $^{208}\text{Pb}$  ions in PADC, the energies lost by  $^{208}\text{Pb}$  ions while passing through various thicknesses of Makrofol-G foils were obtained. An energy-loss curve for  $^{208}\text{Pb}$  in Makrofol-G has been shown in figure 3. The range ( $R_i$ ) of  $17.1 \text{ MeV u}^{-1}$   $^{208}\text{Pb}$  in PADC has been obtained by extrapolating the energy-loss data down to zero energy and is found to be  $248 \pm 3 \mu\text{m}$ . Taking this value of  $R_i$ , the mean ranges of  $^{208}\text{Pb}$  in Makrofol-G at various energies have been determined from the energy-loss curve. The target thickness, maximum etchable track length of  $^{208}\text{Pb}$  in PADC, energy of the transmitted ion and total energy lost by the ion have been listed in table 2.

Figure 4 represents experimental range data plotted with the corresponding theoretical values at various energies calculated from computer codes HB, HUBERT, RANGE and TRIM. The theoretical ranges from various codes are given in table 3 together with the experimental values of ranges at different energies.

The experimental mean ranges are in good agreement with the calculated values from the computer code RANGE for energies above  $4.8 \text{ MeV u}^{-1}$  and are overestimated by a maximum of 7% for energies below  $4.8 \text{ MeV u}^{-1}$ . The ranges calculated by code HB are underestimated by 6% whereas the TRIM code gives values higher by about 6% above  $10 \text{ MeV u}^{-1}$ . The ranges from the HUBERT code are lower by 7% for energies above  $4.8 \text{ MeV u}^{-1}$  and higher by a maximum of 4% for energies below  $4.8 \text{ MeV u}^{-1}$ .

The energy-loss rate data of  $^{208}\text{Pb}$  in Makrofol-G are summarized in table 4. The experimental values of ( $dE/dx$ ) as a function of the ion energy  $E$  (MeV) and mean thickness  $x$  ( $\text{mg cm}^{-2}$ ) are plotted in figures 5 and 6 respectively.

Theoretical data on energy-loss rates from four different computer codes (RANGE, TRIM, HB and HUBERT) are also plotted in figures 5 and 6. It may be observed that values determined from the code HUBERT are very high for energies up to 1000 MeV whereas values from the TRIM code are very low for the range 1000–2500 MeV. The theoretical values of  $dE/dx$  from codes RANGE and HB are in fairly good agreement with the experimental data.

From the data in figure 6, one may conclude that the energy-loss rate remains nearly constant up to a thickness of about  $15 \text{ mg cm}^{-2}$  ( $125 \mu\text{m}$ ), hence  $17.1 \text{ MeV u}^{-1}$   $^{208}\text{Pb}$  ions are suitable for production of about  $100 \mu\text{m}$  thick microfilters with uniform pores using Makrofol-G films.

### Acknowledgments

The authors wish to thank Professor R Brandt and Dr P Vater, Philipps University, Marburg and the staff members of UNILAC, Darmstadt for heavy-ion irradiations. An equipment grant from the German Agency for Technical Corporation (DGTZ) is also acknowledged.

### References

- [1] Mukherjee R N, Das P K, De T K and Syam D 1995 *Radiat. Meas.* **24** 67
- [2] Yadav J S 1995 *Radiat. Meas.* **24** 115
- [3] Fleischer R L and Price P B 1964 *Phys. Rev. B* **133** 63
- [4] Vater P 1988 *Radiat. Meas.* **15** 743 and references therein
- [5] Dey M, Raju J, Ghosh S and Dwivedi K K 1993 *Radiat. Meas.* **22** 907
- [6] Spohr R 1990 *Ion Track and Microtechnology, Principles and Applications* (Braunschweig: Vieweg)
- [7] Brechtmann C, Heinrich W and Benton E V 1989 *Phys. Rev. C* **39** 2222 and references therein
- [8] Heinrich W, Becker E, Dreute J, Hirzebruch S E, Huntrup G, Kurth M, Rocher H, Rusch G, Schmitz M, Streibel T and Winkel E 1995 *Radiat. Meas.* **25** 203
- [9] Wu Rischeng, Zhou Jian and Ke Wei 1993 *Nucl. Tracks Radiat. Meas.* **22** 937
- [10] Durante M, Grossi G F, Pugliese M and Gialanella G 1996 *Radiat. Meas.* **26** 179
- [11] Srivastava A, Lalramengzami R, Laldawngliana C, Sinha D, Ghosh S, Dwivedi K K and Saxena A 1996 *Radiat. Meas.* **26** 291
- [12] Furlan G and Tommasino L 1993 *Proc. Int. Workshop on Radon Monitoring in Radioprotection, Environmental and/or Earth Sciences* (Singapore: World Scientific)
- [13] Vater P, Laue C, Jacobs I, Heise S, Jiang H, Brandt R, Roesch J and Haag J 1993 *Nucl. Tracks Radiat. Meas.* **22** 923
- [14] Roggenkamp H G, Kieswetter H and Spohr R 1981 *Biomed. Technol.* **26** 167
- [15] Gamota G 1973 *Phys. Rev. Lett.* **31** 517
- [16] Dwivedi K K 1991 *Nucl. Tracks Radiat. Meas.* **19** 71
- [17] Hahn R L, Toth K S, Ferguson R L and Plasil F 1981 *Nucl. Instrum. Methods* **180** 581
- [18] Geissel H, Laichter Y, Schneider W F W and Armbruster P 1982 *Nucl. Instrum. Methods* **194** 21
- [19] Bimot R, Gauvin H, Orliong I, Anne R, Bastin G and Hubert F 1986 *Nucl. Instrum. Methods* **17** 1
- [20] Dwivedi K K 1988 *Nucl. Tracks Radiat. Meas.* **15** 345
- [21] Biersack J P and Haggmark L G 1980 *Nucl. Instrum. Methods* **174** 257
- [22] Henke R P and Benton E V 1968 USNRDL-TR-67-122, USA Naval Radiological Defence Laboratory, San Francisco, California
- [23] Hubert F, Bimot R and Gauvin H 1990 *Nucl. Data Tables* **46** 1
- [24] Dwivedi K K and Mukherji S 1979 *Nucl. Instrum. Methods* **161** 317
- [25] Randhawa G S, Garg A K and Virk H S 1995 *Radiat. Meas.* **24** 197
- [26] Ghosh S, Raju J and Dwivedi K K 1995 *Radiat. Meas.* **24** 171