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Intercomparison of experimental and theoretical ranges of heavy ions in plastic track detectors

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Abstract

In the present study, CR-39 and Lexan polycarbonate plastic track detectors have been exposed to various heavy ion beams, i.e. ^{238}U, ^{208}Pb, ^{197}Au, ^{139}La, ^{132}Xe and ^{93}Nb (energy range from 5.6 to 18.0 MeV/u), from the UNILAC accelerator at GSI, Darmstadt. After exposure, the irradiated samples were etched under optimum etching conditions. The total etchable ranges of these heavy ions have been determined experimentally using a Carl Zeiss binocular microscope. In order to check the validity of the various stopping power and range formulations in this energy range, the experimentally determined range values have been compared with the theoretically computed values from the Benton and Henke [Nucl. Instr. and Meth. 67 (1969) 87], Mukherjee and Nayak [Nucl. Instr. and Meth. 159 (1979) 421], Ziegler et al. [Stopping power and range of ions in solids, vol. 1 (Pergamon, New York, 1985); Nucl. Instr. and Meth. B 35 (1988) 215] and Hubert et al. [Nucl. Instr. and Meth. B 36 (1989) 357] formulations.

1. Introduction

The penetration of heavy ions in matter has been a subject of great interest and importance for a long time. For the calibration and use of any charged particle detector, including solid state nuclear track detectors (SSNTDs), knowledge of the accurate stopping power and range formulation is an essential requirement. Solid state nuclear track detectors, a new class of detectors which came into existence about three decades ago, have now become one of the most important tools for many branches of science and technology, e.g. nuclear physics [1], health physics [2], nuclear geophysics [3], environmental sciences [4], cosmic ray and space physics [5], etc. For many fundamental discoveries, such as the first evidence of cluster radioactivity [6], the search for super-heavy elements [7], the determination of very low cross sections (≈ picobarn) [8], etc., the credit goes to these passive detectors. Keeping in view the uses of these detectors, the most sensitive variety of SSNTDs, i.e. plastic track detectors, have been investigated in the present study. Two types of plastic, i.e. CR-39 and Lexan polycarbonate, have been exposed to various heavy ion beams from the UNILAC accelerator at GSI, Darmstadt, Germany. The total etchable ranges of these heavy ions have been determined. To check the validity of various theoretical stopping power and range formulations in the energy range under study, the experimentally determined ranges of the heavy ions have been compared with the theoretically computed values of the Benton and Henke [9], Mukherjee and Nayak [10], Ziegler et al. [11,12] and Hubert et al. [13] formulations. The computer code DEDXT [14], based on Mukherjee and Nayak stopping power equations [10], and "TRIM-95", based on the formulation of Ziegler et al. [11] for the stopping power of heavy ions in solids, have been utilized for range determination.

2. Experimental

2.1. Irradiation

Samples of CR-39 plastic (Pershore Moulding, UK) have been irradiated by ^{238}U (16.53 and 15.0 MeV/u), ^{208}Pb (13.6 MeV/u), ^{197}Au (11.4 MeV/u), ^{132}Xe (14.5, 13.02 and 5.6 MeV/u) and ^{93}Nb (18.0 MeV/u) heavy ions available from the UNILAC accelerator at GSI, Darmstadt, Germany. Similarly, samples of Lexan polycarbonate have been irradiated by heavy ions ^{238}U (16.53, 15.0 and 5.9 MeV/u), ^{208}Pb (13.6 MeV/u), ^{197}Au (13.42 MeV/u), ^{139}La (14.6 MeV/u) and ^{132}Xe (14.5 and 5.9 MeV/u) from the same source. All the irradiations were performed at angles of 45° and 60° under a uniform fluence of 10^4 ions/cm^2.

2.2. Chemical etching and other measurements

After irradiation, the samples of CR-39 and Lexan plastics were etched in 6.25 N NaOH solution at a constant temperature of 60 ± 1°C using a cryostat. Etching of the tracks was performed for short intervals

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Table 1
Experimental and theoretically computed ranges of heavy ions (percentage deviation from experimental values in parentheses) in CR-39 plastic

Ion	Energy (MeV/u)	Experimental range (μm)	Theoretically computed range (μm)			
			Benton & Henke	Mukherjee & Nayak	Ziegler et al.	Hubert et al.
^{238}U	16.53	208	205.52 (−1)	209.22 (1)	237.22 (14)	202.20 (−3)
^{238}U	15.0	190	186.78 (−2)	191.96 (1)	214.56 (13)	181.92 (−5)
^{208}Pb	13.6	166	166.89 (0)	171.23 (3)	189.41 (14)	160.79 (−3)
^{197}Au	11.4	142	138.52 (−3)	144.00 (1)	155.36 (9)	131.91 (−8)
^{132}Xe	14.5	191	182.19 (−5)	195.00 (1)	207.55 (8)	181.88 (−5)
^{132}Xe	13.02	169	161.48 (−5)	173.43 (2)	183.12 (8)	159.46 (−6)
^{132}Xe	5.6	72	69.37 (−4)	75.00 (4)	76.25 (6)	66.11 (−8)
^{93}Nb	18.0	262	244.88 (−7)	265.00 (1)	272.82 (4)	251.24 (−4)

Table 2
Experimental and theoretically computed ranges of heavy ions (percentage deviation from experimental values in parentheses) in Lexan polycarbonate

Ion	Energy (MeV/u)	Experimental range (μm)	Theoretically computed range (μm)			
			Benton & Henke	Mukherjee & Nayak	Ziegler et al.	Hubert et al.
^{238}U	16.53	227	222.01 (−2)	227.00 (1)	256.32 (13)	218.40 (−4)
^{238}U	15.00	203	201.75 (−1)	205.00 (1)	231.22 (14)	196.60 (−3)
^{238}U	5.9	92	89.95 (−2)	92.00 (0)	95.51 (4)	84.66 (−7)
^{208}Pb	13.6	187	180.27 (−4)	186.40 (0)	204.28 (9)	174.27 (−2)
^{197}Au	13.42	181	175.13 (−3)	183.29 (1)	198.58 (9)	168.91 (−7)
^{139}La	14.6	199	195.46 (−2)	208.51 (5)	223.25 (12)	194.35 (−2)
^{132}Xe	14.5	206	196.87 (−4)	209.94 (2)	224.01 (9)	196.98 (−4)
^{132}Xe	5.9	83	78.46 (−6)	87.00 (5)	86.46 (4)	74.87 (−10)

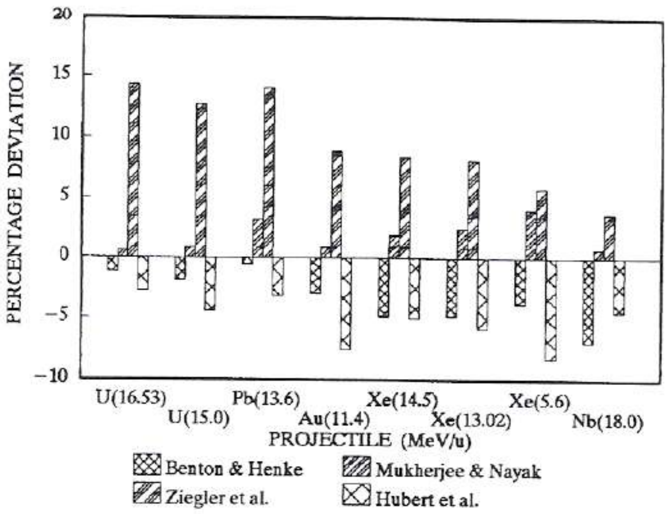

Fig. 1. Percentage deviation of the theoretical ranges from the experimental ranges of various heavy ions in a CR-39 plastic track detector.

of time until the tips of the tracks became round. After successive etching, the samples were washed under running tap water for a few minutes and then dried in the folds of a tissue paper. The dried and etched samples were scanned by a binocular Carl Zeiss microscope at a magnification of $1000\times$. After measuring the projected track length, the total etchable range was determined by applying the corrections due to bulk-etching and over-etching. As it is well established that the critical energy loss $(dE/dX)_c$ is very low for plastic track detectors, the range deficit will be very small (a few hundred Å to 3 μm) and hence we can take the total etchable range as the range of heavy ions in that detector material. The range measurements have an overall accuracy of 5%.

3. Results and discussion

The experimental range values in CR-39 and Lexan polycarbonate plastics for ^{238}U (16.53 and 15.0 MeV/u), ^{208}Pb (13.6 MeV/u), ^{179}Au (13.42 and 11.4 MeV/u), ^{139}La (14.6 MeV/u), ^{132}Xe (14.5, 13.02, 5.9 and 5.6 MeV/u) and ^{93}Nb (18.0 MeV/u) ions are

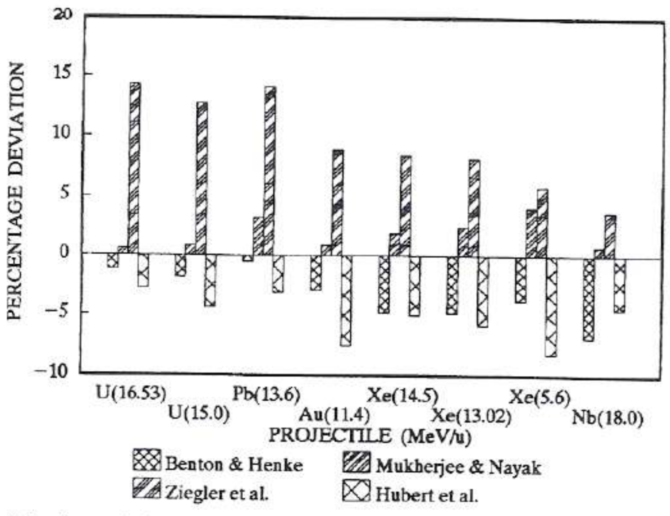

Fig. 2. Percentage deviation of the theoretical ranges from the experimental ranges of various heavy ions in a Lexan polycarbonate plastic track detector.

presented in Tables 1 and 2. The theoretically computed range values from the Benton and Henke, Mukherjee and Nayak, Ziegler et al. and Hubert et al. formulations for these ions at their respective energies are also summarized in these tables. The percentage deviation of the computed values from the corresponding experimental values are also presented in Tables 1 and 2. Further, these percentage deviations are also plotted in Figs. 1 and 2.

From the tables and figures, it is evident that:

(1) The calculated range values determined from the Benton and Henke, Mukherjee and Nayak and Hubert et al. formulations are in close agreement with the experimental results (almost within the limit of experimental errors).
(2) The computed range values from the Ziegler et al. formulation are generally higher than the corresponding experimental range values (maximum deviation is of the order of 14%).

This latter observation is consistent with those of Bimbot et al. [15] and Sharma et al. [16]. These authors have reported that the Ziegler et al. formulation highly underestimates the experimental stopping powers for very heavy projectiles such as U, Pb, Au, Xe, etc., in light targets such as Be, C, Al, etc.; the main constituents of plastic detectors are light elements such as C, H, O, etc. and range is a cumulative effect of stopping power which can be depicted mathematically as

$$R(E) = \int_0^E (\mathrm{d}E/\mathrm{d}X)^{-1}\,\mathrm{d}E.$$

Therefore, the range values computed using the Ziegler et al. formulation for ions such as U, Pb, Au, Xe, etc. in plastic track detectors overestimate the corresponding experimental range values.

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