PRAMANA — journal of physics

Vol. 69, No. 2
August 2007
pp. 191–198

Single-sheet identification method of heavy charged particles using solid state nuclear track detectors

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MS received 29 November 2006; revised 9 March 2007; accepted 11 April 2007

Abstract. The theoretical and experimental investigations of the penetration of charged particles in matter played a very important role in the development of modern physics. Solid state nuclear track detectors have become one of the most important tools for many branches of science and technology. An attempt has been made to examine the suitability of the single-sheet particle identification technique in CR-39 and CN-85 polycarbonate by plotting track cone length vs. residual range for different heavy ions in these detectors. So, the maximum etchable ranges of heavy ions such as ^{93}Nb, ^{86}Kr and ^{4}He in CR-39 and ^{4}He and ^{132}Xe in CN-85 polycarbonate have been determined. The ranges of these ions in these detectors have also been computed theoretically using the Henke–Benton program. A reasonably good agreement has been observed between the experimentally and theoretically computed values.

Keywords. Solid-state nuclear track detectors; track length; residual range; heavy-ions.

PACS Nos 29.40.Gx; 29.40.Mc; 29.40.Wk; 29.90.+r

1. Introduction

One of the applications of solid state nuclear track detector (SSNTD) is recording the damaging effect due to energy dissipated by an ionizing particle interaction with matter [1]. The theoretical and experimental investigations of the penetration of charged particles in matter played a very important role in the development of modern physics. Solid state nuclear track detectors have become one of the most important tools for many branches of science and technology [2–4], for example, in neutron dosimetry, gamma and cosmic rays detection, heavy ion and nuclear physics and corpuscular diagnostics in high-temperature plasma experiments. The passage of heavy charged particles through most insulators leads to the formation (at the micro-structural level) of narrow regions of radiation-damaged matter; referred to as latent tracks [5]. SSNTDs have been improved and characterized in various laboratories for better detection sensitivity, and charge and energy resolutions. Heavy ion research involving track detectors in several fields like nuclear reactions, lifetimes of heavy unstable nuclear particles, ternary fission, particle identification and healthy physics is well-developed by several authors [6–10]. However, the dependence of the ionization on the ion energy is rather complicated and as a result, it is not possible to propose a single principle of particle identification based on the parameters of the observed tracks and valid for the complete range of energies of the incident particle. Therefore, the identification of charged particles in the SSNTDs depends on the energy range of the detected particles [11].

In many of the experiments involving heavy ions, interpretation of the data requires reliable and precise values of stopping power for heavy ions. As regards SSNTDs, a precise energy loss-range formulation is one of the essential requirements to achieve an accurate calibration of the detector for the purpose of identification of charged particles. So, in our present work, we have used the track cone length vs. residual range method of identification using CR-39 and CN-85 polycarbonate detectors irradiated by different heavy ions at different energies. This technique is also called single-sheet identification or LR-plot method of particle identification using SSNTDs. This is one of the highly developed methods, and one that has been applied to all classes of dielectric solids. The main purpose of this work is to study the possibility of using this technique to investigate artificially created ion tracks from accelerators and calibrate naturally occurring tracks and thus establishing their charge and energy.

2. Experimental details

2.1 *Heavy ions irradiation*

CR-39 samples of thickness 500 μm, supplied by Prshore Mouldings Ltd., UK (composition $C_{12}H_{18}O_7$, molecular weight 274 a.m.u., density 1.32 g/cm^3) were irradiated at the UNILAC heavy ion accelerator, GSI, Darmstadt, Germany with collimated beams of 17.7 MeV/nucleon ^{86}Kr and 18 MeV/nucleon ^{93}Nb ions. Similarly, samples of CN-85 polycarbonate (composition $C_6H_6O_9N_2$, density 1.54 g/cm^3) have been irradiated by heavy ion such as ^{132}Xe, available from the UNILAC accelerator at GSI, Darmstadt, Germany. All the irradiations were performed at an angle of 45° with respect to the surface of the detector having the same fluence of 10^4 ions/cm^2.

2.2 *Alpha particles irradiation*

Another set of CR-39 (each 1 mm thick), TASTRAK type (Track Analysis System Ltd., UK), of size 1 cm × 1 cm, and CN-85 were used. They were irradiated with a ^{241}Am alpha source with different incident α-particle energies and having the fluence of 10^7 particles/cm^2. To achieve this, Perspex collimators of different lengths were interposed between the source and the detector (both placed in air), so that the α-particles, after traversing different distances in air, fell vertically upon

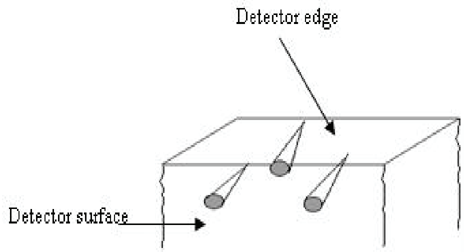

Figure 1. Schematic view of the edge of a broken detector piece.

the detector. Reference measurements of the alpha spectrum were made using a silicon surface barrier detector at the same distance from the source as the track detectors connected to a multichannel pulse height analyzer.

2.3 *Track length measurements*

In order to measure track lengths without any correction in the measurements, all sets were embedded edgewise in epoxy resin and broken into several pieces in such a way that the cut edge lay in the (horizontal) plane defined by the top surface of the epoxy block, and the irradiated surface (now lying in a vertical plane) was perpendicular to the top surface of the block. The etched track length, which penetrated the body of the detector, then also lay in the block's top (horizontal) surface. Then, longitudinal sections of each pit were evaluated at the edges of the detector pieces (see figure 1).

Because the detector material has a good optical transparency, tracks which are situated some micrometers below the edge surface can also be identified. In this way, the complete formation of an etched track along the particle trajectory could be visualized. The sample was polished by means of a polishing machine and washed with distilled water.

2.4 *Etching process*

The samples were etched in 6.25 N NaOH at a constant temperature of 60°C with a control accuracy of ±0.1°C. The samples were washed under running tap water for about 10 min and dried in the fold of a tissue paper. The samples were scanned using an image analyzing system, Leica microscope in steps for sufficiently long etching time, depending on the type of the charged particles to which the samples had been exposed, till the tips of the tracks became round. The detector evaluation was carried out by LEICA image analyzer which consists of a PC with LEICA QWIN program, DMRE optical microscope, equipped with motorized x-y stage and autofocus options controlled by special program operated under Windows 98. This system allows us to analyze the object structures with high spatial resolution. After measuring the projected track length, the total etchable range was determined by

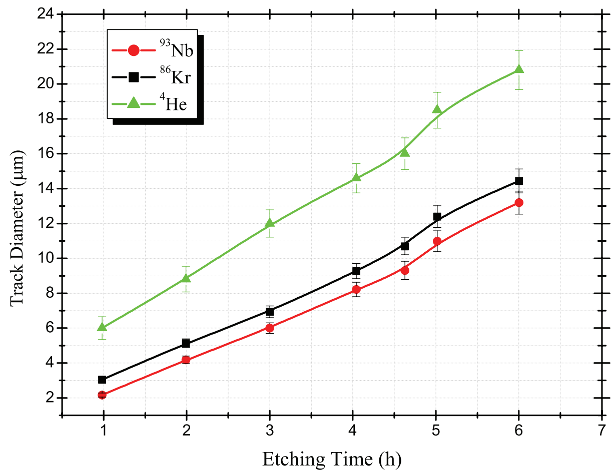

Figure 2. Track diameters of ^{4}He, ^{86}Kr and ^{93}Nb in CR-39, plotted against etching time.

applying the corrections due to the angle of incidence, bulk etching and over-etching [12]. Knowing the total etchable range, it is possible to determine the residual range of different heavy ions. Thus the track cone length and residual range (RR) gives a (L,RR) pair which forms the basis of the single-sheet identification technique. Finally, a comparison was made between experimental and theoretical values of the range computed using the Henke–Benton program [13].

3. Results and discussion

Figure 2 illustrates the values, and the growth, of track diameters of α-particles, and heavy ions as a function of etching time. The single sheet for particle identification contains complete information about the variation of V_T with R, and this method is useful when the etchant reaches the end of the particle's range. In spite of having very close track diameter values, ^{86}Kr and ^{93}Nb are resolved in CR-39 by using L–R plot method. Also the dependence of V_T on the residual range (R) reflects the relation between $\mathrm{d}E/\mathrm{d}x$ and the particle energy (E).

Figure 3 shows the plot of track cone length (L) vs. residual range (RR) for different heavy ions in CR-39. From the figure it is clear that the points corresponding to the different heavy ions lie on different lines. It is also observed that the points corresponding to the plot between track cone length and residual range for the α-particles with different energies (3.5, 4.5 and 5.4 MeV/n) lie on different lines. Hence, it is concluded that the single-sheet identification method is successful for the energy resolution of heavy ions in CR-39. Similarly, figure 4 shows the plot between track cone length and the residual range (RR) for ^{4}He and ^{132}Xe ions in CN-85 polycarbonate. The points corresponding to the graph between track cone length and residual range for α-particles with three different energies lie on three different lines. Thus, it is concluded that the single-sheet particle identification is

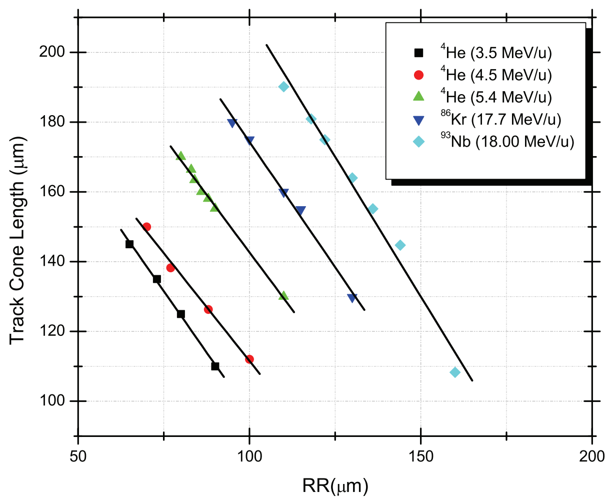

Figure 3. Track length variation with residual range for different heavy ions in CR-39.

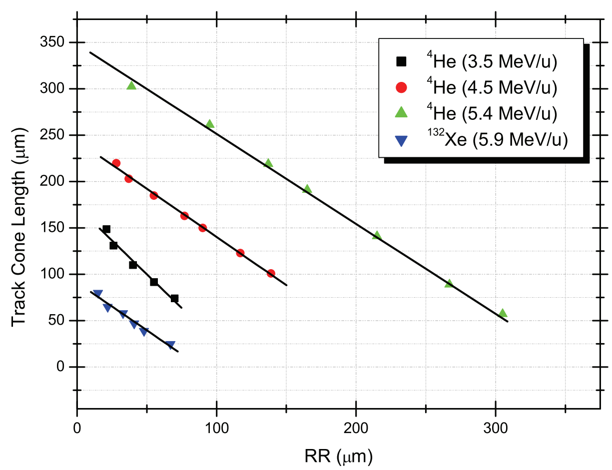

Figure 4. Track length variation with residual range for different heavy ions in CN-85.

also successful for the energy resolution in CN-85 polycarbonate. This method can be used successfully for the identification of low-energy particles, such as solar cosmic ray than one sheet. A comparison of experimental and theoretically computed values of ranges for different heavy ions in CR-39 and CN-85 is shown in tables 1 and 2, respectively. It is evident that the experimental values are less than the corresponding theoretical values of the range. This is so because each detector material fails to record the last few microns of the length of the track where the energy loss rate, $(\mathrm{d}E/\mathrm{d}X)$, of the ion becomes less than the critical energy loss rate, $(\mathrm{d}E/\mathrm{d}X)_{\mathrm{c}}$ for that detector. Thus, it is clear that the values of range computed theoretically are in reasonable agreement with the corresponding experimental values.

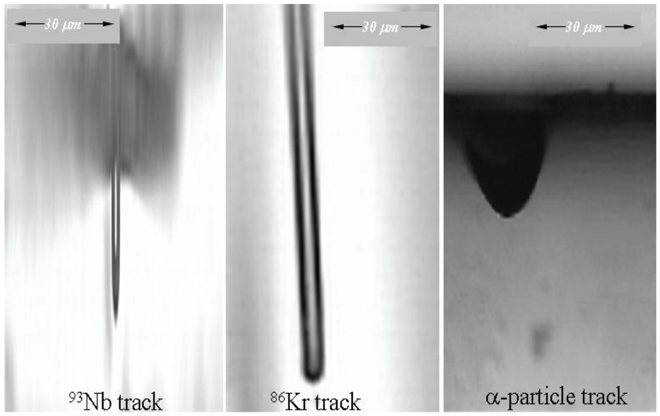

Figure 5. Photomicrographs illustrating the etched track lengths in CR-39 detector.

Figure 5 illustrates the track profiles of the ^{93}Nb and the ^{86}Kr tracks, not fully etched, and the over-etched tracks due to the α-particles. It is obvious from this figure that the heavier ions, which are not fully etched, have sharp tips, while the over-etched tracks of the α-particle has rounded tips. A conical shape of the etch pit is observed at the beginning of the etching process. This means that the track etch rate is approximately constant. With increasing etching time, however, the lower end of the track appears more and more as a sharp tip indicating that the track etch rate increases distinctly. Finally, the conical shape of the etch pit turns to a hemispherical shape. This occurs, when the total particle range is etched. Further prolongation of the etching time does not result in further growing of the track length because the etching now takes place with the bulk etch rate in all directions. Therefore, only the track diameter increases whereas the track length remains approximately constant. Measuring the etched cone length and applying the corrections due to the bulk etching and over-etching, the total etchable range for these ions in these detectors have been measured. The standard deviation in the range measurements is within 5%. These measured values of range are slightly smaller than the actual range (range deficit). This is due to that the end of the portion of the track, where the energy loss produced by the incident ion beam is less

Table 1. Comparison of experimental and theoretical values of range for different ions in CR-39 detector.

Ion	Energy (MeV/n)	Experimental range (μm)	Theoretical range (μm)	REL_{350} (MeV·cm^2/g)	dE/dX (MeV·cm^2/g)
^{93}Nb	18.0	241.22	244.88	24845.20	38269.60
^{86}Kr	17.7	266.32	268.54	19812.20	30754.80
^{4}He	5.4	319.21	317.55	192.70	293.02
^{4}He	4.5	224.41	230.60	227.10	341.04
^{4}He	3.5	145.65	149.88	282.45	417.60

Table 2. Comparison of experimental and theoretical values of range for different ions in CN-85 detector.

Ion	Energy (MeV/n)	Experimental range (μm)	Theoretical range (μm)	REL_{350} (MeV·cm^2/g)	dE/dX (MeV·cm^2/g)
^{132}Xe	5.9	62.41	67.8467	57152.55	84326.6
^{4}He	5.4	287.54	291.32	177.50	274.6
^{4}He	4.5	209.23	212.16	209.10	319.4
^{4}He	3.5	135.12	138.25	259.80	390.637

than the critical threshold, is not revealed by chemical etching. But for high-energy heavy ions, this range deficit becomes negligible in comparison to the total range. Therefore the total etchable range itself can be treated as the range of the ion in the detector.

4. Conclusions

Clustering of the points clearly shows that points corresponding to the same ion lie on a single curve. So, we conclude that, single particle identification technique can be used successfully for the determination of heavy ion ranges in nuclear track detectors. Reasonably good agreement has been observed between computed track ranges and our measured values. The present experiment has generated fairly accurate values of etchable track lengths of several heavy ions in polymer track detectors. The technique for the observation of ancient tracks can be applied to improve the precision of the artificially generated structures. Similarly, artificially created ion tracks from accelerators can be used to calibrate naturally occurring tracks and thus establishing their charge and energy.

Acknowledgement

The authors are very thankful to the staff at UNILAC, GSI, Darmstadt, Germany, for their cooperation in heavy ion irradiations.

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