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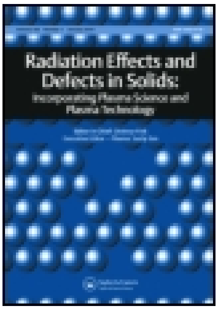

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In the current work, alpha particle spectroscopy is investigated experimentally by utilizing the over-etched track lengths in the CR-39 detector. CR-39 samples were exposed perpendicularly to alpha particles emitted from ^{241}Am with an energy ranging from 0.5 to 5.5 MeV. CR-39 samples were etched in 6.25 N NaOH at $(70 \pm 0.5)°C$ for different durations. The track diameter and track length were measured under an optical microscope. The results show that, the energy-over-etched track length calibration curve is monotonic, in other words, the over-etched track length is a monotonic function in alpha particle energy. On the other hand, the energy-diameter calibration curve is degenerated, *i.e.* alpha track diameter is non-monotonic function in alpha particle energy. These results suggest that the CR-39 detector could be used as a wide range alpha particles spectrometer using an energy-over-etched track length calibration curve.

Keywords: poly allyl diglycol carbonate (CR-39); track-etching rate; over-etched track length; alpha particles spectrometry; monotonic and non-monotonic function

PACS: 2; 78; 07.77.Ka; 61.82._d

1. Introduction

Charged particle spectrometry and particles identification using solid-state nuclear track detectors (SSNTDs) are widely applied in many different fields, including experimental nuclear physics (*1–3*). The CR-39 detector is the most common SSNTD because of unique properties, a recent review of SSNTDs is given by Nikezic and Yu (*4*, and references therein). The different elements that serve as the basis for using CR-39 detector in alpha particle spectroscopy are measurement of track opening parameters or track profile parameters. Concerning the track opening, the diameter or major or minor axes for non-circular track opening are used to measure the alpha particle's energy via a calibration curve between diameter or major or minor and energy of alpha particle (*3*,*5*,*6*). One fundamental limitation of this technique for practical utilization over a wide range of energy is the degeneracy of the alpha particle diameter, where two or more alpha particles possessing different energies may have the same diameter or major or minor at the same etching time. In other words, alpha particle diameter is a non-monotonic function in alpha particle energy (*4*,*7*,*8*). The origin of the alpha particle diameter degeneracy (non-monotonic in energy)

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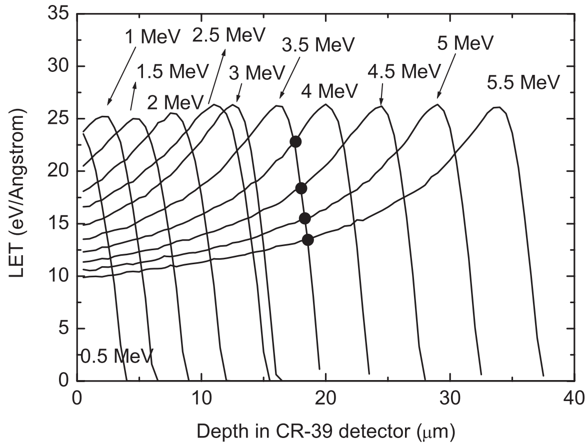

Figure 1. Variation of the linear energy transfer (LET) as a function of the depth in CR-39 detector for different alpha particles energies, calculated by SRIM (*9*,*10*).

can be explained by considering Figure 1, which shows the dependence of the LET of alpha particle on its depth in the CR-39 detector (*9*). One may observe that Bragg curves of alpha particles of different energies are clearly intersecting, see, for example, the black circles between 3.5 MeV curve and 4, 4.5, 5, 5.5 MeV curves, *i.e.* they have deposited the same amount of energy at the same depth in CR-39 detector. Alpha particle of energy 3.5 MeV produces the rate of energy loss as much as for 4 MeV at depth 17.5 μm, therefore the track diameter will be the same for both energies, also 3.5 MeV and 5 MeV will produce the same track diameter at removal thickness 18.3 μm. On the other hand, track profile parameters offer an unique opportunity to measure the actual values of many track parameters including track-etching rate (V_T), alpha particle range (R), and track length (L) (*11–16*).

The importance of track profile parameter in alpha particle spectroscopy can be explained using, the LET Bragg curves within CR-39 detector, which are depicted in Figure 1. Phenomenologically speaking, the maximum energy transfer (Bragg's peak) of alpha particles of different energies within the CR-39 detector never intersecting. This, however, indicates that over-etched track length is a monotonic function in alpha particle energy. Accordingly, for prolonged etching time, where the track is over-etched and the track length unchanged irrespective of the etching time and is a monotonic function of alpha particle energy. To the best of our knowledge, this is the first paper that discusses in detail the alpha particles spectroscopy based on the over-etched track profile. The paper emphasizes the main differences between track opening and track profile used in alpha particle spectroscopy. Earlier authors working on this subject such as Dörschel and Hermsdorf have measured, *e.g.* the track depth and over-etching length, but they never mentioned its importance to use CR-39 detector as an alpha particles spectrometer over a wide range of energy (*11–16*).

This study aims to investigate the utilization of the CR-39 detector as a wide energy alpha particle spectrometry by measuring the over-etched track length. A theoretical background that based on the LET (Bragg curve) with in CR-39 will be briefly discussed. A comparison between alpha particle spectroscopy based on energy-diameter and an energy-over-etched track length relationship will be reported as well.

2. Materials and methods

CR-39 (Pershore; density = 1.32 g/cm^3, molecular composition $C_{12}H_{18}O_7$) of thickness (1500 ± 4) μm were exposed to vertically incident alpha particles from ^{241}Am (main energy 5.49 MeV) of activity 9 μCi in air. Defined alpha energies could be obtained between 0.5 and 5.5 MeV by changing the air column between the ^{241}Am source and CR-39 detector. The cross-section area of the collimator was about 1 mm^2 to ensure that the alpha particles striking the detector surface perpendicularly to avoid the energy's spreading out due to different paths in air. CR-39 samples were etched in an aqueous solution of 6.25 N NaOH at (70 ± 0.5)°C for different durations. The bulk etching rate V_B was measured using the well-known weight decrement method. It amounts to $V_B = (1.26 \pm 0.06)$ μm/h. In order to measure the track lengths, the CR-39 samples were broken into small pieces perpendicular to the detector surface, then carefully polished and irradiated with alpha particle laterally, therefore, visualizing the longitudinal section of the etched track. The track openings and track length were measured under an optical microscope. Every point in the curves represents a mean value of about 50 measurements with relative standard deviation $\sigma = 6$–10%.

3. Results and discussion

Alpha particle spectroscopy using track opening will be briefly discussed, emphasizing the difficulties faced by its utilization. Figure 2 illustrates the track diameter (D) as a function of alpha particle energy (E) at different etching times in 6.25 N NaOH at 70°. It is noteworthy to mention that at a longer etching time duration, the diameter of alpha particles of low energies was hardly seen under an optical microscope. In general, the visibility of tracks decreasing by the increase in the etching time after the end of its range in CR-39. The data in Figure 2 is fitted using the following Lorentzian function:

$$D = D_o + \frac{2A}{\pi} \frac{\Gamma}{4(E - E_c)^2 + \Gamma^2}, \tag{1}$$

where D_o being the offset, A being the area, Γ being the full width at half maximum, and E_c is the center of the peak. All mentioned parameters are fitting parameters which are summarized in Table 1.

The most significant features in Figure 2 and data in Table 1 are: (1) There is a clear track diameter degeneracy, different alpha particles energy may have the same diameter which increases by the increase in etching time which gives rise to an increase of the curve width from 1.85 MeV at etching time 2 h to be 13 MeV at etching time 20 h; (2) The dependence of the Bragg peak

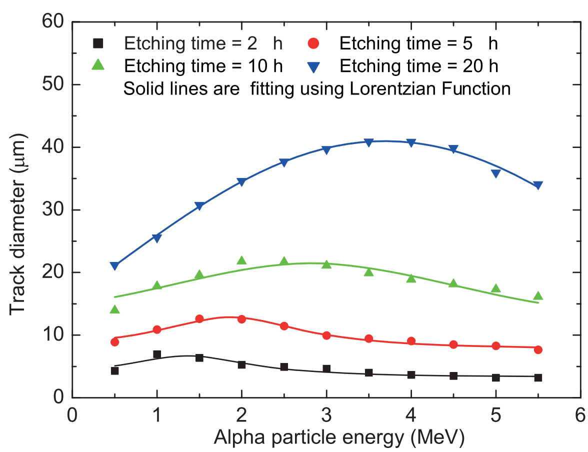

Figure 2. Track diameter as a function of alpha particle energy at different etching time.

Table 1. Fitting parameters of the data represented in Figure 2 for CR-39 detector irradiated with alpha particles of different energies and etched in 6.25 N NaOH 70° results in bulk etch rate of $V_B = (1.26 \pm 0.06)$ µm/h.

Etching time (h)	Width (Γ)	Area (A)	Center (E_c)	offset (D_o)
2	1.85	10	1.36	3.22
5	2.08	17	1.86	7.65
10	5.4	109	2.8	8.70
20	13	2082	3.7	−61.30

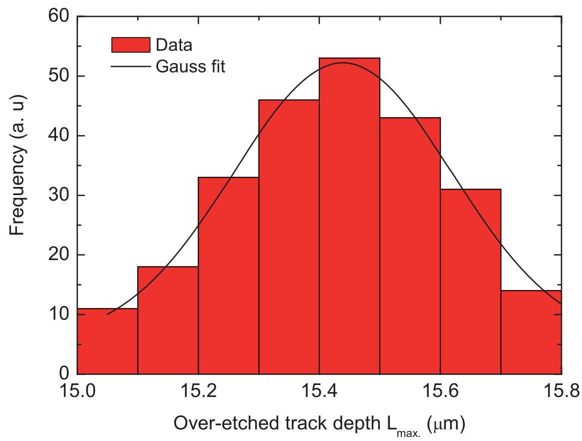

Figure 3. Histogram of the track length of alpha particle tracks incident normally on CR-39 with an energy 4 MeV and Gaussian fitting of data. The etching time $t_e = 10$ h.

position E_c on the etching time, the peak moves toward higher alpha particle energy by increasing the etching time. However, this gives rise to the increase of track diameter degeneracy as well. Since the track diameter provides a measure of radial local energy deposition, dE/dx, at certain length as shown and discussed in Figure 1, the track diameters cannot be used to measure the alpha particle energy when the track is not yet completely etched. As reported in (*8*), this problem can be overcome by selecting the etching time to be $t_e = R/V_T$. Here R being the range of alpha particle and V_T being the track etch rate measured in µm/h. These prerequisites of both R and V_T are difficult to be determined and will increase the uncertainties of measurement since V_T is a rapidly function in depth in CR-30 detector in a similar way to the Bragg curve. This fact shows that to use CR-39 as a wide alpha particle energy spectrometer based on energy-diameter relationship is not an easy task if it were possible.

As mentioned in Section 1, over-etch track length depends on the energy of alpha particle for fixed etching conditions. The histogram of the measured over-etched track length of alpha particle with energy 4 MeV vertically impact CR-39 detector surface is depicted in Figure 3. The etching time is $t_e = 10$ h that means $t_e \gg t_R$, where t_R is the time needed to etch the track to its end R. The etched time of 10 h makes sure that the measured track lengths are beyond the range. The data represented in Figure 3 is over 200 measurements of maximum track lengths L_{max}, data are fitted with the Gaussian function as follows:

$$F = F_o + \frac{A1}{w\sqrt{\pi/2}} \exp\left[\frac{-(L_{max} - L_{maxc})^2}{w^2}\right], \qquad (2)$$

where F is the frequency, $F_o = 5.48$ and being the offset, $A1 = 21.11$ and being the area, $w = 0.36$ and being the full width at half maximum, and $L_{maxc} = 15.43$ and being the center. The Gaussian fitting of the data resulted in the track length of (15.43 ± 0.15) µm.

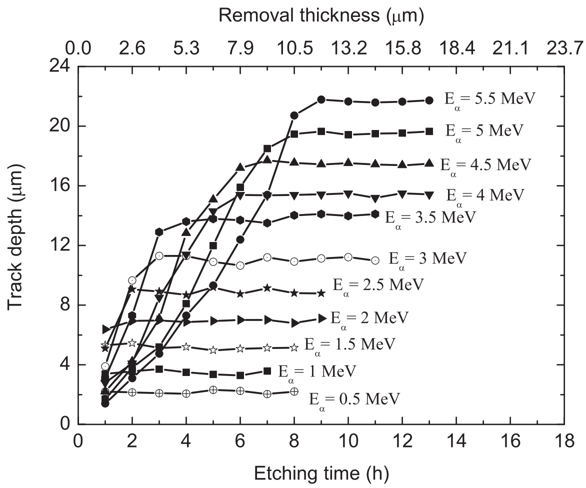

Figure 4. Variation of the measured alpha-particle track length as a function of the etching time in CR-39 detectors.

To study how the track length of alpha particle in CR-39 is changed as a function of the etching time, the track length was measured for different alpha particle energies ranging from 0.5 MeV to 5.5 MeV in step of 0.5 MeV for different etching durations as depicted in Figure 4. For a small etching time, $t_e < t_R$, almost all the curves are intersected. In other words, for small etching time, $t_e < t_R$, the cone lengths are degenerate. When the particle trajectories are completely etched ($t_e > t_R$), the further etching proceeds with the bulk etch rate, V_B, in all directions resulting in a rounded etch track, which may deteriorate the contrast of the track profile.

It is noteworthy to emphasize the fact that the measured maximum track length of alpha particle L_{max} deduced from Figure 4 should be shorter than the depth of the Bragg peak deduced form Figure 5. By considering the, for instance, alpha particle with energy of 4 MeV, a Bragg peak at 22 μm, whereas maximum track length L_{max} is 15.5 μm by considering the removal thickness, $h = V_b * t_e = 1.26 * 6 = 7.6\,\mu m$. Then, the range is $R = 15.5 + 7.6 = 23.1\,\mu m$ which is in good agreement with the frame of uncertainties in calculation (*9*,*10*).

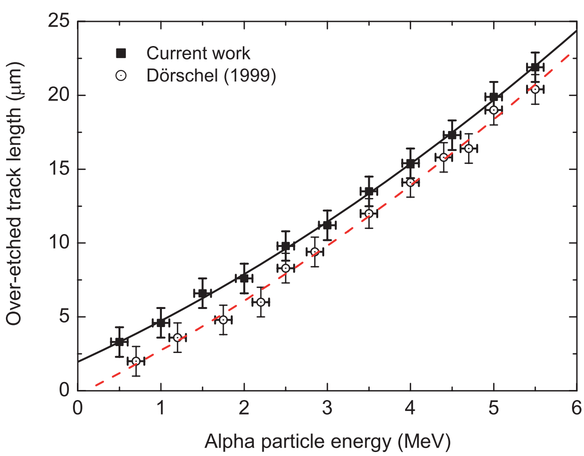

Figure 5. Variation of the measured alpha particle over-etched track length as a function of an alpha particle energy (impact vertically).

The energy resolution of CR-39 detector can be calculated by using a similar equation applied to the track diameter of alpha particle (*5*), which is written in for over-etched track profile as follows:

$$\frac{\Delta E}{E} = \frac{[(E_1 - E_2)/(L_{\max 1} - L_{\max 2})]}{0.5[E_1 + E_2]} \Delta L_{\max}, \tag{3}$$

where E_1 and E_2 are the energies of incident alpha particle, $L_{\max 1}$ and $L_{\max 2}$ the mean over-etched track length corresponding to E_1 and E_2 and $\Delta L_{\max}$ is the width of the distributaries. Unfortunately the lack of equipment, such as an irradiation chamber, in our laboratory hindered the excessive check of the energy resolution.

The dependance of the over-etched track length on the alpha particle energy is shown in Figure 5 at etching time 10 h, furthermore data adapted from (*11*) is presented as well. The discrepancy between the current results and data adapted from (*11*) due to the use of different CR-39 detectors and irradiation conditions. For higher energy alpha particle of more than 5.5 MeV, this calibration curve should be obtained at a higher etching time. The etching time could be reduced for low alpha particle energies since the range of the alpha particle is shorter than for higher energies. On the contrary, of the diameter-energy curve depicted in Figure 2 where the track diameter is a non-monotonic function in energy, the over-etched track length is a monotonic function in energy where an over-etched track length increases with increasing of alpha particle energies. Through the experimental data, the following curve was fitted (*5*),

$$L_{\max} = a + b_1 E + b_2 E^2, \tag{4}$$

where E is the energy of alpha particle in MeV and $L_{\max}$ the corresponding over-etched track length. The values of the fitting parameters of data depicted in the Figure 5 is summarized in Table 2. The discrepancies between the current results and results reported by Dörschel et al. (*11*) are about 13% for a high-alpha particle energy of 5.5 MeV, whereas it is about 39% for a lower alpha particle energy of 0.5 MeV. These discrepancies could be attributed to one or more than one of the following reasons: (1) different materials (CR-39 detector)used in both studies; (2) different etching conditions, which gives rise to different bulk etching rates V_B.

From this calibration curve, energy could be assigned to each over-etched track length individually. Consequently, alpha particle energy can be determined by measuring only the over-etched track length. The alpha particle energy spectrometry based on track-length measurement is a way to shorten the required etching time, which will be very useful if a large amount of detectors have to be measured within a short time, *e.g.* during a large-scale survey, therefore, such a procedure is recommended for alpha particle spectrometry. It is worth mentioning that, there is now no need to measure the track length via side-viewing on the perpendicularly incident alpha particle since it is possible to measure the over-etched track length directly, using 3-D confocal microscopy track analysis (*16*,*17*).

Table 2. A comparison between fitting of the data in Figure 5 from the current work and work of Dörschel et al. (*11*).

Work	a	b_1	b_2
Current work	1.96	2.56	0.195
Dörschel et al. (*11*)	−0.26	2.81	0.180

4. Conclusion

Alpha particle spectroscopy based on an over-etched track length measurement is verified. The alpha particle track diameter is a non-monotonic function in energy of the alpha particle. Consequently, alpha particle spectroscopy based on the energy-diameter calibration curve could be applied under extreme conditions over a narrow range of alpha particle energy. The energy-over-etched track length relationship is monotonic, *i.e.* over-etched track length is a monotonic function in alpha particle energy. Accordingly, alpha particle spectroscopy based on energy-over-etched track length calibration curve is applicable over a wide range of alpha particle energy. In contrast to alpha particle spectrometry based on the energy-diameter relationship which needs a lot of chemical etching and measurements, the alpha particle energy spectrometry based on track-length measurement is a good way to shorten the required etching time. It can be applied in one run, furthermore, it will be very useful when a large amount of detectors have to be measured within a short time, *e.g.* during a large-scale survey.

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