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Numerically and Experimentally Evaluation of Alpha Particle Track Parameters in CR-39 Nuclear Track Detectors

Research Article

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Abstract

The use of our optimum new etching condition (Ashry et al., 2014) was involved in the current experiments. ^{252}Cf and ^{241}Am sources were used for irradiating samples of CR-39 solid state nuclear track detectors (SSNTDs) with fission fragments and alpha particles in irradiation chamber at normal temperature and different air pressure. The normal alpha tracks parameters of energies in the range of 1.0 to 5.0 MeV have been studied. The absorption of alpha particles in air has been studied through a set of experiments in which energy-range data were used to produce energy-distance curves for alpha particles in different air pressure. The rate of energy loss (dE/dx) has been measured experimentally and calculated using a numerical approach. In this approach, the SRIM-2003.26 and Matlab programs were used to calibrate the residual particle energy under different pressure conditions. From fission and alpha track diameters, the value of bulk etching rate was measured. The sensitivity was found to vary with alpha energy from 1.0 to 5.0 MeV. Both the critical angle (θc) and etching efficiency (η) of CR-39 detectors have been determined. A comparison between the measured results and calculated values is given and a good agreement has been found. Results can be successfully applicable in alpha autoradiography studies and detector efficiency determination for track registration in CR-39 plastic detectors at different air pressure.

Keywords: CR-39 detectors; Numerical approach; Energy loss; Critical Angle.

Highlights:

- Samples of CR-39 detectors have been irradiated with fission fragments and alpha particles.
- A numerical approach has been presented
- Critical angle and etching efficiency were determined.
- The dependence of alpha particles energy with pressure at different distances.
- Suitable analyzing software has been used

Introduction

Solid state nuclear track detectors (SSNTDs) have been successfully employed in different applications in science and technology [1, 2]. They have been used in alpha auto-radiography, radiation dosimetry and particle identification [3-8]. They have many advantages as compared with other detectors. They are relatively cheap and provide permanent records of events (tracks), as well as proven to operate successfully under various environmental conditions and have almost no fading under normal storage of temperature and pressure [9-12]. One of the most commonly used detectorsis CR-39, because of its good sensitivity, stability against various environmental factors, and high degree of optical clarity [13, 14]. In addition, CR-39 detectors as a tool of alpha particle spectroscopy have been employed in such measurements for their advantages of having reasonable alpha resolution, low cost, ease of handling, long exposure duration and permanent track record [15-17].

The dominant interaction mechanisms between alpha particles and the molecules of the medium through which they pass are mainly the excitation and ionization processes caused along their paths. Accordingly, energy loss rate (dE/dx) of alpha particles depends mainly on the density of the stopping medium or the air pressure. The air molecules were used as a stopping medium for the incident projectiles alphas using the irradiation chamber [4-18, 19]. Inside the chamber, alphas energy varies via either the adjustment of the source-to-detector distance (x) at fixed

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pressure (P) or by varying the air pressure at fixed distance. The dependency of the energy loss rate (*dE/dx*) on the pressure of air has been evaluated from the experimental data and compared with the theoretical TRIM computer program in [20]. El-Hawary and the collaborators have been studied the absorption of alpha particle in air through a set of experiments in which the stopping power has been measured [21].

It is important to mention that in order a detector to be more efficient for determination of relatively low charged particle fluences or doses, it should have very low or nil background counts. The background track density in the SSNTDs may be due to radon absorption in the detector (depending on the age of the track detectors) or from some inherent defects on the polymer surface. However, no matter what the cause and source of the background is, background track density is determined precisely for each study and application to be considered in the minimum detection limit of the detector [22]. This is in particular important for SSNTDs processed by ECE for low track densities in applications such as environmental sample measurements, radon and its progeny measurements, or neutron dosimetry.

The main objective of this work is to obtain the sensitivity (V) and the critical angle (θ_c) via the bulk etch rate (V_B) and track etch rate (V_T) measurements for normal incidence alpha particles in the irradiation chamber under different air pressure and at different alpha energies (1.0 to 5.0 MeV). The etching efficiency (η) of a detector was then determined from (θ_c) measurements. In addition, studying alpha particles absorption through a set of experiments in which the rate of energy loss (*dE/dx*) as a function of pressure values inside the irradiation chamber has been done. A numerical approach has been introduced in order to calculate the rate of energy loss data as a function of pressure in and compared with the measured values.

Materials and Methodology

Experimental

Sheets of CR-39 (TASTRACK) which are a $C_{12}H_{18}O_7$ polymer with a density of 1.3 g/cm^3 and a thickness of 250 μm were used. CR-39 sheets were cut into pieces with an area of 1.0 × 1.0 cm^2. A group of CR-39 detectors were exposed to thin open ^{252}Cf disk source as an alpha fission fragment and fast neutrons source of activity 9.65×10^{-3} μCi and surface area of 19.64 mm^2. Another group was exposed to thin ^{241}Am disk source that emit alpha with energy of 5.5 MeV and activity 0.924 μCi. Using a variable length of air column, energies from 1 to 5 MeV were used. All samples were exposed to normal incidence particles in irradiation chamber. Inside the chamber, alpha energy could be varied via either the adjustment of the source-to-detector distance (x) at fixed pressure (P) or by varying the air pressure at fixed distance (see figure 1). Figure 1 shows a schematic diagram for irradiation chamber was used.

For etching process, all samples are etched using our new etching solution (8 ml of 10N NaOH+ 1 ml CH_3OH) at 60^{o}C for 45 min [23]. All etched samples were held at the same depth in the etchant solution. After etching the samples were immersed in running water for suitable time interval to remove all etchant products from the surfaces. Finally, the samples were carefully dried and then used for analysis. For estimation of track diameter an optical microscope fitted with a magnification of 400 X was used. The microscope was connected with a web digital camera to capture the sample image from microscope and save it in P.C unit, software program (INFINITY ANALYZE software) was used to analyze the tracks after calibration.

The bulk etch rate V_B is the rate of removing of the undamaged surface of the detector due to the chemical reaction between the etching solution and the detector material, and it can be determined using the following equation [24]:

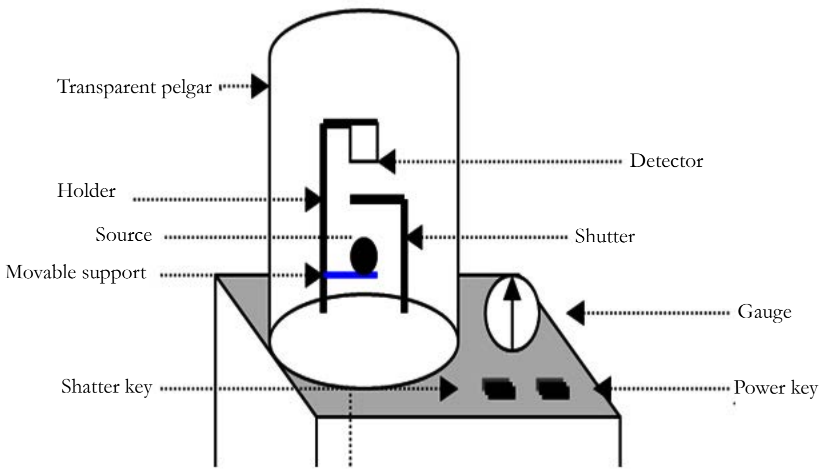
$$V_B = \frac{D_{ff}}{2t_e} \text{ ----- (1)}$$

where D_{ff} is the track diameter of fission fragment projectile that bombarded the detector and t_e is the etching duration. Another method is used to determine the bulk etch rate V_B, based on the detector mass decrement [25].

$$V_B = \frac{\Delta M}{2St\rho} \text{ ----- (2)}$$

Where, ΔM is mass difference, S is the etched surface area, ρ is the density of the detector, and t is the etching time.

Figure 1. A Schematic Diagram for Irradiation Chamber.



The sensitivity (V) of an etched track detector to alpha particle is a strong function of detector material properties, particle charge, energy and direction of the incident ions. The sensitivity (V) of the detector has been determined from the following equation [26].

$$V = \frac{V_T}{V_B} = \frac{4V_B^2 t^2 + D^2}{4V_B^2 t^2 - D^2} \quad \text{----- (3)}$$

where V_T is the track etching rate, D is the track diameter, and t is the etching time. The relation between V_T and D takes into account the removal of a detector layer h = $V_B t$ and bulk etching rate.

The critical angle of etching (θ_c) represents the minimum angle to the detector surface that a track canmake in order to be revealed by etching, and it can be determined by equation [26]:

$$\sin\theta_c = \frac{1}{V} = \frac{V_B}{V_T} \quad \text{---- (4)}$$

The etching efficiency (η) of a detector is defined as the proportion of tracks etched out expressed as a fraction of particles actually incident on the detector surface. The etching efficiency (η) can be measured using the formula[27]:

$$\eta = 1 - \sin\theta_c \quad \text{---- (5)}$$

Methodology

The range of alpha particle in any medium depends on its density. Semi empirical formulas have been developed for giving the range as a function of particle kinetic energy. For alpha particles, the range in air at normal temperature and pressure is given by the following relations [28, 29]:

$$Range(mm) = \exp\left(1.61\sqrt{T\,MeV}\right) \qquad 1 < T \le 4MeV \quad \text{----(6)}$$

$$Range(mm) = \left(0.05T + 2.85\right)T^{\frac{3}{2}}\,(MeV) \qquad 4 \le T \le 15\ MeV \quad \text{----(7)}$$

where T is the kinetic energy of the particle in (MeV).

Another an empirical relation between the range (cm) of alpha particle in air and its energy (MeV) can derive from Eqs. (6 and 7) [30]:

$$Range = 0.32E^{1.5} \quad \text{------ (8)}$$

Further, the value of energy as a function of range can be written as:

$$E = 2.1375 Range^{0.6667} \quad \text{----- (9)}$$

Using above relation, the residual energy at distance x from the source can be now computed as:

$$RE = 2.1375(Range - x)^{0.6667} \quad \text{----- (10)}$$

The energy as well as the residual energy of alpha particles can be obtained by using one of two alternative ways: by changing the density of the medium between the source and the detector at a fixed distance or by changing the source-to-detector distance at a fixed medium density. The relationship between the density of the air and its pressure, at a room temperature of 25°C, is given below:

$$\rho_{air} = \frac{pressure}{R_{air}\,(273.16 + 25)} \quad \text{----- (11)}$$

where R_{air} = 287 J/kg = the gas constant for air.

Results and discussion

Bulk etch rate V_B measuring

The bulk etch rate of CR-39 was determined in the present work using our new chemical etchant solution (8 ml of 10N NaOH+ 1 ml CH_3OH) at 60°C for 45 min etching time [23]. VB for CR-39 was measured by two methods; firstly from fission and alpha track diameters, then applying in Eq. (1). Secondly, using the detector

Figure 2a. Variation of alpha particle track diameter with energy at different removed layer ((h= 2.025, 2.70, 3.375, and 4.050 mm)).

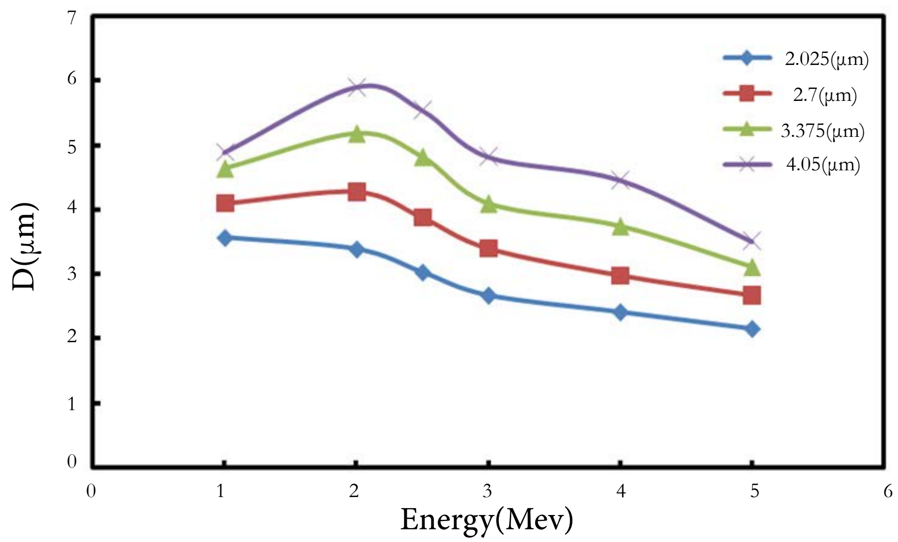
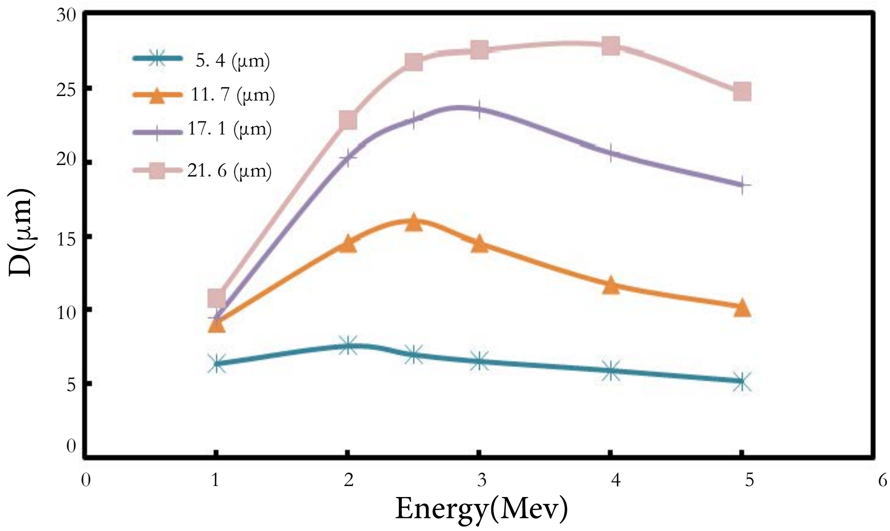


Figure 2b. Variation of alpha particle track diameter with energy at different removed layer (h= 5.40, 11.70, 17.10, and 21.60 mm)



mass decrement using Eq. (2). The value of bulk etching rate is the same in both methods and equal to 2.73 μmh^{-1}, this result is in agreement with our previous work [23].

Figures 2a and b depict the relationship between the energy of alpha particle and the etch pit diameter at different removed layer (μm). They show that under our optimum etching conditions, when the removed layer increases up to h=2.0 μm, the track diameter of 1.0 MeV alpha particles started to increase relative to 2.0 MeV alpha particles. This result may be refers to exceed the path of 1.0 MeV alpha particles after this point the value of damage inside the material started to decrease and the rate by which the track diameter was increasing started to decrease.

Sensitivity, critical angle, and etching efficiency of CR-39 detector determination

The sensitivity was determined using Eq. (3), it obtained by measuring the track diameter and the removed layer. Figure 3 demonstrates the variation of the sensitivity of the detector with alpha particle at the new etching conditions. It is shows that the sensitivity decreases with increasing alpha energy from 1.0 to 5.0 MeV.

Critical angle of etching (θc) was determined using Eq. (4); it was obtained by measuring the track diameter and the removed layer. The etching efficiency of CR-39 detector (η) was determined from critical angle measurements using Eq. (5). Figure 4 depicts the variation of critical angle and etching efficiency as a function of alpha particle energy. The results show that the values of the critical angle increase with increasing the energy of incident alpha particles, while the etching efficiency of CR-39 detector decreases with increasing alpha particle energy from 1 to 5 MeV. This implies that both of the critical angle and the etching efficiency strongly depends on alpha particle energy.

Rate of energy loss dE/dX determination

In the irradiation chamber, the air molecules were used as a stopping medium for the incident projectiles alpha particles. It was taken into consideration that alphas energy can be varied via either the adjustment of the source-to-detector distance (x) at fixed pressure (P) or by varying the air pressure at fixed distance. A group of curves represent the relation between the range of alpha particles in (cm) and their energy in (MeV) at various values of air pressure (e.g., 10, 20, 73.5, 220, 294, 400, 500 and 760 torr, respectively) is illustrated in figure 5. It is clear that the range increases with increasing of the energy at a fixed pressure; meanwhile the range increases with decreasing of the pressure at fixed energy.

Figure 6 illustrates the relation between alpha particles energy in (MeV) and the pressure in (torr) inside the irradiation chamber at fixed distances x in (cm) (x=1 to 10 cm). The curves indicate that the energy of alpha particle decreases with increasing the pressure (P) at fixed distance. In addition, the slope of each curve decreases with decreasing of the pressure. This means that the smallest energy loss occurred with decreasing of the pressure at constant distance. Must be reminded in this point that the dominant interaction mechanisms between alpha particles and the molecules of the medium through which they pass are mainly the excitation and ionization processes caused along their paths. Accordingly, energy loss rate of alphas depends mainly on the density of the stopping medium or the pressure inside the chamber as long as the incident energy is fixed.

The dependency of the energy loss rate (dE/dx) on the pressure has been evaluated from the data of figure 6. The corresponding theoretical values of (dE/dx) are calculated by solving Eqs. (8 and 11) using SRIM-2003.26 and Matlab computer programs [31, 32]. Comparison between the measured (dots) and calculated (solid curve) values of energy loss (dE/dx) as a function of pressure (P) is shown in figure 7. It is clear that a good agreement between the measured and the calculated values is obtained. The deviations observed between the experimental and the theoretical data may be attributed to the stopping power given by SRIM-2003.26 program might be too high. This procedure can also be used in alpha range evaluation in the stopping medium as a function of pressureinside the chamber which is aimed to be done in another article using different gases.

Figure 3. Variation of sensitivity of the detector with alpha particle energy.

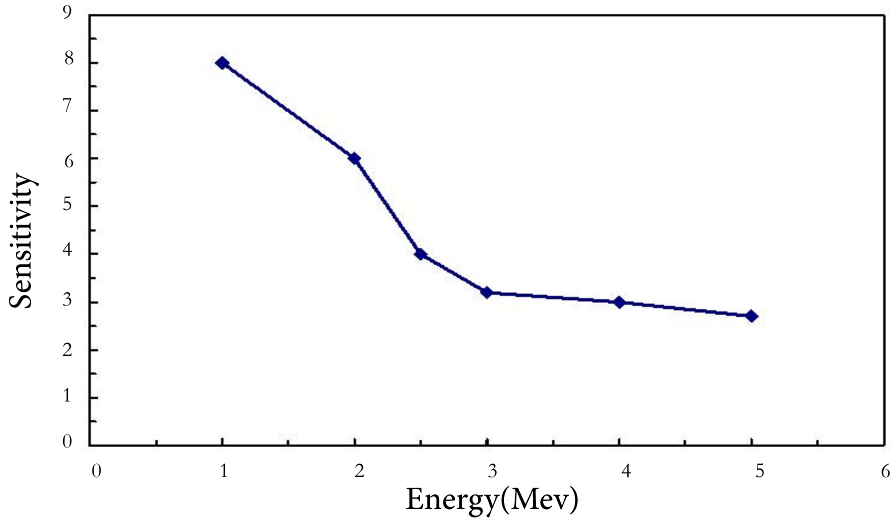


Figure 4. Variation of critical angle and etching efficiency as a function of alpha particle energy.

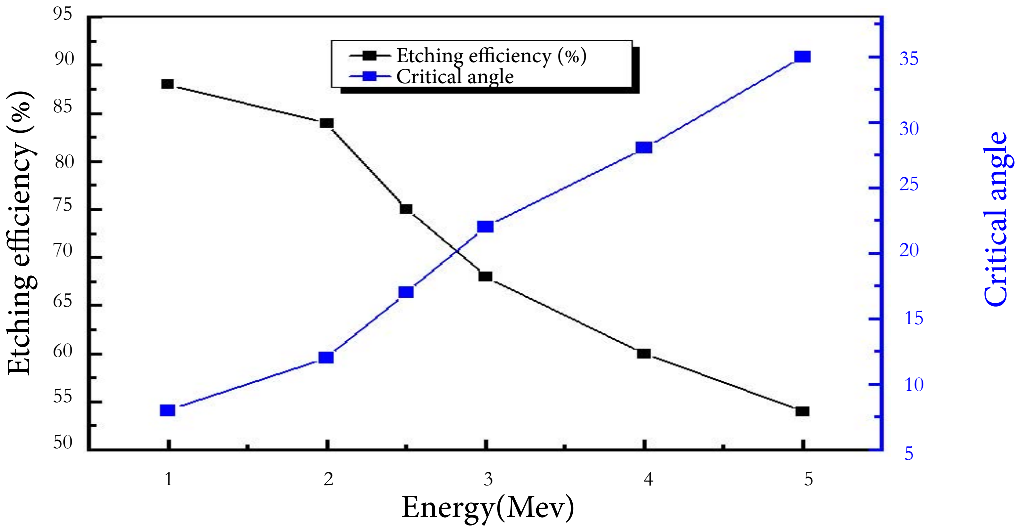


Figure 5. Variation of the range of alpha particle in (cm) as a function of the energy in (MeV) at different pressure in (torr).

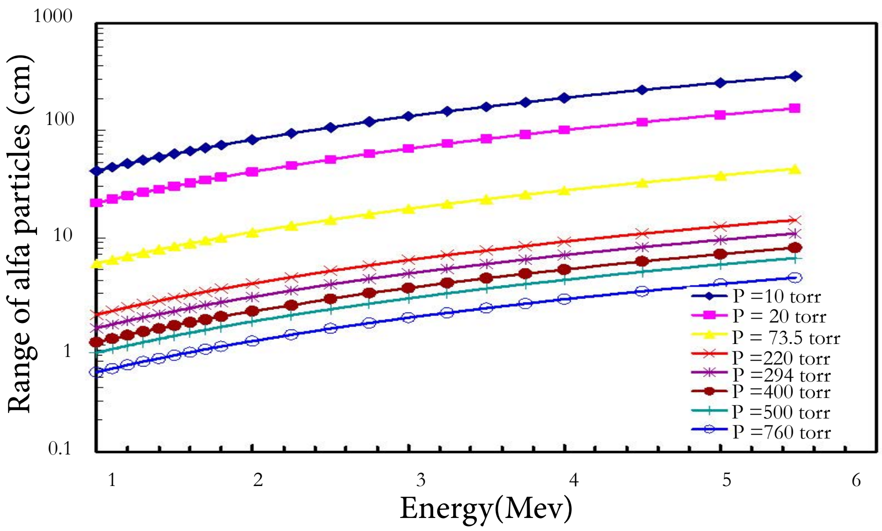


Figure 6. The relation between alpha particle energy in (MeV) and pressure in (torr) inside the irradiation chamber at different distances x in (cm).

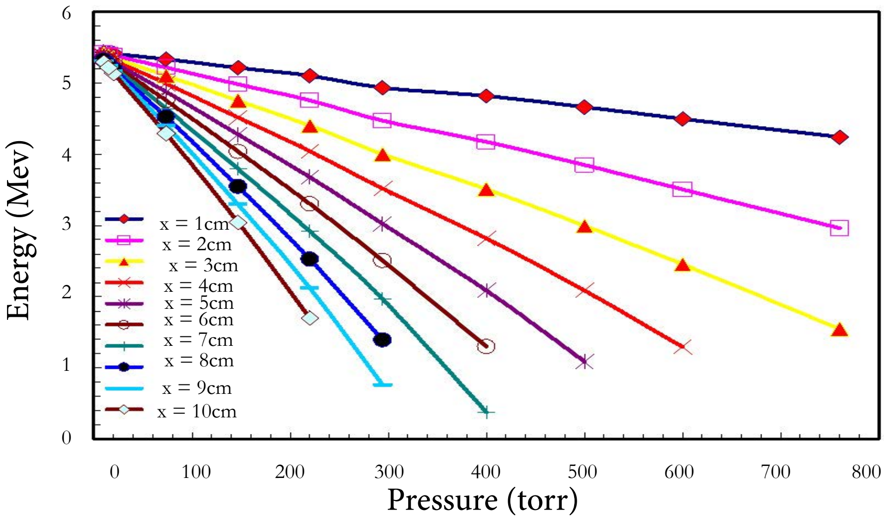


Figure 7. Comparison between the measured (point) and calculated (solid curves) values of energy loss (dE/dx) as a function of pressure (P).

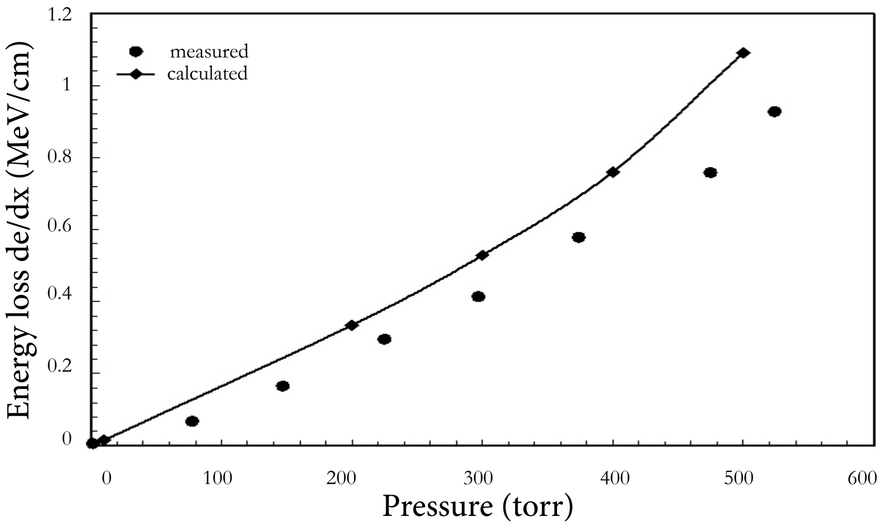


Figure 8a. The variation of the measured (dots) and calculated (solid curves) values of energy with the pressure (P) at distances (5, 8, and 11 cm).

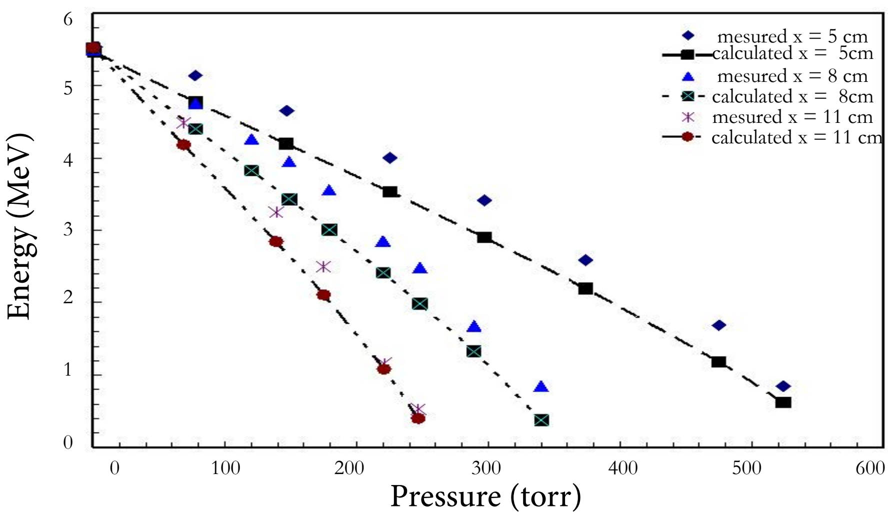


Figure 8b. The variation of the measured (dots) and calculated (solid curves) values of energy with the pressure (P) at distances (7 and 10 cm).

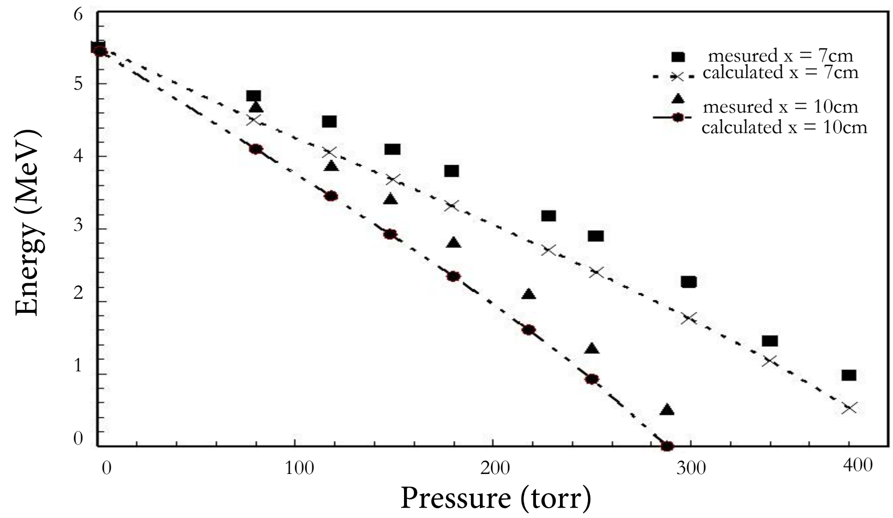
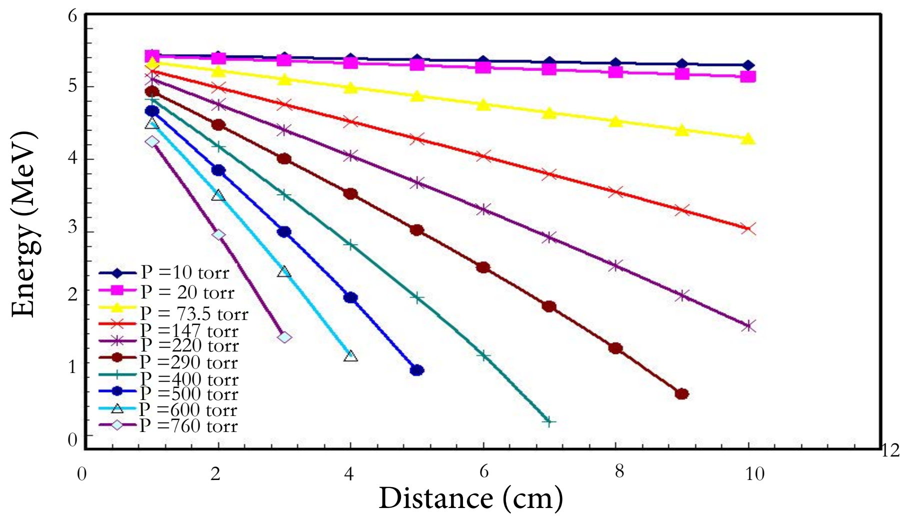


Figure 9. The dependence of alpha particles energy in (MeV) with the distance in (cm) at different pressure (P).



The dependency of the energy as well as the energy loss rate (dE/dx) on the pressure has been shown in figure 8a and 8b. Figure 8a illustrates the dependency of alpha particles energy in (MeV) on the pressure in (torr) at fixed distances (x= 5, 8, and 11 cm), while figure 8b shows the same relation at different fixed distances (x=7 and 10 cm). Both mentioned figures reveal a good agreement between the calculated values and the measured ones. The deviations observed between the measured and calculated values may be attributed to different causes, as follows: the effect of the humidity upon the range of alpha particle, since the density of air decrease with increasing the humidity; the systematic error during experimental procedures. Anyway, the obtained results are also in good agreement with observations made in [33].

The dependence of alpha particles energy in (MeV) with the distance in (cm) at different pressure (P=10, 20, 73.5, 147, 220, 290, 400, 500, 600 and 760 torr, respectively) is plotted in figure 9. The results show that the energy of alpha particles decreases with increasing of the distance of irradiation inside the chamber. Furthermore, the curves given in figure 9 could be used as calibration curves for the determination of the energy of alpha particles. It must be mentioned that, after determination of alphas energy by using the calibration curves, one has to make precise adjustment both on the pressure and the distance value to obtain the desired value of energy.

Conclusion

Characteristics studies for alpha particle absorption and normal incidence track parameters in CR-39 plastic detectors inside irradiation chamber was investigated. A set of experiments have been carried out in order to energy-range data used to produce energy-distance curves for alpha particles in different air pressure. From fission and alpha track diameters, the value of bulk etching rate was measured. The sensitivity was found to vary with alpha energy from 1.0 to 5.0 MeV. Both the critical angle (θ_c) and etching efficiency (η) of CR-39 detectors have been determined. The rate of energy loss (dE/dx) has been measured experimentally and calculated using a numerical approach. A comparison between the measured results and calculated values is given and a good agreement has been found. The variation of the measured and calculated values of energy with the pressure (P) at different distances inside the irradiation chamber was studied. Results can be successfully applicable in alpha autoradiography studies and detector efficiency determination for track registration in CR-39 plastic detectors at different air pressure.

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References

[1]. Price PB (2005) Science and technology with nuclear tracks in solids. Radiat Meas. 40: 146–159.
[2]. Price PB (2008) Recent applications of nuclear tracks in solids. Radiat Meas. 43: S13–S25.
[3]. Hussein A, Higazy AA, Ewaida MA (1989) Gamma-ray dosimetery using zinc phosphate glasses. J Mater Sci. 24(2): 457-461.
[4]. El-Hawary MM, Hussein A, El-Rahmany A, Ammar AA, El-Sersy AR (1995) Construction of a charged particles irradiation chamber for the use with plastic detectors. Nucl Instr Meth B. 103(1): 94-98.
[5]. Ellis WR (1986) Advantages of solid state nuclear track detectors for the assessment of alpha emitters and fission elements. Nucl Tracks and Radiat Meas. 12(1): 773-780.
[6]. Singh NP, Singh S, Virk HS (1988a) Activation energy of track annealing in minerals as a function of interatomic spacing. Nucl Tracks Radiat Meas. 15(1-4): 235-238.
[7]. Singh J, Singh S, Virk HS (1988b) Etching studies of CR-39 plastic track detectors, Nucl, Tracks, Radiat, Meas. 15(1-4): 187-190.
[8]. Suzuki T, Tomura K (1990) Neutron dosimetery for fissiondating at irradiation facilities TRIGA type TRIGA reactors. Nucl Tracks Radiat Meas. 17(3): 223-226.
[9]. Todd P (1992) An analysis of particle track effects on solid mammalian tissues. Nucl Tracks Radiat Meas. 20(1): 241-246.
[10]. Hussein A (1994) Determination of uranium and thorium concentration in some Egyptian rock samples. J Radiat Nucl Chem. 188(4): 255-265.
[11]. Abou El-Khier AA, El-Shahawy M, Hussein A, El-Samman H, El-Hofy M (1993a) The use of lexan polycarbonate detector in alpha particles and neutron dosimetery. Polymer Degradation and Stability. 39(2): 169-172.
[12]. Abou El-Khier AA (1993b) Measurements of alpha-activity concentration in Egyptian geological samples using CR-39. Nucl Tracks Radiat Meas. 21(2): 291-293.
[13]. O'Sullivan D, Thompson A (1980) The observation of a sensitivity dependence on temperature during registration in solid state nuclear track detectors. Nucl Tracks. 4(4): 271–276.
[14]. Kodaira S, Yasuda N, Tawara H, Ogura K, Doke T, et al., (2009) Temperature and pressure conditions for the appropriate performance of charge and mass resolutions in balloon-borne CR-39 track detector for the heavy cosmic rays. Nucl Instrum MethodsPhys Res. 267(10): 1817–1822.
[15]. Awad EM, Soliman AA, Rammah YS (2007) Alpha particle spectroscopy for CR-39 detector utilizing matrix of energy equations. Phys Lett A. 369(5): 359–366.
[16]. Awad EM, Soliman AA, El-Samman HM, Arafa WM, Rammah YS (2008) Alpha spectroscopy in CR-39 SSNTDs using energy simulation and matrix of energy equations for open field studies. Phys Lett A. 372(17): 2959–2966.
[17]. Bondarenko OA, Salmon PL, HenshawDL, Fews AP, RossAN (1996) Alpha-particle spectroscopy with TASTRAK (CR-39 type) plastic, and its application to the measurement of hot particles. Nucl Instrum Methods A. 369(2): 582-587.
[18]. Enge W (1980) Introduction to plastic nuclear track detectors. Nucl Tracks. 4(4): 283-308.
[19]. Soharbi M, Khajein EK (1981) Some electrochemical etching studies on the registration of alpha particles tracks in polycarbonate. Nucl Instrum Methods. 185(1): 407-413.
[20]. Ziegler JF, Biersack JP, Littmark U (2003) The Stopping and Range of Ions in Solids. Pergamon Press, New York. 93-109
[21]. El-Hawary MM, Mansy M, Hussein A, Ammar AA, El-Sersy AR (1999) Alpha particle and inclined incidence track parameters evaluation in plastic detectors. Radiat Phys Chem. 54(6): 547-550.
[22]. Sohrabi M, Khodadadi F, Hakimi A (2015) Broadening alpha registration energy range of 250 mm polycarbonate detectors by a single 50 Hz-HV ECE method. Radiat Meas. 75: 39-44.
[23]. Ashry HA, Abdalla AM, Rammah YS, Eisa M, Ashraf O (2014) The use of CH3OH additive to NaOH for etching alpha particle tracks in a CR-39 plastic nuclear track detector. Rad Phys Chem. 101: 41-45.
[24]. Nikezic D, Yu KN (2004) Formation and growth of tracks in nuclear track materials. Materials Science and Engineering. 46(3): 51-123.
[25]. Kocsis ZS, Dwivedi KK, Brandt R (1997) Studies on the track formation mechanism of the heavy ions in CR-39. Radiat Meas. 28(1): 177-180.
[26]. Durrani SA, Bull RK (1987) Solid state nuclear track detection: principles and applications. Pergamon Press, Oxford, England.
[27]. Yu KN, Ng MFM, Nikezic D (2005) Measuring depths of sub-micron tracks in a CR-39 detector from replicas using atomic force microscopy. Radiat Meas. 40(2): 380 – 383.
[28]. Nichol T (1995) Measurement and detection of radiation. (3rd Edn), Taylor & Francis. 2: 381-433.
[29]. Ahlen SP (1980) Theoretical and experimental aspects of the energy-loss of relativistic heavily ionizing particles. Rev Mod Phys. 52 (1): 121–173.
[30]. Bataller G, Girard de Vasson O (1989) Use of Nuclear Track Detector to Measure Very Low Alpha Radioactivity in Urine. Radiat Protect Dosimetry. 26 (1/4): 217-221.
[31]. Rammah YS, Abdalla AM, Ashry HA (2013) New approach for alpha particle residual energy calibration. J Nucl Res Dev. 6: 49-54.
[32]. SRIM-2003.26 program, 2001.
[33]. KN Yu, CWY Yip, D Nikezic, JPY Ho, VSY Koo (2003) Comparison among alpha-particle energy losses in air obtained from data of SRIM, ICRU and experiments. App. Rad. and Iso. 59(5): 363-366.