The Impact of Laser on the Activation Energy and Sensitivity of CR-39 Detector

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Abstract

The influence of laser radiation on bulk and etch rates, and as well detector sensitivity, before and after being irradiated with alpha particles at 5 MeV emitted from a 241Am source, are examined at different etching temperatures (65, 67, 69, 71, 73, 75, 77, 79 ,81, 83, and 85)°C in this paper. A laser source with a wavelength of 480 nm and a pulse energy of 50 mJ/pulse at a repetition rate of 9 Hz was used to investigate the activation energy of a CR-39 polymer. The rates of bulk etch, Vb, and track etch, Vt, slightly increase with laser radiation. Whereas sensitivity decreases as temperature increases, besides, alpha-laser samples have quite better sensitivity than other samples. The activation energies of the bulk etch rates, Eb, are equivalent to 0.94 ± 0.07, 0.88 ± 0.05, and 0.95 ± 0.06 eV for laser-alpha, alpha-laser, and no laser samples, respectively. While, the activation energies associated with track etch rate, Et, for the CR-39 samples under study are 0.86 ± 0.04, 0.77 ± 0.03, and 0.76 ± 0.03 eV. The results manifest that laser exposure has a slight influence on activation energies of bulk etch rate within experimental uncertainties of the CR-39 samples. Additionally, the CR-39 set of laser-alpha samples reveals that Et is increased based on the cross-linking process. The increase in Et relates to hardening of the detector material, which has several uses, specifically in radiation detection.

Key Words: CR-39 Detector, Sensitivity, Activation Energy, Alpha Particles; Temperature.

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Introduction

Polymeric materials are sensitive to irradiation, and their characteristics may be changed by presenting them to a variety of ions and radiation, such as gamma rays, charged particles, and heavy ions. In general, a track's shape and size are determined by the ion's electric charge and velocity, and the material's stopping power. The CR-39 polymer is frequently utilized in space research, nuclear physics, and nuclear particle detection experiments (Séguin et al. 2003; Lipson et al. 2000). Furthermore, if the particles release enough energy throughout the interaction process, the CR-39 can identify multiple particles with 100% accuracy. An etching process is necessary to analyze the properties of the track parameters. The etching process is regulated by a number of factors, including etching duration, temperature, and NaOH solution concentration, most of which vary from experiment to experiment, resulting in varying track characteristics even for the same etching duration (Mishra et al. 2005; Ishigure, N., & Matsuoka 1984). Low linear energy transfer radiation has been reported to influence the registration properties of solid nuclear track detectors (Durrani and Abu-Jarad 1995; Jaleh et al. 2004; Benton, E.V., & Henke 1968). Electromagnetic rays usually cause changes in the detector material. Several factors influence these changes, including detector formation, irradiation time, type of radiation, irradiation condition, and etching process.

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Many authors have conducted studies to better understand the effects of radiation on polymer properties (Fleischer, Price, and Woods 1969; Crawford, W.T., DeSorbo, W., & Humphrey 1968; Khayrat and Durrani 1995; Kassim and Alkhayat 2021). Cross-linking scission, and emission of atoms and molecules occurs when radiation interacts with polymeric solid-state nuclear track detectors, damaging the detector's initial structure. Their properties, such as density conductivity, optical absorption, and molecular-weight distribution, vary as a result of this. The efficiency of these modifications in the polymer is determined by its structure. Bond secession and cross-linking are two significant processes that occur when low linear energy transfer radiation is used to irradiate the CR-39 detector (Davenas et al. 1990; Schiestel, Ensinger, and Wolf 1994). Bond secession causes surface degradation, which increases bulk and track etch rates, whereas cross-linking leads to surface hardening, which reduces bulk and track etch rates. The polymer becomes hardened when the probability of cross-linking reactions exceeds the probability of chain scission; otherwise, it will soften (Marletta 1990; Puglisi et al. 1987).

The effect of lasers on solid state nuclear track detectors is dependent on laser properties such as wavelength, repetition rate, and energy density, as well as detector properties such as density, thickness and other factors. The interaction of a laser with SSNTDs results in thermal changes in most cases. The impact of infrared and ultraviolet lasers on the CR-39 detector's characteristics has been investigated (Jaleh et al. 2004; Radwan 2001; Abu-Jarad et al. 1992; Dwaikat et al. 2007, 2008). The activation energy of the CR-39 polymer detector is the amount of energy necessary to initiate the reaction between the detector material and the etchant solution. Thus, the activation energy of the SSNTDs has been the subject of many studies (Radwan 2001; Awad and El-Samman 1999; Hussein, A., Shnishin, K., & Abou El Kheir 1993; Singh and Neerja 2007). The influence of laser irradiation on the activation energies of the bulk and track etch rates and sensitivity on the CR-39 plastic detector have been investigated in this study.

Experimental Executions

1. Irradiation Procedure and Materials

CR-39 plastic detector samples of typical thickness (1400 μm) with geometric size (2 cm x 2 cm) from Page Moulding Worcetershire, UK were used in this research. Thirty-three detectors were divided into three groups, each of eleven samples. The first group (no laser) was exposed to alpha particles using only a ^{241}Am source with activity of 37 kBq. The second group (alpha-laser) was pre-exposed to alpha before being treated with a 480 nm laser pulsed at a rate of 9 Hz with a pulse energy of 50 mJ/pulse. The third group (laser-alpha) was pre-exposed to laser before being exposed to alpha particles in the same way as the earlier group. Individual samples were subjected to a maximum laser fluence of 10 J/cm^2. All CR-39 samples were etched in a 6.25 N NaOH solution by water bath (Model: YCW-01) for 3.5 hours at varied temperatures extending from 65 to 85 degrees °C with 2 °C increment. The energy of 5 MeV alpha particles was employed to expose the CR-39 samples after adjusting the distance between the CR-39 detector and the ^{241}Am source in the open air.

2. Track Diameter Measurements

After the etching process, the CR-39 detectors are cleaned carefully and allowed to dry in open places. A high-resolution digital camera (MDCE-5A) attached to a 1000x magnification optical microscope was performed to measure the sizes of alpha particles in all of the samples. The alpha track diameters of each sample were measured several times to obtain the average values. In this study, an estimated uncertainty of roughly 4% was recorded. The residual energy of the alpha particle in CR-39, simulated by SRIM (Ziegler, Ziegler, and Biersack 2010), is shown in Fig.(1-a). Figure (1-b) further illustrates the simulation process of the average alpha particle fluence at energy 5 MeV in the CR-39 detector using MCNP6 software (Werner et al. 2018). The green lines reflect the alpha particle's small energy dissipation and secondary emissions in the detector material, while the red line represents the track of the alpha particle when it stops. The stopping length of alpha particles is around 27 μm as shown in Fig. 1.

3. Bulk and Track Etching Rate Measurements

The thickness measurement technique (Torrelles et al. 1988) was utilized to determine the bulk etch rate, Vb, by measuring the thickness of the CR-39 detector before and after etching time as follows (Durrani, S. A., & Bull, n.d.):

$$V_b = \frac{\Delta h}{2t}, \qquad (1)$$

where Δh is the removal thickness layer, and t denotes the etching duration expressed in hours.

While the track etch rate, Vt, was determined using the following equation (Mheemeed, Hussein, and Kheder 2013):

$$V_t = \frac{4V_b^3 t^2 + V_b D^2}{4V_b^2 t^2 - D^2} \qquad (2)$$

here, the diameter of a circular track (in μm) is symbolized by D.

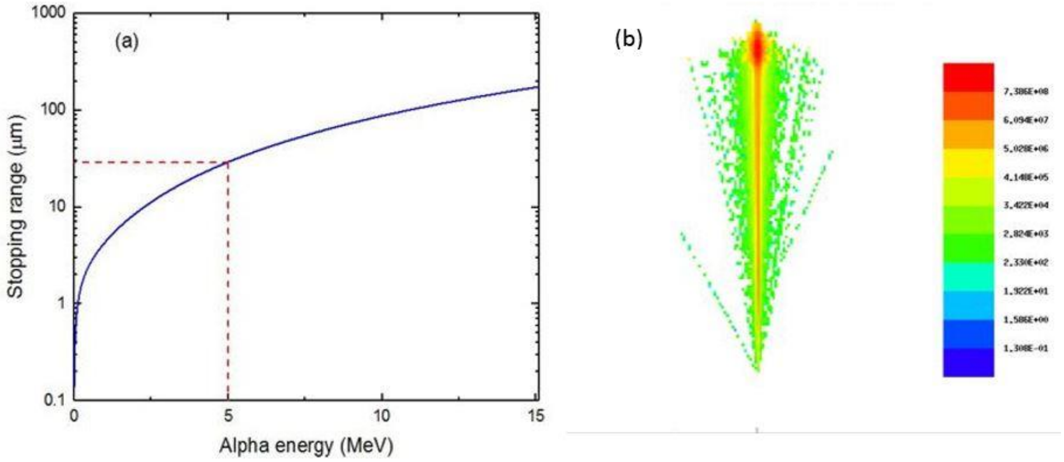

Figure 1. Alpha particle stopping process in the CR-39 material. (a). The alpha particle's energy range, (b). The average track of alpha path

Results and Discussion

1. Alpha Track Diameters

Figure 2 depicts the etching temperatures as a function of the sizes of shapes created by alpha particles released from a 241Am source. It is obvious that the diameter increases as the temperature increases. Furthermore, at higher temperatures, the difference in track diameters is noticeable, and exposed samples have a larger diameter than pristine samples. The microscopic images of the circular track diameters at different etching temperatures are presented in Fig.3.

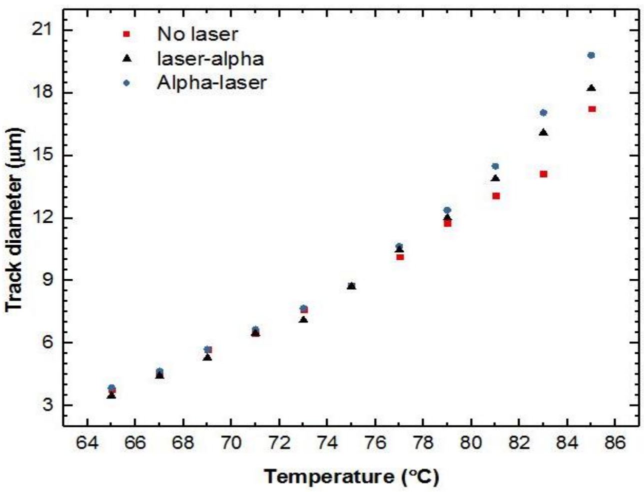

Figure 2. The diameter of the circular track is dependent on the temperature of the NaOH solution. The experimental data for no laser, laser-alpha, and alpha-laser samples are represented by solid red squares, blue circles, and black triangles, respectively.

2. Measurement of Activation Energy

The activation energies for the track etch rates, Et is determined using Arrhenius equation as follow:

$$V_t = A\, e^{-E_t/KT} \qquad (3)$$

where A is a fitting parameter, K is a Boltzmann constant, and T is a temperature (in K). An equivalent equation is used for Eb. The activation energies corresponding to bulk and track etch rates were estimated by plotting the natural logarithm of bulk and track etch rates and temperature in Figs 4 and 5, respectively. For each set of alpha, alpha-laser, and laser-alpha CR-39 samples, the slopes of the three linear plots were used to calculate the activation energies for bulk Eb and track Et etch rates. The calculated results of the activation energy, Eb indicate that there is only a small difference between exposed and unexposed samples. However, the activation energy, Et, for the laser-alpha sample is higher than for the alpha-laser and no laser samples. The increase in amount of Et can be directly linked to increase cross-linking in the CR-39 detector, which causes the detector surface to harden. Moreover, the presence of atmospheric oxygen may cause an increase in etching parameters because oxygen interacts with free radicals created and causes bond breakdown to be stabilized through oxidation (Heins and Enge 1986). Furthermore, the Et calculated values for all used samples were mostly observed to be decreased than the Eb values. It further clearly shows that the etch rate on the track is higher than the bulk etch rate. The activation energy values that correspond to Eb and Et are listed in Table1. Eb and Et have an average value of 0.92 ± 0.03 eV and 0.77 ± 0.02 eV, respectively.

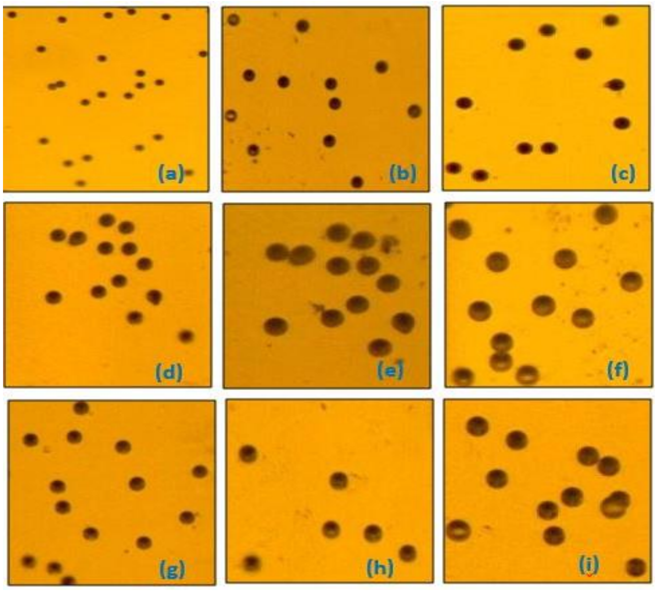

Figure 3. Influence of laser exposure on the track diameter of alpha particles in CR-39 for the three sample groups (a, b, c) no-laser (d, e, f) alpha-laser, and (g, h, i) laser-alpha samples, at 69, 73, and 77 °C (from left to right) respectively

Table 1. Values of activation energy

Samples	Eb, eV	Et, eV
No laser	0.95 ± 0.06	0.76 ± 0.03
Alpha-laser	0.88 ± 0.05	0.77 ± 0.03
Laser-alpha	0.94 ± 0.07	0.86 ± 0.04

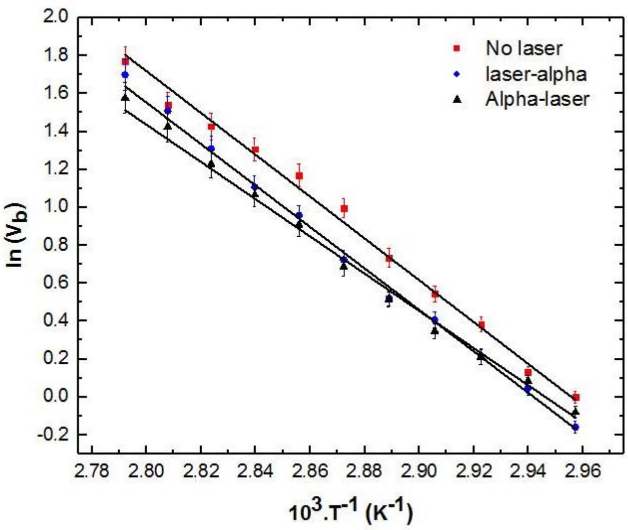

Figure 4. ln(Vb) versus 10^3 T^{-1} at various etching temperatures. The black lines point out the best fits

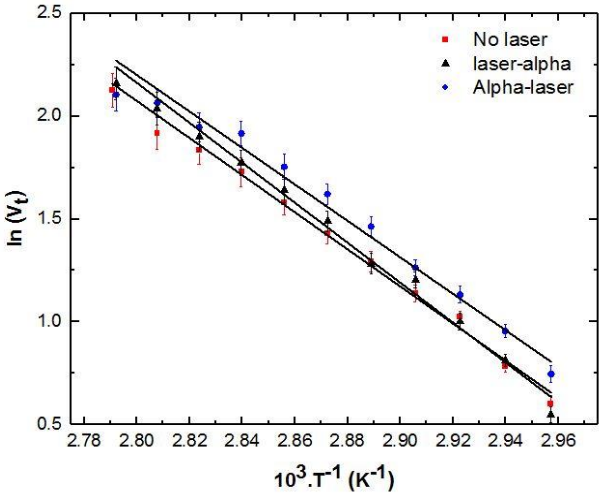

Figure 5. ln(Vt) versus 10^3 T^{-1} at various etching temperatures

3. Detector Sensitivity

The sensitivity, V, is obtained through the ratio between Vt and Vb (V=Vt/Vb). The sensitivity of the CR-39 detector for no laser, alpha-laser and laser-alpha samples are displayed in Fig.6. The sensitivity of alpha-laser detector samples is higher than of laser-alpha and no laser samples, and that peak was observed at 74 °C etching parameter. As a consequence, this temperature can be considered the efficient sensitivity temperature for the alpha-laser sample. If, the temperatures longer than 74 °C, the sensitivity of the detector decreases due to increased hardness of the detector surface, which is also related to an increase in Vb particularly compared to Vt. It is important to observe that the optimum etching temperature is 72 and 69°C for laser-alpha and no laser, respectively, as illustrated in Fig. 6. In addition to laser exposure, increasing the temperature of NaOH solutions causes a decrease in sensitivity, particularly at temperatures above 74°C, which may have maximized or minimized the effect of the laser on the etching characteristic of the CR-39 detectors. In fact, the CR-39 detector sensitivity is decreased with alpha energies. Fig.6 shows that the laser-alpha curve does not decline considerably, therefore it can be used to detect high energies. However, it is recommended that the CR-39 detector be exposed to the laser following the irradiation process for low energy particles.

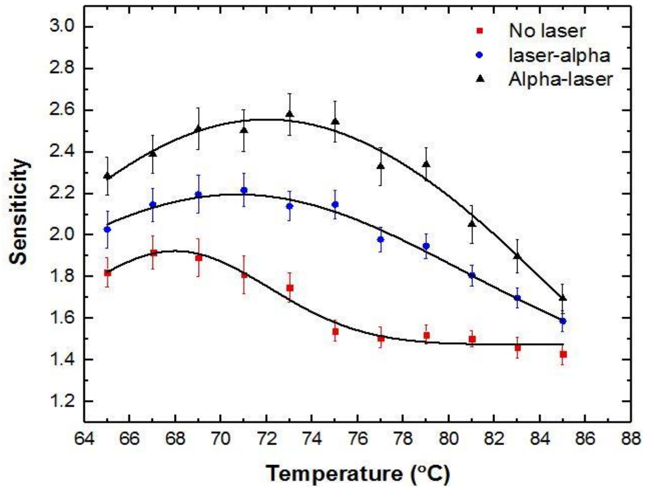

Figure 6. Sensitivity of CR-39 samples as a function of temperature

Conclusion

This study shows that laser exposure has a small effect on the activation energy of bulk etch rate, Eb. This indicates that Eb is a detector bulk material property. The substantial increase in Et for laser-alpha samples compared to alpha-laser and no laser samples suggests that cross-linking occurs in CR-39 materials. This process has many applications, including detection of a high-energy ion without increasing detector thickness by exposing the CR-39 detector to a laser before irradiating into to ions. Whereas sensitivity decreases with increasing temperature, alpha-laser samples have significantly higher sensitivity than other samples.

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