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The Impact of Molarity of Two Different Chemical Solutions on the Etching Rates of Nuclear Track Detector CR-39.

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Abstract

Solid-state nuclear track detectors such as CR-39 are used in the detection of charged particles and heavy ions. In this paper, the effect of two types of chemical etching solutions on the etching properties of the detector CR-39 of 400μm thickness was studied. The etching properties involved the calculation of the etching parameters which are the bulk and track etch rates (V_B and V_T) respectively as well as the etch rate ratio (V), and then comparing them for the two types of etching solution. We used two sets of detectors each piece of dimensions (1×1)cm^2. The detectors were irradiated with alpha particles of energy (2, 3, 4, 5) MeV using a ^{241}Am source to obtain tracks of alpha particles in the detector. To reveal the latent tracks, the irradiated detectors were treated with aqueous KOH and NaOH solutions. Both groups of irradiated detectors were etched under the same conditions of different molarities ranged from $(3-11)$ N at temperature $(70 \pm 1)^{\circ}$C for both solutions for time periods ranging from (3) h. The V_B was measured by the method of removal thickness difference from the detector surface by etching for the specified periods. By measuring the diameters of the tracks and the diameter growth rates (V_D) for the specified intervals, the V_T and V were measured in correlation with the V_B for the both types of the solution used. By comparing the results, it was appeared that the etching rates with NaOH solution is greater than that etched with KOH for V_B and V_T.

1. Introduction:

The use of solid-state nuclear detectors (SSNTDs) in radiation research and dosimetric applications for radiation protection has a lot of potential, as they can be used to detect charged particles, heavy ions and neutrons through the damage caused (also known as latent paths) along the paths of those particles in the detector. The formed tracks can be enlarged by treating the detector with a proper chemical solution to etch the damaged areas up to a micron scale to be observed by the ordinary optical microscope [1]. The CR-39 nuclear track detector is used to detect alpha particles, protons, fission by-products, and heavy ions. Since chemical etching grows etching tracks along ion trajectory in the material, it is widely used as a material target as well as to determine the cross-section [2]. When heavy charged particles pass through the nuclear track detectors, they lead to ionization of the atoms of the detection material [3], and thus produce damage region along its path in the material in the form of a latent track. The latent track can be revealed by chemical etching process using a suitable chemical solution, and then viewed with an ordinary optical microscope [4].

The chemical etching (CE) process is a necessary step for forming and showing the track The chemical etching can be performed, to reveal the latent tracks, using suitable alkaline chemical solutions such as KOH or NaOH, with concentra-

tions ranging from 3 to 11 N depending on the thickness of the detector for a few hours, the detectors where be etched by putting them in etchant solution in volumetric flask putted inside the water bath tank at a temperature of 70 °C. The interaction of the chemical solutions with the detector material leads to decompose the areas affected by the particles by more and faster rate than the undamaged regions [3], [5], [6] [7].

The track etching rate (V_T) along the impacted path towards the depth of the detector and the bulk etching rate (V_B), which is a constant for the detector at the used etching conditions, are the two main parameters that control the geometry of the track shape and its evolution with the etching advancement [8]. The values of V_B depend on the etching conditions such as the type of etching chemical solution, its temperature and concentration, etching time, as well as the type of the detector used. The V_B values can be measured either by irradiating the detector with charged particle or without irradiating it, (ie with or without tracks existing). In this study, we have used a detector irradiated with particle to measure the V_B [7], and calculated by using the removed layer thickness from the detector method. Also there are other methods used to measure the general excavation rate, including the impact length-diameter method, which also gives similar results [9].

The Track formation principle in the detector is based on the energy of the particles bombarding the detector. Low-energy particles penetrate short distances and quickly lose their energy within the detector material, creating trails. These tracks required short etching times to be revealed due to their proximity to the detector surface. Particles with higher energies reach longer distances in the detector, so the resulting tracks needs a longer etching time than the particles with lower energies to appear [7]. It is clear that the value of the etching rate V_T will be increased along the path as the energy increases.

The track shape has two phases, the first when $V_T > V_B$, which is called acute conical phase. The second is the over etched stage when $V_T = V_B$, where the etching process crosses the end of the damaged path in the detector towards the undamaged area. The change in track hole shape and geometry, the diameter (D) and length (L) of the track can be accurately measured using Track Profile Technology (TPT). The TPT has been used in many researches to identify a variety parameters of the etched track [10]. The etching rates are highly dependent on the etching rates, and the etch rate ratio V which are strongly related to the etching rates by the relationship $V = V_T/V_B$ [11].

The purpose of the paper is to investigate the impact of changing the etching molarity of two different chemical solutions, NaOH and KOH, on the bulk and track etching rates (V_T) and (V_B), and track etch ratio (V).

2. Experimental:

A CR−39 nuclear track detector of 400 μm thickness manufactured by (Track Analysis Systems Ltd (TASL), England), have been used. Alpha particles with an energies (2, 3, 4, 5) MeV from ^{241}Am source were used to irradiate the detector. Four groups each of five pieces of dimension (1×1) cm^2 of CR−39 were irradiated with alpha particles for 30 s.

The irradiated detector pieces were etched in a water bath with two types of chemical solutions of aqueous NaOH and KOH of different molarities (3, 5, 7, 9 and 11) N at a temperature $(70 \pm 1)^o$C for successive periods of time of (3 h). The diameters of the tracks for all selected times and molarities have been measured.

2.1 Calculations:

Alpha tracks in CR−39 were viewed, counted, and their diameters were measured using an optical microscope supplied with a digital camera and software (Scope Image). The following formula was used to determine the alpha particle energy that the detector irradiated with.

$$R_{air} = 0.322 {E_\alpha}^{3/2} \tag{1}$$

$$E_R = \left[\frac{R_{air} - d}{0.322}\right]^{2/3} \tag{2}$$

$$d = R_{air} - 0.322\ {E_R}^{3/2} \tag{3}$$

where R_{air} (cm) is the alpha particle's range in air , $E\alpha$is the alpha particle's energy, E_R is the residual energy between the source and the target (detector surface), d is the air distance (cm).

The bulk etch rate (V_B), track etch rate (V_T) and etch rate ratio (V) were all calculated to show the variation in values by using two different chemical etching solutions. The etching parameters were calculated according to the following relationships [7], [11] and [12].

The bulk etch rate is

$$V_B = \frac{1}{2}\frac{\Delta h}{\Delta t} \tag{4}$$

where Δ h is the removed layer thickness from the detector surface at time Δ t. The $1/2$ factor that appears in the previous equations is due to the etching of the two faces of the detector.

The track etch rate is.

$$V_T = V_B \left[\frac{V_B^2 + V_D^2}{V_B^2 - V_D^2}\right] \tag{5}$$

where, V_D is the track diameter growth rate calculated from the slope of the relationship between the change in track diameter and the etching time ($V_D = \Delta D/\Delta t$).

The etch rate ratio (V) r the response of the detector is the ration f track etch rate to bulk etch rate as:

$$V = \frac{V_T}{V_B} \tag{6}$$

3. Results and Discussions:

For both varieties of NaOH and KOH etching solutions, the V_B, V_T, and V etching rates were computed over a 3 h etching period and are shown in Table 1.

Table 1. Alpha energy and etching parameters of the detector using two chemical solutions NaOH and KOH.

		aqueous KOH solution			aqueous NaOH solution		
E_α (MeV)	Molarity N	V_B $(\mu m/h)$	V_T $(\mu m/h)$	V	V_B $(\mu m/h)$	V_T $(\mu m/h)$	V
2	3	1.02	2.13	2.25	1.62	2.42	1.49
2	5	1.74	5.78	3.32	2.45	6.93	2.83
2	7	2.42	9.19	3.79	3.02	13.07	4.33
2	9	2.89	10.51	3.46	3.84	15.36	4.12
2	11	4.36	13.64	3.13	5.81	22.4	3.85
3	3	1.02	1.68	1.64	1.62	2.17	1.33
3	5	1.74	4.74	2.57	2.45	5.93	2.42
3	7	2.42	6.84	2.83	3.02	8.23	2.72
3	9	2.89	7.65	2.65	3.84	9.79	2.55
3	11	4.36	10.24	2.35	5.81	12.3	2.12
4	3	1.02	1.52	1.49	1.62	2.02	1.24
4	5	1.74	3.39	1.95	2.45	5.39	2.21
4	7	2.42	5.95	2.52	3.02	7.52	2.49
4	9	2.89	6.65	2.3	3.84	8.72	2.27
4	11	4.36	9.16	2.1	5.81	10.47	1.82
5	3	1.02	1.24	1.21	1.62	1.78	1.09
5	5	1.74	2.79	1.6	2.45	4.23	1.72
5	7	2.42	5.49	2.27	3.02	4.99	2.02
5	9	2.89	5.66	1.96	3.84	5.88	1.53
5	11	4.36	7.47	1.71	5.81	7.66	1.32

Table 1 shows that when the CR−39 is etched with NaOH and KOH, the etching rates V_B,V_T, and V increase significantly. This increment is due to increasing of the reaction rate between the chemical etchant molecules and the molecules of the detector material. The etch rate ratio (V) is the most important factor, where it appeared for the KOH etchant solution with lower values than that for the NaOH etchant solution as shown in Figures 1, 2, 3 and 4. The V_B value remains constant for all energies, because it does not depend on the energy of the alpha particle, the duration of the etching, but rather depends on the type of detector and the factors affecting it, the etching conditions such as the concentration and temperature, and the additive solutions that can be added to the etching solutions[13]. The bulk etch rate (V_B) is defined as the amount of the material that removed from the detector surface per unit time, and it is less than the track etch rate (V_T) as a condition for the appearance of the track by the chemical solution.

For the analyzed alpha energies, it was found that the bulk etch rate (V_B), track etch rate (V_T), and etch rate ratio (V) all vary in accordance with changes in the etching solution's

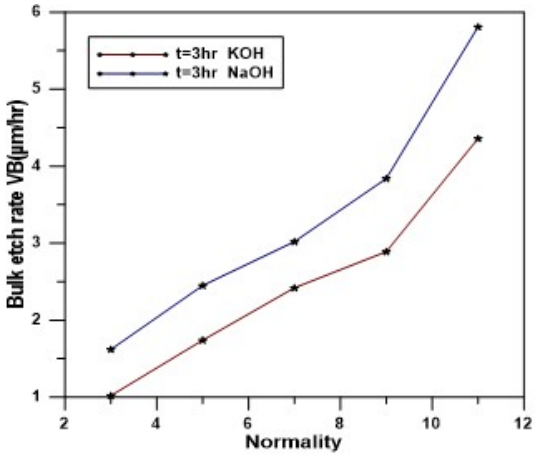

Figure 1. The Track etching rate V_T as a function of KOH and NaOH etchants normalities for alpha energies (2, 3, 4, 5) MeV.

molarity as well as with the alpha energies. It is observed that the rates of etching increase as the molarity of the etching solution increases until it reaches its maximum value under ideal etching conditions, which is $(7-8)$ N. However, when the molarity increases over this value, the etching rates will decline, which is consistent with many earlier studies. It should be noted that the etching rates are higher at low energies of alpha particles than at high energies, because low energies have a shorter range inside the material and lose its energy more quickly at short distance inside the detector. Then, for low energies, the rate of linear energy loss per unit distance (or the rate of energy absorbed per unit distance) in the detector will be higher than for higher energies, leading to more extensive damaged paths. As a result of the action of etching solution, the rate of decomposition of the damaged areas caused by low energies will be greater. This causes the rates of etching to grow more for tracks due to low energies than for high energies, whose range is larger inside the material, and the rate of linear loss of energy per unit distance to be smaller, which causes the rates of etching to be lower. Because the V_B and V_T are affected by the etching circumstances as well as the type of the detector, they are referred to as etching and detecting parameters, respectively. As a result, any change in the etching circumstances or the type of the detector will cause a change in the etching rates V_B and V_T, which determine the development of the track geometry. Any increase in the concentration of the etching solution signifies a rise in the quantity of reactive ions $(-OH)$ which responsible for the hydrolysis of the polymer via link breaking and the production of free radicals, resulting in polymer degradation.

For a chemical reaction to occur, the molecules must have more energy than the activation energy. Then, an increase in the number of collisions means an increase in the number of molecules that obtain the transferred energy (at a constant

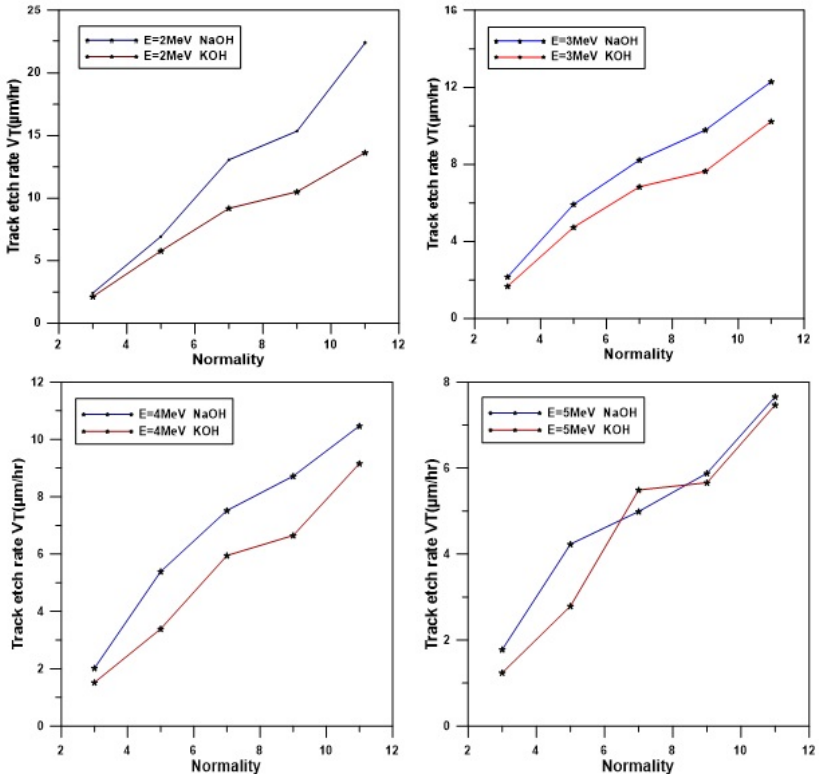

Figure 2. The Track etching rate V_T as a function of KOH and NaOH etchants normalities for alpha energies (2, 3, 4, 5) MeV.

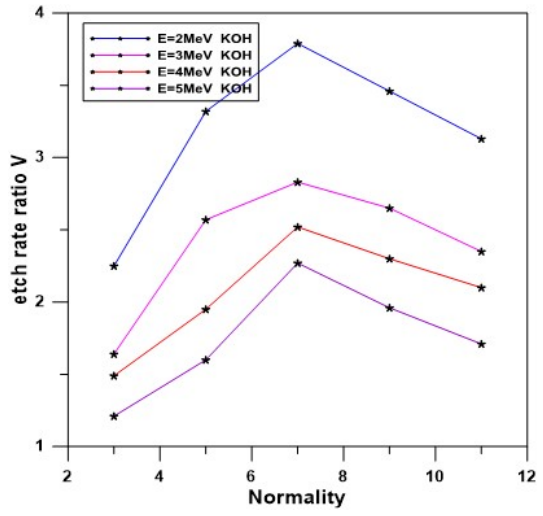

Figure 3. The etch rate ratio (V) as a function of normality of the KOH solution at different alpha energies (2, 3, 4, 5) MeV.

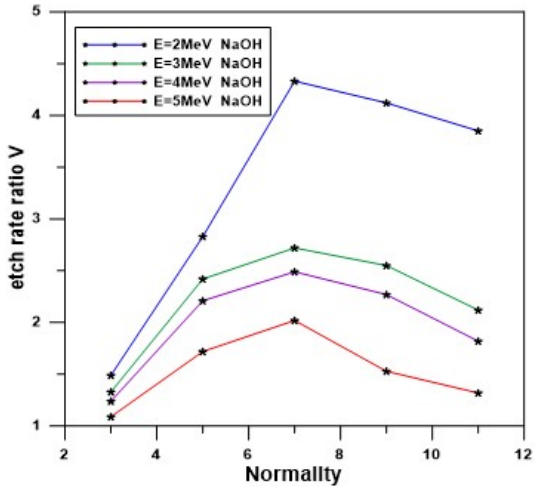

Figure 4. The etch rates ratio V as a function of normality of the NaOH solution at different alpha energies (2, 3, 4, 5) MeV.

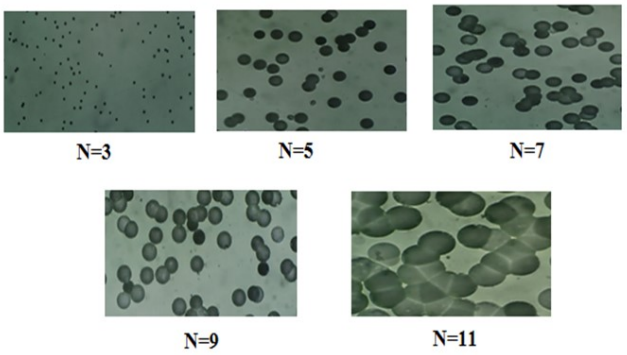

Figure 5. Alpha particles tracks of energy 3 MeV in CR−39detector.

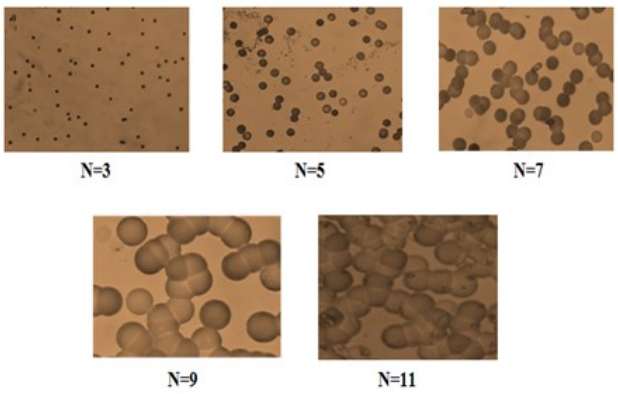

Figure 6. Alpha particles tracks of energy 3 MeV in CR−39 detector.

temperature), which leads to an increase in the number of molecules with energy larger than the activation energy to initiate a chemical process (decomposition and product formation). The rate of reaction is increased either by increasing the number of attacking ions or by increasing their energy. An increase in the number of molecules with energy greater than the activation energy implies an increase in the reaction rate of the decomposition process to generate products, which increases the number of degraded polymer molecules. As a result, the number of dissolved polymer molecules increases, followed by an increase in the amount of material removed from the detector's surface as well as the impacted regions per unit time, which increases the track diameters and etching rates as shown in Figures 5 and 6.

4. Conclusions:

Because the ionic size of Na^+ is less than that of K^+, the aqueous NaOH solution is more efficient than KOH. Due to the comparatively high attraction between Na^+ and OH^-, NaOH experiences less ionization than KOH, making it a weaker base than KOH. As these compounds dissolve, they form ions, and the size (radius) of the ions varies from one element to another, contributing to the so$^-$ called Stier impedance of compounds. Since the volume of sodium in NaOH is less than potassium in KOH, the tracks of alpha particles are more impacted by sodium than by potassium. This leads to the fact that the bulk and track etch rates (V_B and V_T) for CR−39 are higher when etched by NaOH solution than when etched by KOH. This has also been observed in the track diameter values and growth rates of the track diameters (V_D), which are higher for the NaOH solution than the KOH solution.

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تأثير عيارية نوعين من المحاليل الكيميائية على معدلات القشط لكاشف الأثر النووي $CR-39$

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الخلاصة

دُرِست تأثير نوعين من المحاليل الكيميائية القاشطة في الخصائص القشطية لكاشف الأثر النووي الصلب $CR-39$ ، ومن ثَم حساب المعلمات القشطية لها مثل معدلات القشط العام (V_B) ، وقشط الأثر (V_T) ومعدل نسبة القشط (V) والمقارنة بينهما لنوعي المحلول. فقد استخدمنا مجموعتين من كاشف $CR-39$ بسماكة $400\ \mu m$ بابعاد $(1\times1)cm^2$. شُعّعت الكواشف بجسيمات ألفا ذات طاقات $(2,3,4,5)MeV$ باستخدام مصدر ^{241}Am للحصول على آثار جسيمات ألفا في الكاشف. لإظهار الآثار، قُشطت الكواشف المشعّعة بمحلولي هيدروكسيد الصوديوم والبوتاسيم المائي $(NaOH\&KOH)$. المجموعة الأولى والثانية قُشطت تحت الظروف القشطية نفسها بعيارية $N(3-11)$ ودرجة حرارة قشط $(70\pm1)^oC$ لفترة زمنية $3h$. تم قياس V_B بطريقة فرق السمك المزال من الكاشف بفعل القشط لأزمان القشط المحددة. بقياس أقطار الآثار ومعدل نمو الأقطار (V_D) الناتجة في الكاشف لأزمان القشط المحددة، فقد تم قياس V_T و V بالترابط مع V_B لنوعي المحلول المستخدم. بمقارنة النتائج ظهرت معدلات القشط بمحلول هيدروكسيد الصوديوم بنسبة اكبر من معدلات القشط بهيدروكسيد البوتاسيوم بالنسبة لـ V_B و V_T

الكلمات الدالة: كواشف الأثر النووي الصلبة؛ كاشف $CR-39$ ؛ القشط الكيميائي؛ معدلات القشط.

التمويل: لايوجد.

بيان توفر البيانات: جميع البيانات الداعمة لنتائج الدراسة المقدمة يمكن طلبها من المؤلف المسؤول.

اقرارات:

تضارب المصالح: يقر المؤلفون أنه ليس لديهم تضارب في المصالح.

الموافقة الأخلاقية: لم يتم نشر المخطوطة أو تقديمها لمجلة أخرى، كما أنها ليست قيد المراجعة.