Radiation Damage in the Structure of the CR-39 Nuclear Detector Material as A Result of the Alpha's Energy Loss

Khalid R. Flaih

Department of physics, College of science, University of Anbar, Iraq

A B S T R A C T

In this work, the damage caused by the passage of alpha particles inside the CR-39 nuclear detector material on its chemical structure was studied. All samples at room temperature using a 241Am-Be neutron source with a flux of 105 neutrons.cm-2.s-1 were neutron-irradiated. In the CR-39 nuclear track detectors, chemical etching is a critical step in expanding latent tracks. At 70 °C, a NaOH in 6.25N etchant was found to be useful in expanding alpha traces in the CR-39 detector. The track depths of the Alpha particle as a function of etching time for the various energies were increased as etching time increases. The current study uses the nuclear track detector technique to estimate the range of alpha particles. Track etch rates are frequently determined using 2-dimensional photographs of track openings (diameter) or etching time data. The chemical structure along latent tracks and the track formation process were investigated in PADC(poly allyl diglycol carbonate). The findings showed that the measurement of bulk etch rate values by the weight method was 1.42 ± 0.02 μm/h. In addition, the results for the alpha particle range from 4.47 ± 0.05 and 5.8 ± 0.19 μm for alpha energy 1.47 MeV and 1.2 MeV, respectively

1. Introduction

As is well known, the track registration properties of various polyamide etched track nuclear detectors vary[1,2]. The aim of polymer latent track research should be to develop molecular arrangements that are sensitive enough to detect alpha and other charged particles in every application. For more than 30 years, the CR-39 detector has been employed as an etched nuclear sensor[2]. In the CR-39 structure, poly alkyl chains are linked by diethylene glycol dicarbonate linkages[3]. Allyl bound set (CH2==CH-CH2-), ether bound set (–CH2–O–CH2–), and carbonyl bound set (C=O) are the three bound sets found in the monomer. These functional groups, on the other hand, are authorities responsible for the changes in physicochemical characteristics that occur after exposure to each type of radiation.[4]. The particular ionization energy loss from decelerating charged particles determines the degree of damage[5]. Detailed knowledge of material excitation parameters and track structure along the route of a rapid heavy-ion entering through a solid is essential[6]. It's also useful for a variety of applications, such as Nanostructuring, charged particle detection, track membrane fabrication, and oncological ion therapy[7,5].

─────────

* Corresponding author at: Department of physics, College of science, University of Anbar, Iraq
 khalid-rokan478@uoanbar.edu.iq

The peak-like (the Bragg peak) credence of the ion energy, the ion stopping power in a solid as the CR-39 track detector is well known: the Bragg curve, with the projectile energy maximum at ∼3 to 4 MeV/u.[8]. It is necessary to understand the relation between the track etch rate and the bulk etch rate with restarting power in order to comprehend the track formulation operation in nuclear track detectors[9]. When a heavily charged particle goes through a medium, it causes the substance to ionize widely, which is how the nuclear track detector works. gIn cellulose nitrate, for epitome, an alpha particle having a 6 MeV energy produces around 150,000 ion pars. Because the range of alpha particles with an energy of 6 MeV in this material is only around 40 μm, 3–4 ion pairs per nanometer (nm), or 3700 ion pairs per micrometer (m), are formed on average. Almost every molecule in its path is ionized by an alpha particle[10]. Almost every molecule in its path is ionized by an alpha particle. [10,11]. This basic ionizing step sets in motion a cascade of additional chemical reactions that produce loose radicals and other ions species. A latent track is a term for this damaged area[10,12]. These damages fill a latent track, which is a rotational-symmetric zone following the trajectory of an incident particle. The size of radial latent tracks are nanometers. Zones that have been damaged in the detectors can be seen directly with an electron microscope

or indirectly with an optical microscope after an etching using chemical etchant operation expands the latent track and makes it at the micrometer scale, it is apparent[13,14]. The objective of this work is to study radiation damage to a system composed of a CR-39 detector coupled with a boron film. The alpha particles incoming from the boron membranes are used to measure the boron neutron reactions and the damage they cause in the polymer material and is detected by this detector. For this study, the CR-39 detector films were subjected to alpha particles with an incident energy of roughly 1.47 MeV. The damage that occurred inside the polymeric material of the detector was estimated through the parameters of the TRAK-TEST program.

2. Theoretical approach

When alpha particles are irradiated into PADC, irreversible damage is left in the shape of latent traces along all ion routes. The latent tracks above the detection threshold appear as etch pits due to chemical etching (normally NaOH) with an alkaline solution. [15].

2.1.The bulk etching process:

The bulk etches rate V_B is one of the most important parameters that determine track formation[10]. The key observed feature of the V_B is an exponential relationship between temperature and etching bath concentration. Carbonate ions are liberated in enormous quantities in the etching fluid in the bulk etch operation described by V_B. Organic alcohols make up the majority of bits of organic matter created during PADC's bulk etch operation [16,17]. It is necessary to expound on the bulk etch methodology of the CR-39 detector. The reaction between the free radicals generated by the passage of alpha particles and the oxygen that makes up the detector will damage it[18].

2.2.Nuclear track recording:

The radical libertarian It is well known that the stability of free radicals reduces as the radical atom's electronegativity increases. The free radical is more unstable the closer the partially empty orbital is to the nucleus. Because PADC is made up of only three elements: hydrogen, carbon, and oxygen, alkyl radicals should be expected to be present during the initiation stage[17,19]. The physical damage in the incident particle latent track is determined by the target's atomic composition damage[17]. The physical damage in the incident particle latent track is determined by the target's atomic composition damage. Its atomic composition and bonding have a big impact on the Z-detection threshold[20].

3. Experimental

Pershore Moulding LTD Co. UK supplied CR-39 plastic sheets with a thickness of 500μm with a composition: of C12H18O7 and a density: of 1.32 g.cm^{-3}[21]. The sheets of CR-39 detectors were cut into sections

with geometric dimensions of (1×1) cm^2. All samples were neutron-irradiated at room temperature using a ^{241}Am-Be neutron source with a flux of 10^5 neutrons provided by Radio-Chemical, Ltd., England. cm^{-2}.s^{-1}. After the CR 39 pieces were exposed, chemical etching was performed utilizing methods such as the commonly used 6.25M NaOH solution at 60°C. The CR-39 pieces were disinfected in distilled water after chemical etching. These detector components were observed at a greater magnification (40×) using an optical microscope with a digital camera and Magvision software It is necessary to determine the thickness of the removed layer Δm and, as a result, it gets a value of V_B, based on the known density ρ and mass difference of the detector as in the following equation[22].

$$V_B = \frac{\Delta m}{2\rho At} \qquad (1)$$

where Δm denotes the mass loss during chemical etching of the time of t (hour).

The bulk etches rates were calculated using Eq. (1) for the standard etchant 6.25 N NaOH and were kept at 70 °C. The value of the bulk etches rate is 1.42± 0.02 μm h−1. The rest of the parameters, such as path length and depth, track etch rate and track etch ratio, and other empirical data and calculation results were calculated by using the authentic program, TRACK_TEST, which was evolved for alpha path calculations. Experimental parameters of trajectory depth versus etching time and energy are calculated using alpha particle data. This software has a sophisticated experimental modeling procedure. The experimental equations for the trace depth obtained are [23].

$$L(t) = A_1 \tanh(U)^{A_4} \qquad (2)$$
$$U = \exp[(t - A_2)/A_3] \qquad (3)$$

L(t) denotes the trajectory depth after etching for t time (hours).
The four parameters A1, A2, A3, and A4 have the following dependence on alpha particle energy as

$$A_1 = a_1 E - 1.4 \qquad (4)$$
$$A_2 = a_2 sxp(\frac{E^{0.5}}{a_3})E^{b_1} \qquad (5)$$
$$A_3 = a_4/E^{b_2} \qquad (6)$$
$$A_4 = (\frac{1}{A_1 A_2 A_3}) \qquad (7)$$

The scaled parameters a1, a2, a3, a4, b1, and b2 should have the same scaled amounts across all energies[24].

When the energy of alpha is 1.4MeV, the values of the parameters a_1, a_2, a_3, a_4 are 3.78, 0.58, 4.74, 0.50 respectively.

4. Results and discussion

The Beere Lambert law states that absorbance is proportionate to the number of bonds between chemical atoms taken into account[2,25]. Ionization occurs when charged particle ionizes atoms in their path, producing

multiple secondary electrons that can also cause ionization. In a uniform medium that has lots of equivalent chemical bonds, the nearer bond to the charged path has a much-increased likelihood of being broken[2]. In the CR-39 detector, a periodic monomer unity construction is shown in Fig.1. In theory, the energies transmitted by 5 MeV particles are due to dissolving all chains in this detector, of which the strongest is -C = C- with dismantling energy of 6.4 eV. [22, 26,27,28]. Fig .2. show that, alpha particles create narrow tracks along their trajectories as they enter the CR-39 nuclear track detector. Latent traces are these thin trails. These latent patterns are increased with etchants that are appropriate and etching conditions (concentration of etchant and temperature), which differ from one substance to the next, and tracks that are bigger can be observed with an optical microscope in the track etch process.

Because of their simplicity, durability, and high efficiency, the CR-39 detectors (SSNTDs) have a better chance of succeeding in this field than other nuclear detectors. Because the entire trajectory of the ion tracks' trajectory, from its arrival at first glance to practically its conclusion, can be observed optically, the CR-39 detectors deliver a unique service chance to quantify the spectrum of heavy ions. [26]. The track depths of the Alpha particle as a function of etching time for the various energies were measured and presented in Fig. 3. The inclination of the curves increases as etching time increases, demonstrating that the pace at which the track etches along the particle route is a function of alpha particle depth. Furthermore, when the saturation is reached, the depth of trajectory depends on the energy of the alpha particle[13]. It can give you a rough estimate of the particle's range for a certain etching time. It's worth noting that the etching effectiveness of the detector's disturbance zone drops dramatically along the deceleration route of nuclei with energy greater than E_{max} . Chemical etching of a track occurs at a significantly slower rate in this situation, and much longer-term etching is required to produce a visible trace. Figure 4 shows the depth of the alpha particle trajectory within the CR-39 detector material as a function of the etching time for a particle's various energies. The amount of energy lost is proportional to the stretch traveled by the initial energy of the ion and its type. The initial energy of the ions and the depth x below the surface of the original detector are crucial determinants in the occurrence of particles perpendicular to the detector. This agrees with the researcher's findings[29]. Figure 5. shows the alpha particle range within the CR-39 detector material as a function of the different energies alpha particle.

When the track has been entirely etched up to the particle range's end at a given point in time t, etching continues in all directions at the bulk etch rate V_B. The etch pit's depth does not increase any further after that. It is possible to compute the range of an alpha particle and its energy from the track length measurement for particle incidence that is normal. The results for the alpha particle range from 4.47 ± 0.05 and 5.8 ± 0.19 μm for alpha energy 1.47 MeV and 1.2 MeV, respectively.

Figure 6 shows the curve in order to calculate the etch ratio $V = V_T / V_B = V$ (REL) as a function of alpha particles with different energies. The etch rate ratio of the CR-39 detector $V = VT/VB$ is measured differently depending on the etching provisions [30]. The tracking form has two phases, the acute conical phase at $V_T > V_B$ and the excess etched phase at $V_B = V_T$.
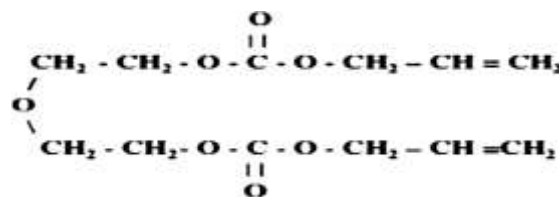

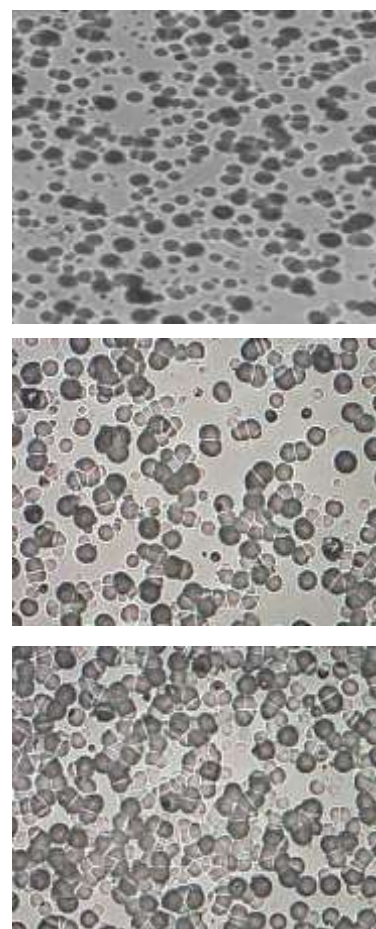Figure. 1. A periodical monomer unity constructure in the CR-39 detector. [4].

Figure. 2. Optical microscope image of alpha particles on the surface of CR-39 nuclear track detector samples at
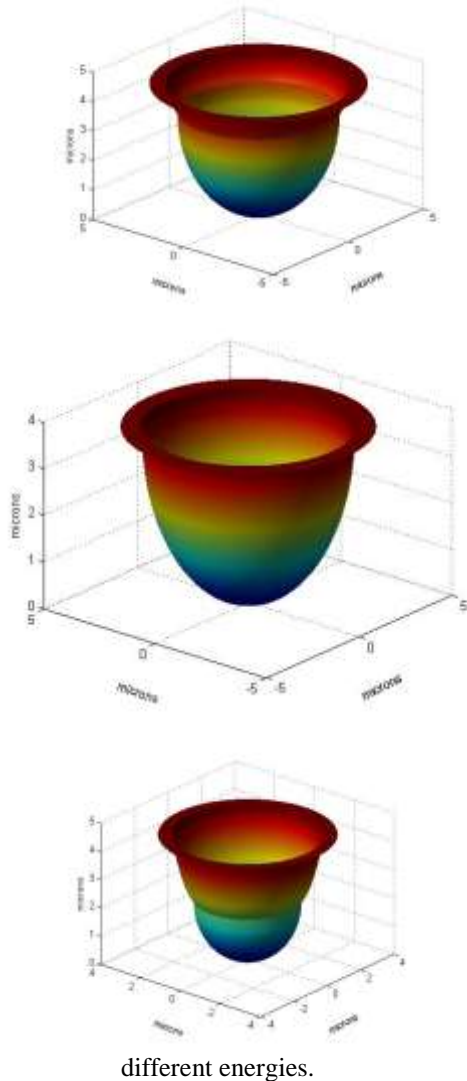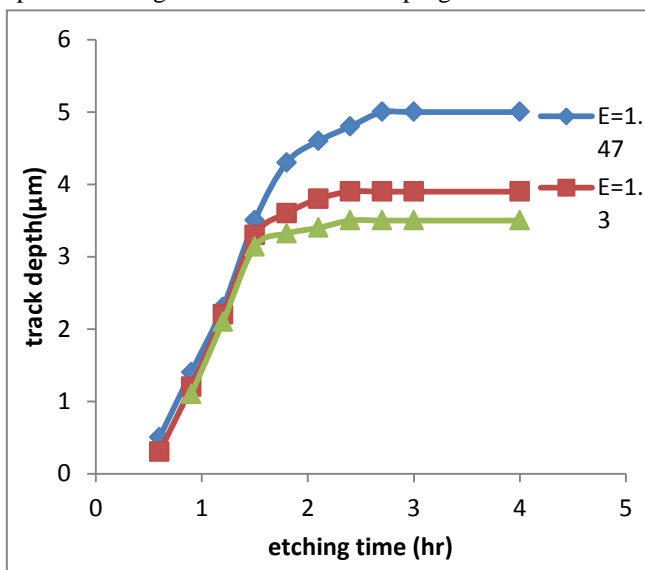
nuclear track detector samples at different energies.

Figure.4.shows the depth of the alpha particle path within the detector material as a function of the different etching time for the different energies of the particle with etchant solution of 6.25N NaOH at 70±1 ºC.

different energies.

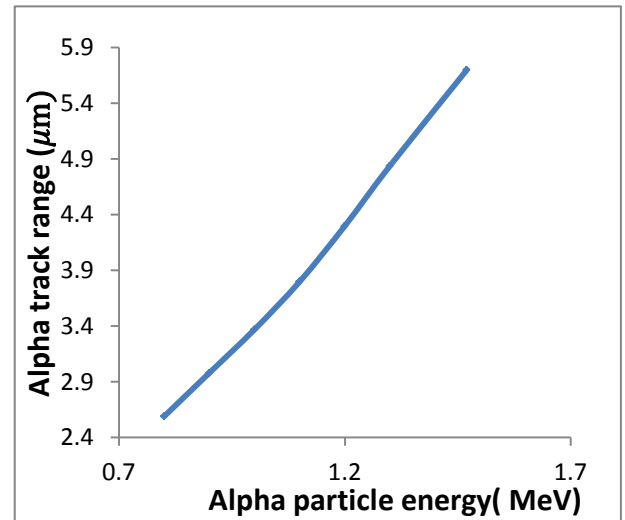Figure.3. shows three phases to track development Alpha particles image from TRAK-TEST program of CR-39

Figure. 5. Alpha particle range as a function of the different energies in the CR-39 nuclear track detector and etched in 6.25N NaOH at 70±1 ºC.
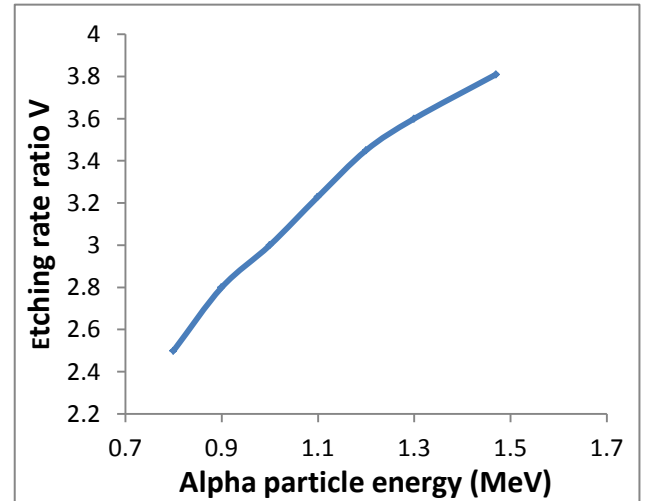

Figure. 6. etch rate ratio as a function of the alpha particles with different energies in the CR-39 nuclear track detector and etched in 6.25N NaOH at 70±1 ºC.

5. Conclusions

The damage resulting from the passage of charged particles such as alpha particles and protons inside the detector material can be studied through direct vision by means of a microscope after etching it with an etchant substance such as sodium hydroxide, where the effects are clear and represent the damage in the detector material. Or through the TRAK-TEST program after providing the

program with the type of particle, its energy, and the type of detector. The program provides us with three-dimensional images of the impact of the falling particle resulting from its lost energy inside the detector material, causing the polymeric chains of this material to break. It also provides us with the depth and range of the particle as a function of the etching time. One of the most important functions that have been studied that represent the damage caused to the detector material is the ratio of the etching rate, which is equivalent to the lost energy as a result of the passage of charged particles inside the detector material.

6. References

1- 1-Saad, A.F., Fromm, M., Ibraheim, M.H., El-Namrouty, A.A., Nwara, A.M., Kandil, S.A. and Dawood, M.S., 2021. Loss of chemical bonds induced by high doses of γ-radiation in a PADC polymer film: The influence of dose and dose rate on radiation chemical yields. Radiation Physics and Chemistry, 187, p.109579.

2- Yamauchi, T., Kaifu, S., Mori, Y., Kanasaki, M., Oda, K., Kodaira, S., Konishi, T., Yasuda, N. and Barillon, R., 2013. Applicability of the polyimide films as an SSNTD material. *Radiation measurements*, *50*, pp.16-21.

3- Tse, K.C.C., Ng, F.M.F. and Yu, K.N., 2006. Photo-degradation of PADC by UV radiation at various wavelengths. *Polymer Degradation and Stability*, *91*(10), pp.2380-2388.

4- El Ghazaly, M. and Hassan, H.E., 2014. Spectroscopic studies on alpha particle-irradiated PADC (CR-39 detector). *Results in Physics*, *4*, pp.40-43.

5- Bagulya, A.V.E., Kashkarov, L.L., Konovalova, N.S., Okat'eva, N.M., Polukhina, N.Y.G.E. and Starkov, N.I., 2013. Search for superheavy elements in galactic cosmic rays. *JETP letters*, *97*(12), pp.708-719.

6- Komarov, F.F., 2017. Nano-and microstructuring of solids by swift heavy ions. *Physics-Uspekhi*, *60*(5), p.435.

7- Alexeev, V., Bagulya, A., Chernyavsky, M., Gippius, A., Goncharova, L., Gorbunov, S., Gorshenkov, M., Kalinina, G., Konovalova, N., Liu, J. and Zhai, P., 2016. Charge spectrum of heavy and superheavy components of galactic cosmic rays: Results of the olimpiya experiment. *The Astrophysical Journal*, *829*(2), p.120.

8- Rymzhanov, R.A., Gorbunov, S.A., Medvedev, N. and Volkov, A.E., 2019. Damage along swift heavy ion trajectory. *Nuclear Instruments and Methods in Physics Research section B: Beam Interactions with Materials and Atoms*, *440*, pp.25-35.

9- Dörschel, B., Hermsdorf, D. and Kadner, K., 2002. Studies of experimentally determined etch-rate ratios in CR-39 for ions of different kinds and energies. *Radiation measurements*, *35*(3), pp.183-187.

10- Nikezic, D. and Yu, K.N., 2004. Formation and growth of tracks in nuclear track materials. *Materials Science and Engineering: R: Reports*, *46*(3-5), pp.51-123.

11- Hecht, A.A., Galo, R., Fellows, S., Baldez, P. and Koonath, P., 2021. Radiolytic ozone yield G (O3) from 210Po alpha-particle radiation in air. *Radiation Physics and Chemistry*, *183*, p.109387.

12- Fleischer, R.L., Price, P.B., Walker, R.M. and Walker, R.M., 1975. *Nuclear tracks in solids: principles and applications*. Univ of California Press.

13- Al-Khalil, Y.T., Fromm, M., Awad, E.M., Alkhayat, R.B., Zakar, A.T. and Al-Jubbori, M.A., 2022. On the question of track etch rate amplitude variation in the Bragg-peak vicinity: Experimental verification for low-energy α-particle tracks in CR-39. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *1031*, p.166516.

14- Dörschel, B., Hermsdorf, D., Kadner, K. and Starke, S., 2002. Variation of the track etch rate along the trajectories of light ions in CR-39. *Radiation measurements*, *35*(3), pp.177-182.

15- Kusumoto, T., Barillon, R., Okada, S., Yamauchi, T. and Kodaira, S., 2020. Improved criterion of the mechanism for forming latent tracks in poly (allyl diglycol carbonate) based on the number of interactions induced by secondary electrons. *Radiation Measurements*, *138*, p.106445.

16- Awad, E.M., Ditlov, V.A., Fromm, M. and Hermsdorf, D., 2009. Description of the bulk etching rate of CR-39 by an extended Arrhenius-like law in increased intervals of temperature and etchant concentration. *Radiation measurements*, *44*(9-10), pp.813-820.

17- Fromm, M., Kodaira, S., Kusumoto, T., Barillon, R. and Yamauchi, T., 2019. Role of intermediate species in the formation of ion tracks in PADC: A review. *Polymer Degradation and Stability*, *161*, pp.213-224.

18- Yamauchi, T., 2003. Studies on the nuclear tracks in CR-39 plastics. *Radiation measurements*, *36*(1-6), pp.73-81.

19- Chapiro, A., 1988. Chemical modifications in irradiated polymers. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *32*(1-4), pp.111-114.

20- Rana, M.A., 2008. Nuclear track formation and skewness of particle trajectories in the target: A new perspective. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *266*(15), pp.3487-3490.

21- Yamauchi, T., Yasuda, N., Asuka, T., Izumi, K., Masutani, T., Oda, K. and Barillon, R., 2005. Track core size estimation for heavy ions in CR-39 by AFM and UV methods. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *236*(1-4), pp.318-322.

22- El Ghazaly, M. and Hassan, N.M., 2018. Characterization of saturation of CR-39 detector at high alpha-particle fluence. *Nuclear Engineering and Technology*, *50*(3), pp.432-438.

23- Azooz AA, Al-Nia'emi SH, Al-Jubbori MA. A parameterization of nuclear track profiles in CR-39 detector. Computer Physics Communications. 2012 Nov 1;183(11):2470-9.

24- Azooz, A.A., Al-Nia'emi, S.H. and Al-Jubbori, M.A., 2012. Empirical parameterization of CR-39 longitudinal track depth. *Radiation measurements*, *47*(1), pp.67-72.

25- Yamauchi, T., Kanasaki, M. and Barillon, R., 2021. Methodological and Conceptual Progresses in Studies on the Latent Tracks in PADC. *Polymers*, *13*(16), p.2665.

26- Diwan, P.K. and Virk, H.S., 2015. heavy ion range measurements in SSNTD materials: A Review. *Solid State Phenomena*, *238*, pp.174-195.

27- Dolenko, T.A., Burikov, S.A., Dolenko, S.A., Efitorov, A.O., Plastinin, I.V., Yuzhakov, V.I. and Patsaeva, S.V., 2015. Raman spectroscopy of water–ethanol solutions: the estimation of hydrogen bonding energy and the appearance of clathrate-like structures in solutions. *The Journal of Physical Chemistry A*, *119*(44), pp.10806-10815.

28- Stejny, J., Carrell, J. and Palmer, M.J., 2000. Polymerization, structure and track recording properties of CR-39 cured with UV photoinitiators. *Radiation measurements*, *32*(4), pp.299-305.

29- Dörschel, B., Hermsdorf, D., Kadner, K. and Starke, S., 2002. A new approach to characterising the etch rate ratio in CR-39 using a function of two variables. *Radiation measurements*, *35*(4), pp.293-299.

30- EL-Araby, E.H. and Shabaan, D.H., 2022. Measurement of alpha particle range in CR-39 detector using nuclear track profiles. *Journal of Radiation Research and Applied Sciences*, *15*(1), pp.139-144

الأضرار الإشعاعية التي لحقت بهيكل مادة الكاشف النووي CR-39 نتيجة فقدان طاقة جسيمات ألفا

خالد روكان مفلح

قسم الفيزياء ،كلية العلوم ،جامعة الانبار

الخلاصة

في هذا العمل تمت دراسة الضرر الناجم عن مرور جسيمات ألفا داخل مادة الكاشف النووي CR-39 على تركيبته الكيميائية. تم تشعيع جميع العينات في درجة حرارة الغرفة باستخدام مصدر نيوتروني ^{241}Am-Be بتدفق 10^5neutrons.cm^{-2}.s^{-1}. في كاشفات المسار النووي CR-39 ، يعد القشط الكيميائي خطوة حاسمة في توسيع المسارات الكامنة. عند C° 70 درجة مئوية ، وتكون عيارية هيدروكسيد الصوديوم هي 6.25N مفيدة في توسيع آثار ألفا في الكاشف CR-39. كانت أعماق مسار جسيم ألفا كدالة لوقت الحفر لمختلف الطاقات تزداد مع زيادة وقت القشط. تستخدم الدراسة الحالية تقنية كاشف المسار النووي لتقدير نطاق جسيمات ألفا. يتم تحديد معدلات حفر المسار باستخدام صور ثنائية الأبعاد لفتحات المسار (القطر) أو بيانات وقت الحفر. تم فحص التركيب الكيميائي على طول المسارات الكامنة وعملية تكوين المسار في PADC (كربونات بولي أليل ديجليكول). أظهرت النتائج أن قياس قيم معدل الحفر الكتلي بطريقة الوزن كانت . $1.42 ± 0.02$ μm h^{-1} ، كانت نتائج مدى جسيمات ألفا من $4.47 ± 0.05$ μm لطاقة ألفاMeV 1.2 إلى $5.8 ± 0.19$ μm لطاقة ألفا MeV. 1.47 .