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Dependence of alpha particle track diameter on the free volume holes size using positron annihilation lifetime technique

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ABSTRACT

The alpha particle track diameter dependence of the free volume holes size (V_f) in DAM–ADC and CR-39 nuclear track detectors was investigated using positron annihilation lifetime technique. The effect of temperature on the alpha particle track diameter and free volume were also investigated in the T-range (RT-130 °C). The obtained results revealed that the values of ortho-positronium lifetime τ_3 and V_f increases while I_3 slightly increases as T increases for the two detectors. The values of τ_3, V_f and I_3 are higher in CR-39 than DAM–ADC. The interpretation of obtained results is based on the fact that increasing T leads to significant enhancement of thermal expansion of the polymer matrix and consequently V_f increases. The track diameter increases as T increases. This can be explained by the fact that the increase in T increases the crystal size and V_f in the polymer. A relationship between V_f and the alpha particle track diameter was obtained. Moreover results of detector irradiation, along with free volume evaluation are addressed and thoroughly discussed.

1. Introduction

Solid state nuclear track detectors (SSNTDs) are a type of insulating solid materials that used to detect the nuclear particles like neutrons, alpha particles and fission fragments. There are several materials act as SSNTDs like; crystals, glasses and polymers [1]. Recently, many investigators focused on these materials to use them in new applications [2–4].

Diallyl maleate (DAM) is a highly active monomer with a powerful affinity for many materials. Therefore, DAM is used as a raw material for many chemical products, such as adhesives and ion exchange resin [5]. Allyl diglycol carbonate (ADC) commercially known as CR-39 is a plastic polymer commonly used as SSNTDs and also in the manufacture of eye glass lenses [6,7]. The copolymer of DAM and ADC show intermediate characteristics between DAM and ADC polymers [8]. The ADC and DAM monomers contain two of allyal functional groups [CH2═CH–CH2–] and have a chemical structure mentioned in the work of Tsuruta et al. [5].

Positrons that entered a polymer matrix may annihilate directly with electrons or may capture some electrons from the surrounding medium to form a positronium atom (Ps). There are two states of Ps which are the singlet state (total spin zero) and is called para-positronium, p-Ps and the triplet state (total spin one) and is called ortho-positronium o-Ps. Positron annihilation spectroscopy (PAS) is a useful non-destructive nuclear tool in studying the physical properties of metallic materials [9,10]. Indeed, Positron annihilation lifetime spectroscopy (PALS) is an ideal tool for studying the free volume holes in polymers (the small amount of unfilled volume associated with the end of the polymer chains or between these chains). This concept explains many physical properties of polymers like electrical [11–13] and mechanical properties [14]. O-Ps lifetime component (τ_3) is a measure of free volume holes size by using the Tao–Eldrup semi-empirical equation, Eq. (1), [15,16]; the cavity hosting of Ps is assumed to be a spherical void with an effective radius R. The relationship between τ_3 and radius R is as the following:

$$\tau_3 = 0.5\left[\frac{\Delta R}{R+\Delta R} + \frac{1}{2\pi}\sin\left(2\pi\frac{R}{R+\Delta R}\right)\right]^{-1} \qquad (1)$$

where the units of R and τ_3 are nm and ns, respectively, ΔR = 1.656 and is derived from fitting the observed o-Ps lifetimes in molecular

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solids with known hole sizes [17]. Indeed, the intensity (I_3) reflects the concentration of free volume holes because it is a measure of the o-Ps formation probability. The free volume hole radius R can be obtained from Eq. (1), then used to determine the mean size of free volume holes V_f, using Eq. (2):

$$V_f = \frac{4}{3}\pi R^3 \tag{2}$$

To the best of our knowledge, there are five papers on DAM–ADC as a nuclear track detector. Tsuruta et al. [5] aimed to identify a suitable curing process to cast pure DAM plates and copolymer plates of DAM and ADC to confirm the usefulness of these plates as nuclear track detectors. El-Samman et al. [18] focused on studying the etching characteristics for the detection of alpha particles in DAM–ADC nuclear track detector. Ashry et al. [8] studied the dependence of alpha particle track diameter on the hardness of DAM–ADC. Rammah et al. [19] introduced a new etchant solution for DAM–ADC detector to investigate several important parameters that control the track formation, such as the bulk etch rate and registration efficiency for alpha particles at a short etching time in order to approve the benefit of these plates as nuclear track detectors. Abdalla et al. study CR-39 and DAM–ADC as fast neutron detectors by using new etching conditions [20]. The dependence of neutron track density on the neutrons fluence was also investigated. In PADC poly (allyl diglycol carbonate), the amount of OH groups per unit distance along the ion tracks against the stopping power has been examined by means of FT-IR spectroscopy. It was found that, the amount of OH groups increased monotonically with increasing the stopping power [21]. It is important to understand the factor affecting the track diameter to development track detectors with higher sensitivity. The present work focuses on the dependence of alpha particle track diameter on the free volume holes size in nuclear track detectors using positron annihilation lifetime technique.

2. Experimental work

In the present work, plastic sheets of two different track detectors were used (with an area of 1.0 × 1.0 cm^2 were carefully cut using laser beam). The first detector was DAM–ADC with 15:85 ratio and was supplied by Yamamoto Kogaku, Japan. The molecular formula is [$C_{22}H_{30}O_{11}$], the thickness is 1 mm and the density is 1.2 g/cm^3.The other detector was CR-39, obtained from TASTRAK, UK, used for comparative study.

PALS was performed using a conventional fast–fast coincidence system. It was conducted in the temperature range from 25 up to 130 °C in 5° steps in a vacuum. A positron source (^{22}Na), sealed in a thin Kapton foil (7 μm thick), was mounted in a sample (1.0 × 1.0 cm^2 with a thickness of 1 mm)–source–sample sandwich. The time resolution of the system was 240 ps (full width at half maximum, FWHM) for the ^{60}Co γ-rays with a time calibration of 53 ps/ch. The PAL spectra containing 1.5 × 10^6 counts were finite term analyzed using LT 9.0 program in terms of three lifetime components τ_1, τ_2 and τ_3 with relative intensities I_1, I_2 and I_3 without source correction [22]. It should be mentioned that, the short lifetime component (τ_1 = 0.125 ns) and the intensity I_1 are attributed to the p-Ps self annihilation and it has very weak interaction with the environment so it is nearly equal to the vacuum lifetime of p-Ps and was kept fixed during the analysis.

To study the effect of annealing temperature upon the alpha particle track diameter, the sheets were annealed at the temperature range (RT-130 °C) for three hours then quenched in liquid nitrogen. After that, the DAM–ADC and CR-39 detector sheets were irradiated in air (at normal temperature and pressure) at normal incidence using collimator. They were exposed to a thin electroplated ^{210}Po, as an alpha source, of activity 0.1 μCi for three hours. The energy of alpha particles was varied by changing the source–detector distance in air. The residual energy of alpha particles was determined from the equation below [23],

$$RE = \frac{(r - x)^{0.667}}{0.32} \tag{3}$$

where RE is particle's energy in MeV, r is the range of alpha particles of ^{210}Po in the air and x is the distance between the alpha particles' source and the detector in cm. In this study, the energy of alpha particles is equal to 3.7 MeV. After irradiation, the plates were etched in aqueous solution of 6.25 N NaOH by using a temperature stabilized water bath of accuracy ±0.5 °C. They were kept at the same depth of etching solution. After etching at 65 °C for 6.5 h, the sheets were washed in running distilled water, and then carefully dried by dry air. The diameters of thirty circular alpha particle tracks in the sheets were measured after etching. For estimation of track diameter, the microscope was connected with a digital camera to capture the sample image from the microscope and save it in P.C unit; soft ware program (INFINITYANALYZE software) was used to analyze the tracks after calibration. This measurement was repeated several times in order to obtain an average value. The standard deviation was calculated. An estimated error of about 5% was found in the present work.

3. Results and discussions

Figs. 1 and 2 show τ_3, V_f and I_3 as a function of annealing temperature T for DAM–ADC and CR-39 detectors. It was found that; (i) the values of τ_3 and V_f increases while I_3 slightly increases as T

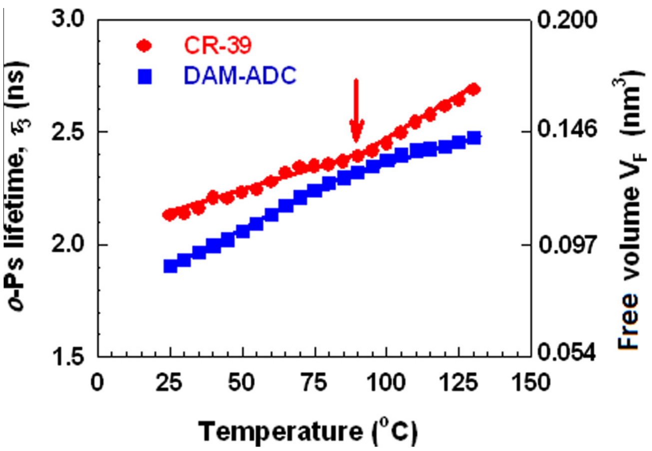

Fig. 1. The change of τ_3 and V_f with the annealing temperature T for DAM–ADC and CR-39 detectors.

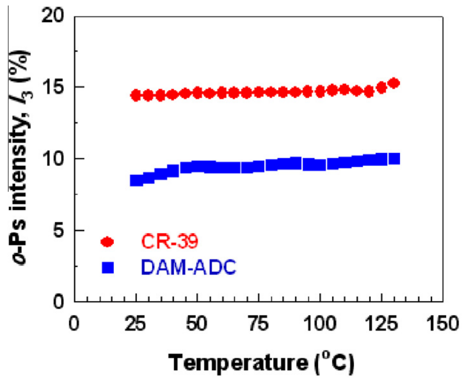

Fig. 2. The change of I_3 with the annealing temperature T for DAM–ADC and CR-39 detectors.