Iraqi Journal of Physics, 2010 *Vol. 8 No.11, PP. 77- 83*

Investigation of Beta and Gamma Rays Total Interaction Cross Section and Effective Atomic Number for CR-39Nuclear Track Detector

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Abstract

CR-39 is a solid state nuclear track detector (SSNTD) that has been used in many research areas. In spite of the assumption that the CR-39 detectors are insensitive to beta and gamma rays, irradiation with these rays can have significant effects on the detector properties. In this study, beta and gamma rays mass attenuation coefficients μ/ρ ($cm^2\ g^{-1}$) for the CR-39 detector have been measured using NaI(Tl) scintillation spectrometer along with a standard geometrical arrangement in the energy region of (0.546-2.274) MeV beta rays and standard gamma sources having energy 0.356, 0.5697, 0.6617 and 1.063 MeV. The total atomic cross-section (σ_{tot}), total electronic cross-section ($\sigma_{T\,E}$) and the effective atomic number (Z_{eff}) of gamma rays at energy of 1keV- 10^5 MeV have been also calculated using the Winxcom and MathCAD programs. The data base and the calculated results were compared with the measured experimental values. It has been found that the mass attenuation coefficients vary with the type of interaction of radiation, photoelectric interaction gives dominant contribution to the total mass attenuation coefficients for CR-39 detectors. Further, the Z_{eff} changes with change of energy.

Keywords
Beta and Gamma Rays
CR-39Nuclear Track Detector

Article info
Received: Mar. 2010
Accepted: Apr. 2010
Published: oct. 2010

دراسة مساحة المقطع العرضي الكلي لتفاعل أشعة بيتا وكاما و العدد الذري المؤثر لكاشف الأثر CR-39

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الخلاصة

يعتبر CR-39 من كواشف الأثر ذات الحالة الصلبة والذي يستخدم في مختلف المجالات العلمية. بالرغم من أعتبار هذا النوع من الكواشف غير حساسة لأشعاعات بيتا و كاما، لكن التشعيع بهذا النوع من الأشعاعات قد يؤدي الى أحداث ثاثيرات مهمة على خصائص الكاشف. في الدراسة الحالية تم حساب معاملا التوهين الكتلي الكلية μ/ρ ($cm^2\ g^{-1}$) لأشة بيتا و كاما للكاشف CR-39 باستخدام منظومة محلل متعدد القنوات الخاصة بالكاشف الوميضي NaI(Tl) و بترتيب هندسي قياسي وبمدى طاقة يتراوح MeV (0.546-2.274) لاشعة بيتا وباستخدام مصادر قياسية لاشعة كاما بطاقات 0.356 ، 0.569 ، 0.6617 و 1.063 MeV. كما تم ايضا حساب مساحة المقطع العرضي الكلي الذري للتفاعل (σ_{tot}) ، مساحة المقطع العرضي الالكتروني للتفاعل ($\sigma_{T\,E}$) و العدد الذري المؤثر (Z_{eff}) لاشعة كاما بمدى طاقة 1keV- 10^5 MeV باستخدام البرامج Winxcom وMathCAD . ولقد تم مقارنة الحسابات النظرية مع القيم العملية المقاسة. وجد ان معاملات التوهين الكتلي الكلي لاشعة كاما تتغير طبقا الى نوع التفاعل للاشعاع وان التفاعل بالتاثير الكهروضوئي يعطي اعلى مساهمة بالاضافة الى ان قيمة العدد الذري المؤثر تتغير بتغير الطاقة.

Introduction

CR-39 is a passive solid state nuclear track detector (SSNTD) that has been used in many research areas including nuclear physics, solid state physics, cosmic ray studies and geology. The advantages of CR-39 for these applications are that it is inexpensive, robust, it interacts with both charged particles and neutrons, and it is insensitive to gamma and beta radiation and electromagnetic noise [1, 2].

CR-39 is a polymer ($C_{12}H_{18}O_7$) with a density of ~1.3 g/cm^3. When a charged particle crosses the detector surface it causes radiation damage along the trajectory. This zone of structure damage may be increased to 10^{-4} –10^{-2} cm by etching in a chemical reagent [3]. Chemical etching transforms the latent tracks into optically visible tracks by supplying the required amount of energy for enlargement process. The mount of chemical change depends both on total quantity of radiation energy available and on the rate at which energy is deposited. Linear energy transfer (LET) is a measure of rate of energy deposition and is defined as the linear rate of loss of energy by an ionizing particle traversing a material medium [3,4].

In spite of the assumption that the CR-39 detectors are insensitive to beta and gamma rays, irradiation with these rays can have significant effects on the properties of track detectors. When the projectile consists of beta particles, collision between two particles of equal mass can transfer all kinetic energy to the stationary particle. Large energy transfers are thus possible and the path-length is much less well-defined. Further, a light particle is much more readily deviated by the nucleus and so scattering angles will be larger and the path length will be much more crooked. It follows that the range of beta particles is not necessarily as great as its path-length. At higher energies (kinetic energy >1 MeV), the energy-loss of beta particles is chiefly due to bremsstrahlung and the probability of this process happening increases with the amount of energy. Beta particles are low LET radiations, which mostly affect the physical and chemical properties of polymeric films.

The effect of gamma rays on the track registration response of CR-39 is also interesting in relation to neutron spectrometry applications. An appreciable gamma field may accompany the neutron field [1]. Such gamma exposure can induce changes in the bulk detector material and in the latent damage tracks, if the damage tracks were induced in the material before or during gamma irradiation. Correction of any induced detector effect requires knowledge of the nature of this effect.

The present research was focused on calculation of the beta and gamma rays mass attenuation coefficients in CR-39 detector material as prototype of SSNTD, and uses the theoretical values of CR-39 mass attenuation coefficients for gamma ray to calculate the total atomic cross-section (σ_{tot}), total electronic cross-section (σ_{TE}) and the effective atomic number (Z_{eff}) for which they were of prime importance. The present research has many technological applications in diverse fields such as detection and shielding studies, radiation biophysics and geophysical prospecting.

Theory and Methodology

The accurate values of mass attenuation coefficients of beta and gamma rays for various media are useful for dosimetry, radiation shielding, radiometric gauging, as well as for many nuclear and solid state physics experiments. The experimentally observed transmission curves of continuous energy electrons (beta particles) are of a characteristic exponential shape. This exponential behavior of the attenuation of beta particles, over a limited penetration range, is of the same form as that of gamma ray. Hence, it is the usual practice to evaluate the mass attenuation coefficient of beta particles for an absorber as the slope of the linear portion of the semilog plot of measured transmission versus thickness of the absorber.

When a beam of radiation is focused on a material of thickness x and density ρ, a fraction of the beam is absorbed by the material. The intensity of the beam that emerges is linked to intensity I_o of the incident beam by the exponential attenuation law which is valid for continuous and monoenergetic beam of radiation [5]:

$$I(x) = I_o e^{-(\mu/\rho)x}, \tag{1}$$

where I and I_o are incident and transmitted of radiation respectively, μ/ρ (cm^2 g^{-1}) is the mass attenuation coefficient and x (g.cm^{-2}) is the mass thickness defined as the mass per unit area. The mass attenuation coefficient is the probability of suffering beam attenuation to the processes depends on the type of radiation and its energy. Beta ray interacts with the matter through elastic and inelastic scattering with atomic electrons and through elastic scattering with nuclei [6]. While the interaction of gamma ray with matter is due to three different processes depending on its energy range, photoelectric absorption, scattering and pair production, only the first two effects will occur with all the gamma energies. The pair production will occur only when gamma energy is at least 1.022 MeV in nuclear field and 2.044 MeV in electron field [7,8]. Furthermore, the transmission of radiation depends upon the atomic number and the density of the absorber which will enhance the previous interactions and, to some extent, on the geometry of the experimental setup. For materials composed of various elements, the attenuation process is related to effective atomic number Z_{eff} which varies with energy [9]. In this case, the total attenuation coefficient $(\mu/\rho)_T$ is related to (μ/ρ) values of constituents by the following mixture rule

$$(\mu/\rho)_T = f_1(\mu/\rho)_1 + f_2(\mu/\rho)_2 + f_3(\mu/\rho)_3, \tag{2}$$

where f_i are weight fractions of constituent elements such that

$$f_1 + f_2 + f_3 = 1 \tag{3}$$

From the measured values of μ/ρ, the total atomic cross-section σ_{tot} is obtained by the following relation [10]:

$$\sigma_{tot} = (\mu/\rho)_T \frac{A_r}{N_A} \tag{4}$$

Where

$$A_r = \frac{\sum_i n_i A_i}{\sum_i n_i} \tag{5}$$

N_A is Avogadro's number, A_r is the average atomic mass of the compound, n_i is the number of atoms (with respect to mass number), A_i is the atomic mass of the *ith* element in a molecule. σ_{tot} can also be calculated using the following relation [11,12]

$$\sigma_{tot} = \frac{(\mu/\rho)_T}{N_A \sum_i f_i / A_i} \tag{6}$$

Furthermore, σ_{tot} in turn can be written as the sum of the partial cross-sections:

$$\sigma_{tot} = \sigma_{coh} + \sigma_{incoh} + \sigma_{photo} + \sigma_{pair\,elec} + \sigma_{pair\,nucl} \tag{7}$$

in which σ_{coh}, σ_{incoh} are the coherent (Rayleigh) and the incoherent (Compton) scattering cross sections respectively, σ_{photo} is the atomic photoelectric cross-section, $\sigma_{pair\ elec}$ is the pair production cross-section in electron field and $\sigma_{pair\ nucl}$ is the pair production cross-section in nuclear field.

The total electronic cross-section is related to $(\mu/\rho)_T$ as given by the following relation [13]:

$$\sigma_{T.E} = \frac{1}{N_A} \sum f_i \frac{A_i}{Z_i} (\mu/\rho)_i \tag{8}$$

The total electronic cross-section is also related to effective atomic number (Z_{eff}) of the compound through the formula

$$Z_{eff} = \frac{\sum_i n_i z_i \sigma_{T.E}}{\sum_i n_i \sigma_{T.E}} \tag{9}$$

as given by Ref. [14]. Other expressions for the effective atomic numbers are found in Refs. [12, 13, 15].

Experimental Details

The experimental arrangement with the electronic configuration is schematically shown in Fig. (1). A 5.08 cm ×5.08 cm NaI(Tl) crystal detector having an energy resolution of 8.4% at 0.662 MeV gamma ray from the decay ^{137}Cs was coupled to Norland 5300 Multichannel analyzer (MCA) of 1024 channels. The crystal photomultiplier assembly was shielded in hollow lead cylindrical parts with a wall thickness of 4.5 cm. The inner face of the cylindrical lead parts was lined with aluminum sheet. The source was placed in a perspex plate below a cylindrical lead collimator of 13.3 cm in height and a 1.11cm inner diameter, and a wall thickness of 6.56 cm at a distance of 12 cm from the face of the detector.

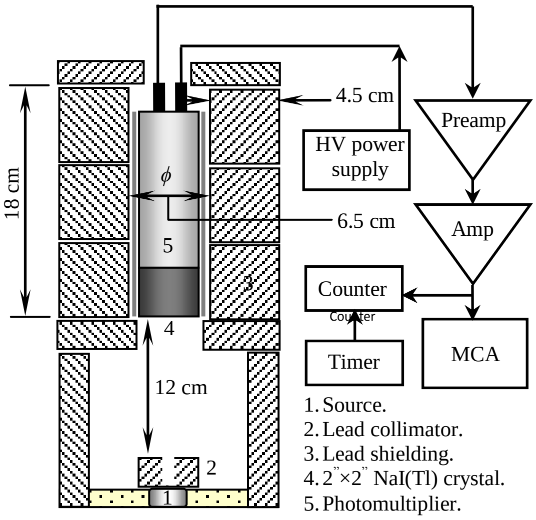

Fig. (1) Experimental setup.

The radioactive sources ^{90}Sr/^{90}Y beta source of energy range (0.546-2.274) MeV and ^{133}Ba (0.383 MeV), ^{137}Cs (0.662 MeV), and ^{207}Bi (0.569 and 1.064 MeV) gamma sources were used in the present research.

CR-39 samples of size 1×1 cm^2 were cut from commercially available sheets (thickness ≈ 0.518 mm). It must be emphasised that it is desirable to use very thin absorbers to estimate the absorption coefficient in order to diminish the background caused by bremsstrahlung. The attenuator samples were placed close to the collimator so that almost all the transmitted rays could be detected. The attenuator thickness was increased in steps and the corresponding transmitted rays intensities were determined for fixed preset time in each experiment. The statistical uncertainty was kept below 0.3% by choosing the counting time (600 sec) so that 10^4-10^5 counts were recorded. The counting rates corrected for back ground.

Result and Discussion

The beta ray spectra after attenuating in deferent thickness of CR-39 samples are shown in Fig.(2). In the case of ^{90}Sr/^{90}Y, it is not possible to estimate the absorption coefficients of ^{90}Sr and ^{90}Y through Eq. (1) due to the equilibrium mixture of both radionuclides. Therefore, we assume that the count rate I through external absorbers of thickness x is represented by [16]

$$I(x) = \frac{I_o}{2}\left(e^{-\mu_{Sr-90}x} + e^{-\mu_{Y-90}x}\right) \tag{10}$$

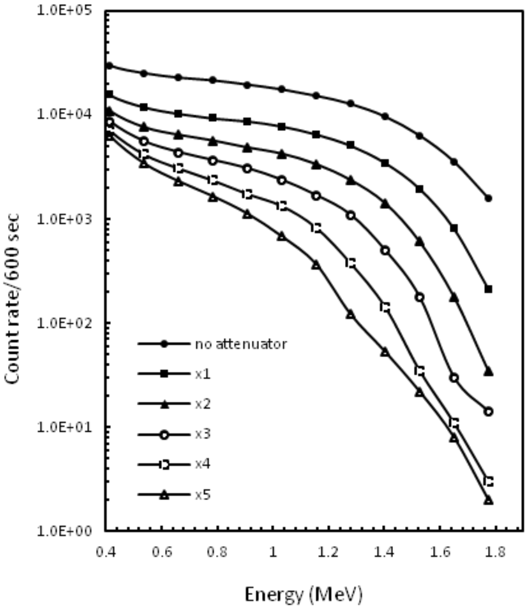

Fig.(2): The spectra of ^{90}Sr/^{90}Y beta rays attenuation in different thickness of CR-39 samples.

Fig. (3) shows the *I(x)* as a function of attenuator thickness. The experimental data were fitted using Equ. (10). The number of fitting points was chosen depending on the range of beta rays. The experimental values of ^{90}Sr and ^{90}Y mass attenuation coefficients through a CR-39 samples were found to be 10.06 cm2 g^{-1} and 8.31 cm^2 g^{-1} respectively.

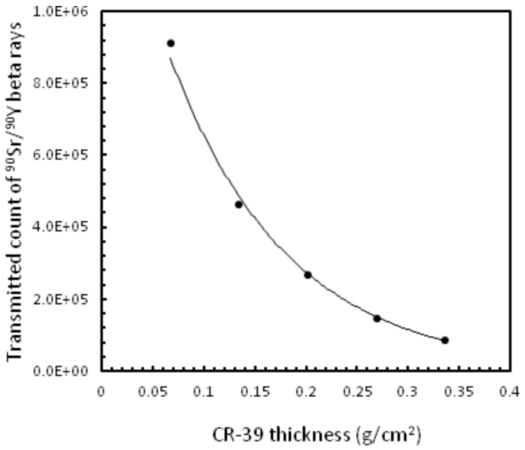

Fig. (3): Count rate as a function of CR-39 attenuator thickness for ^{90}Sr/^{90}Y

With regards to gamma rays, the total mass attenuation coefficients $(\mu/\rho)_T$ were calculated as a function of gamma energies ranging from 1keV- 10^5 MeV via a very accurate computer programs WinXCOM and MathCAD and the data base prepared Berger et al [17].The calculated results are shown in Fig. (4). A comparison was made between the experimental and theoretical values and displayed in Fig. (5). As can be seen from these figures, the $(\mu/\rho)_T$ decrease with the increasing photon energies and comparison with the measurements gives fine agreement.

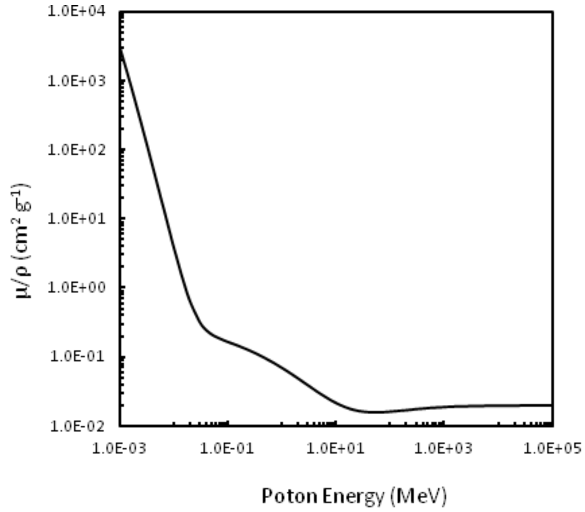

Fig.(4): Total mass attenuation coefficients for CR-39 as a function of photon energy.

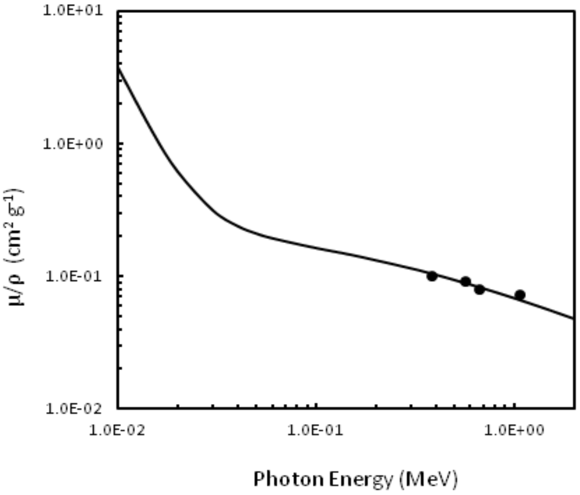

Fig.(5): Comparison of experimental values of CR-39 mass attenuation coffeicients (filled circles) with theoretical values

coefficients for photoelectric absorption, scattering (coherent and incoherent) and the pair production process are displayed in Figs.(6-7) as a function of photon energy.

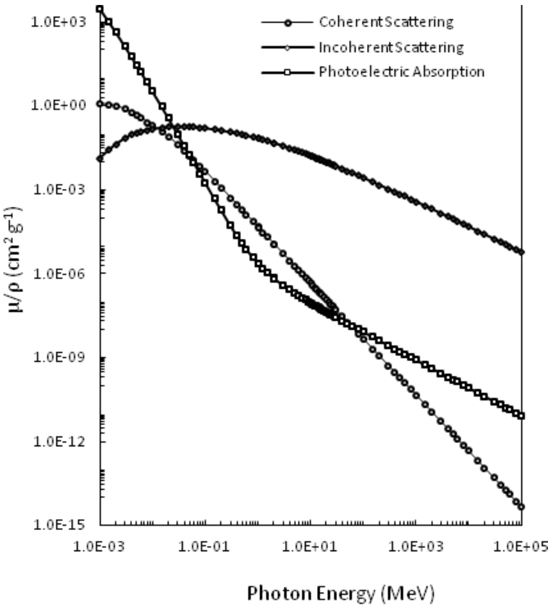

Fig.(6): Gamma ray mass attenuation coefficients vs photon energy for photoelectric absorption, coherent and incoherent scattering.

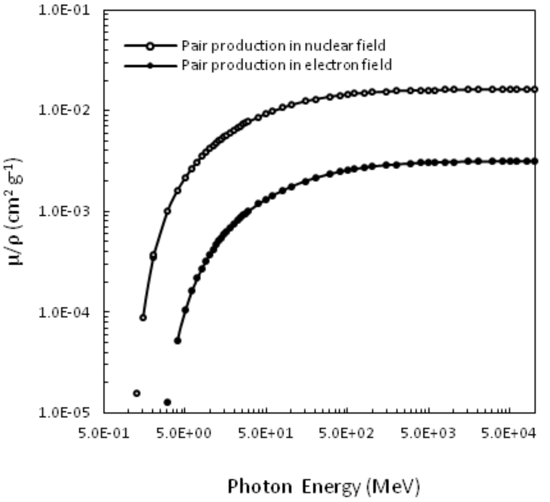

Fig.(7): Gamma ray mass attenuation vs photon energy for pair production in electron and nuclear fields

It can be seen from those figures that: Although photoelectric absorption and scattering are the dominant reaction channel in the low photon energy region the atomic photoelectric absorption is a major contributor to the attenuation coefficients.

Although all three processes are possible in the middle energy region, the scattering process is the main reaction channel. In the case where high-energy region pair production process becomes the dominant reaction channel, the others are possible but in very small value.

The theoretical values of total and partial mass attenuation coefficients have been used to calculate total atomic and electronic cross-section of CR-39 detector using Equs. 6 and 8. The results are depicted in Fig. (8) which in turn were used to find the effective atomic numbers. The plots of cross-section with photon energy show an almost similar behavior $(\mu/\rho)_T$ plot.

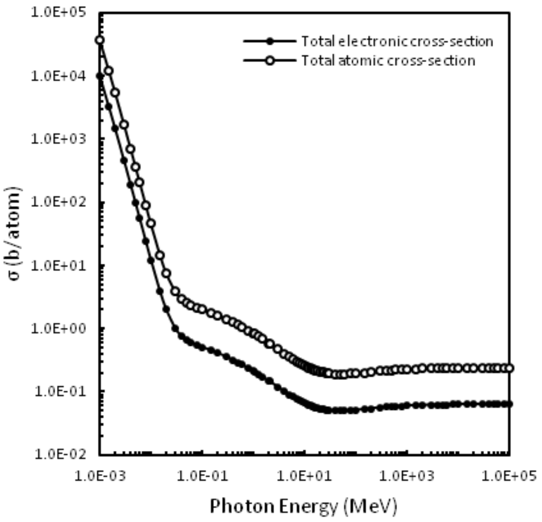

Fig.(8): Variation of tota atomic and electronic cross-section vs photon energy

The variation of Z_{eff} versus photon energy is shown graphically in Fig. (9). It shows the dominance of different interaction processes in different energy regions which is in line with previous researches [18] which reported that Z_{eff} is different for different interaction processes. In the low energy region, photoelectric interaction is dominant, Z_{eff} varies in a similar way as in case of photo interaction process. From 10-20 keV onward, there is sharp decrease in Z_{eff} with energy up to 200 keV, showing the contribution of scattering processes which d Ref. [19] who confirmed that Z_{eff} of compound material for photoelectric interaction is greater than of other processes.

From 200-1200 keV Z_{eff} is almost independent of energy. This may be due to the dominance of incoherent scattering in this energy region.

From 1.2-1200 MeV, there is a regular increase in Z_{eff} in photon energy. This behavior is due to mixed contribution of incoherent scattering and pair production. Above 1200 MeV, the Z_{eff} remains almost constant. This may due to the dominance of pair production in high energy region.

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