Study the Attenuation Ability of γ-Rays Emitted from Co-60 Radioactive Isotope in PES/CaFe2O4 Composite Shields

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Abstract:

In this present study, nuclear composite shields were prepared from polyester (PES) as a matrix material and reinforcement it with a ferrite spinel powder (CaFe2O4) prepared with three different sintering temperatures (800, 1000, and 1200Co) by the ceramic method to obtain a different granular size powder . Attenuation parameters of γ-rays emitted from the Co-60 radioactive isotope were studied using GM counter tube for six types of shields. The first type was PES pure shield, and the others were composite shields consist two types of PES reinforced by 15% concentration of reinforced powder prepared with different sintering temperature degrees (800, 1000Co), and three types with different concentrations (2%, 7% and 15%) of reinforced powder prepared with sintering temperature degree of 1200Co. The results showed that the transmission factor (TF) value decreased with increasing of the sintering temperature degree of reinforcement powder and its concentration in composite shields, and increased with increasing of the thickness of the shield. Also, the linear attenuation coefficient (μ) calculations showed increasing its value with increasing of concentration and sintering temperature degree of reinforced powder. In addition, It was observed that when both of the concentration and its sintering temperature degree of reinforced powder were increased, the values of half value layer (HVL), the tenth value layer (TVL), and the mean free bath (λ) were decreasing. These results show that the PES/15%CaFe2O4 that prepared at 1200Co was the best shield because it achieved a higher value of μ and lowest values of HVL, TVL and λ compared to the other shields.

Keywords: Gamma rays, Composite shields, Ferrite spinel, Attenuation coefficient, Transmission factor.

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1.INTRODUCTION:

The radiation in the form of particles such as protons, neutrons, alpha, and beta or in the form of electromagnetic radiation such as Gamma and x-ray is described by its mass, kinetic energy, and charge. All these parameters determine the type of interaction of these radiations with the matter. Generally all those interactions either ionize the atoms of the matter by losing a number of orbital electrons of the atoms and make them excited state and transform them to positive ions or excite them by transferring its electrons to higher orbits. Generally the charged particles loss most of its energy by ionization, while neutrons and photons loss its energy by scattering and absorption [1].

The transition of the photonic radiations within the matter, they either may pass without interaction with the matter or may be partially or completely absorbed by absorption or scattering interactions respectively, therefore, the attenuation process do to these interactions depends on the geometry of the beam where the photons may be absorbed or reached the target point with its original energy if the beam is collimated, but if it is uncollimated, the photons will loss part of its original energy by scattering interactions so these photons with different energies will reach the detector furthermore the incident photons and that cause uncertainty in shielding properties calculations and in design nuclear shields [2].

Interaction of Gamma rays with the material is a complex process. Some characteristics related to this process can only described by electromagnetic quantum theories. The photon interacts with the material in twelve reactions, but the most famous of these interactions are Photoelectric effect, Compton scattering, and Pair production[3]. It should be noted here that the conditions for these interactions vary from one interaction to another [4]. There are many materials that can be used for attenuation of radiation as a radiation shields because they have the ability to attenuate and absorb radiation. Radiation shields are used as container of radioactive sources or to make radiation shields [5]. Therefore, it is possible to manufacture nuclear shields from composite materials that are easy to manufacture and configure and in the same time are lightweight and can be used instead of heavy shields such as lead. Note that composite materials are solid materials resulting from the participation of two or more materials so that each material represents a separate phase in the system, and the purpose of this participation is to obtain materials with good properties combining the properties of the constituent materials and exceeding the undesired properties to be suitable for technological applications. It can be defined as a link between two or more material to form a substance that has better qualities and different from the original components [6]. The composite material consists of:

Basic material: (Matrix material) which is one of the components of the composite material and its main function is to connect the reinforcement material, and to maintain the materials of the reinforcement from the weather conditions and change in temperature and oxidation and corrosion and also transfer the load to the reinforcing materials [7]. The matrix material is often characterized by low density, hardness and resistance compared to reinforcement materials [8]

Reinforcement materials: These materials strengthen the matrix material, and it may be a metal, ceramic, or polymeric material and characterized by general characteristics depending on the type of material and the purpose that used for it, and its classified depending on the shape and dimensions into particles, fibers or flakes [10, 9].

The final properties of the composite material reinforced by particles are affected by a number of factors, some of which relate to the properties of the matrix material and the properties of the reinforcing material such as the type, size, and shape of the particles and their distribution within the matrix material. The strength of the bond between the matrix material and the particles has a great effect on determining the properties of the final composite material [11]. Ferrite materials are considered to be a reinforcement type of reinforcement in particles, the ferrite is a ferromagnetic material that has unique properties that make it with different and important applications [12]. Ferrite materials are compounds containing iron, in addition to other metals such as calcium, nickel, etc. It possesses self-magnetic under a certain temperature in addition to possession of magnetic fields, and the materials of ferrite are classified into three varieties: Spinel Ferrites, Garnet Ferrites, and Hexagonal Ferrites [13.[

2.EXPERIMENTAL DETAILS:

The practical part consists of two main parts. The first part includes the preparation of nuclear shields used in this research and the second includes experimental arrangements for the electronic counting system, the geometrical arrangement of the system and the special calculations of the coefficient of attenuation of gamma rays.

The calcium ferrite ($CaFe_2O_4$) powder prepared according to the ceramic method (the solid state reaction method). It is a mixture of Fe_2O_3 with calcium carbonate ($CaCo_3$) according to the atomic weights of each. The material is mixed with solid state and liquid state by adding distilled water and then it dried with temperature 150 Co. This powder is sintered in three different temperatures (800, 1000, and 1200Co) to get pure calcium ferrite with different powder size [12]. After that, this prepared powder of ferrite is added to the polyester (as a reinforced material) according to the sintering temperature degrees and with variable concentrations. Polyester material (PES) is in the form of paste hardened by adding the hardener material. Therefore, six types of nuclear shields were prepared, one of shields is a pure PES, two of them is PES with 15% concentration of $CaFe_2O_4$ powder prepared with sintering temperatures of 800 and 1000Co, and the last three shields of PES with 2%, 7% and 15% concentrations of $CaFe_2O_4$ powder prepared with sintering temperatures of 1200Co. For each of these six types of shields, four thicknesses were prepared (0.9, 1.8, 2.7 and 3.6cm). Note that the samples are cylindrical with a circular section of 4cm diameter and 0.9cm thickness, and to obtain a narrow beam of Gamma rays, lead collimator were used with appropriate dimensions. The choice of PES from many polymers is due to many reasons, the most important one is that it can be formed in any shape we want through the mold that is designed for this foundation, which then hardened by the addition of the hardener. The second reason is that the polyester is characterized by strong bonding and then its strong resistance against Gamma rays [14.[

The system of work and measurement was used in this research consists of the following parts:

.2.1The Geiger-Muller (GM) counter which has the following specifications: (GAT: PA1885-020,030 / TYPE ABC, hi-energy ALPHA/BETA/GAMA/ INDUSRIAL EQUIPMENT & CONTROL PTY. LTD. AUSTRALIA). The operating voltage of the GM counter was 500V and the timer of the count rate was placed a time of 100s.

.2.2The radioactive source that used in this study is Co-60 isotope with radioactive activity 0.699μCi and a half-life of 5.27y, which emits two Gamma photons 1.333MeV and 1.173MeV, that is, it emits γ-rays at a rate of 1.253MV. It was placed at a distance of 11cm from the detector window .

For the purpose of studying the attenuation coefficient of the manufactured shields, two collimators were used to obtain a good geometric arrangement as shown in Fig. 1. These collimators are made of lead material with dimensions of 5×5×1.5cm with dimensions (5×5×1.5)cm with a 1.6cm diameter circular hole.

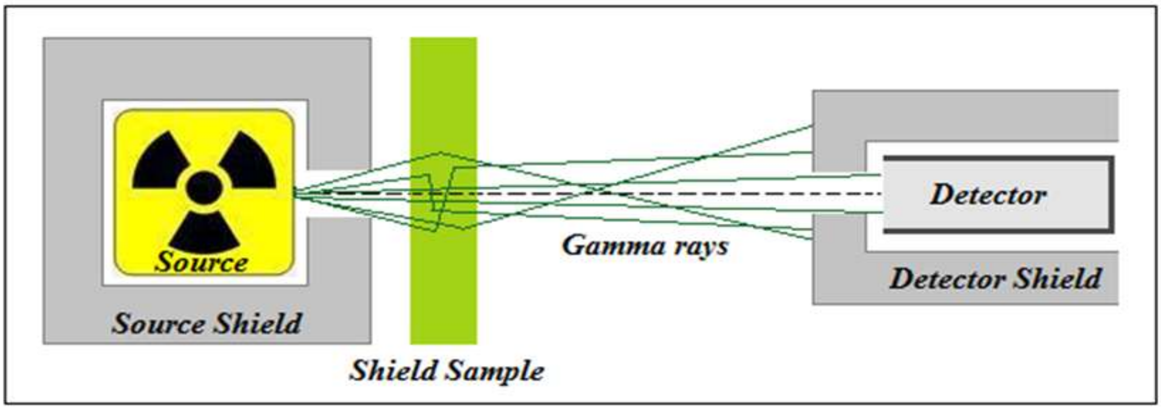

Fig. 1 - The system of work and measurement.

3.THEORETICAL CONCEPTS

The absorption process of rays is called the attenuation that is known as a reduction in the intensity of the rays out of the material and can be calculated as an exponential function:

$I=I_o e^{(-\mu x)}$…………………(1)

where I is the intensity of Gamma rays passing through the absorbent medium, Io is the intensity of γ-rays before entering the medium, x is the thickness of absorbent medium, and μ is the linear attenuation coefficient.[5[

To calculate the linear attenuation coefficient, a natural logarithm is taken for the ratio between the I to Io , from equation (1) we obtain:

$\ln(I/I_o) = -\mu x$…………………(2)

By plotting the linear relationship between the values of $\ln(I/I_o)$ as a function of the thickness values (x), we obtain a straight line whose slope equals (-μ).

The transmission factor (TF) is defined as the ratio between the intensity of the radiation passed within a material (I) and the incident radiation intensity in the absence of the shield material (Io) which is a function of the radiation energy, and the medium type and thickness can be written as:[15].

$TF=I/I_o$ ………………………(3)

The mean free path (λ) is defined as the mean of the distance the photon travels inside the material before absorbing, and it can be calculated by the following formula:

$\lambda=1/\mu$……………….………(4)

Also the half value layer (HVL) can be defined as the thickness of the shield material required to reduce the value of the rays intensity to half of its original value at a specified energy given by the following formula:

$HVL=\ln/2\mu$…………………(5)

Moreover, the tenth value layer (TVL), which represents the thickness of the shield material to reduce the value of the rays intensity to 10 times of its original value, as in the following formula [16]

$TVL=\ln/10\mu$………………(6)

4.RESULTS AND DISCUSSION

Each type of used composite shields was assigned own symbol and arranged in table 1, for easy reference in tables and graphs.

Table 1 - The shield symbol, type, concentration, and sintering temperature degree.

Symbol	**Type of Shield**
P	Pure Polyester
P1	Polyester + 15% Spinel Ferrite prepared at $800C^0$
P2	Polyester + 15% Spinel Ferrite prepared at $1000C^0$
P3	Polyester + 2% Spinel Ferrite prepared at $1200C^0$
P4	Polyester + 7% Spinel Ferrite prepared at $1200C^0$
P5	Polyester + 15% Spinel Ferrite prepared at $1200C^0$

The results and calculations of this study were arranged in tables 2, 3 and 4 respectively. The relationship between variables was plotted in two-dimensional graphs.

Table 2 - The count rate (I) and the $\ln(I/I_o)$ values of the γ-rays as a function of the shield material thickness X in units of cm and the type of shield using Co-60 radioactive isotope.

Type of Shield		X (cm)	0	0.9	1.8	2.7	3.6
	P	I (#/100s)	1454	1217	1085	991	893
		$\ln(I/I_o)$	0	-0.1779	-0.2927	-0.3834	-0.4875
	P1	I (#/100s)	1454	1179	978	864	691
		$\ln(I/I_o)$	0	-0.2097	-0.3966	-0.5205	-0.7439
	P2	I (#/100s)	1454	1112	908	729	592
		$\ln(I/I_o)$	0	-0.2682	-0.4708	-0.6904	-0.8986
	P3	I (#/100s)	1454	1101	958	790	598
		$\ln(I/I_o)$	0	-0.2781	-0.4172	-0.6100	-0.8885
	P4	I (#/100s)	1454	1076	885	710	575
		$\ln(I/I_o)$	0	-0.3011	-0.4965	-0.7168	-0.9277
	P5	I (#/100s)	1454	1041	847	668	547
		$\ln(I/I_o)$	0	-0.3341	-0.5404	-0.7778	-0.9776

Table 3 - The calculated values of TF as a function of the type and thickness values (X) of studied shields using Co-60 radioactive isotope.

X (cm)	TF					
	Type of Shield					
	P	P1	P2	P3	P4	P5
0	1	1	1	1	1	1
0.9	0.8370	0.8108	0.7648	0.7572	0.7400	0.7160
1.8	0.7462	0.6726	0.6245	0.6589	0.6087	0.5825
2.7	0.6815	0.5942	0.5014	0.5433	0.4883	0.4594
3.6	0.6142	0.4753	0.4071	0.4113	0.3955	0.3762

From calculation of the ratios of the counting rates (I/Io), that represents TF, for all samples, we can have Fig. 2 by plotting its values as a function of the shield thickness (X). Then by calculate the natural logarithm of the counting rates (Ln(I/Io)) and plot its values as a function of the shield thickness (X) in Fig. 3.

From those figures, we deduce that the TF value decreases as the thickness increases as shown in Fig. 2 , and the Fig. 3 shows that the slope of the straight line of the relationship between the Ln(I/Io) as a function of X that represents the linear attenuation coefficient of the shield material against γ-rays at studied energy (1.253MV.(

Table 4 - The values of μ in units of cm^{-1}, HVL, TVL and λ in units of *cm* as a function of shield type using Co-60 radioactive isotope.

Type of Shield	μ (1/cm)	HVL (cm)	λ (cm)	TVL (cm)
P	0.1312	5.2831	7.6220	17.5502
P1	0.1998	3.4692	5.0050	11.5245
P2	0.2466	2.8108	4.0552	9.3373
P3	0.2343	2.9584	4.2680	9.8275
P4	0.2523	2.7473	3.9635	9.1264
P5	0.2665	2.6009	3.7524	8.6401

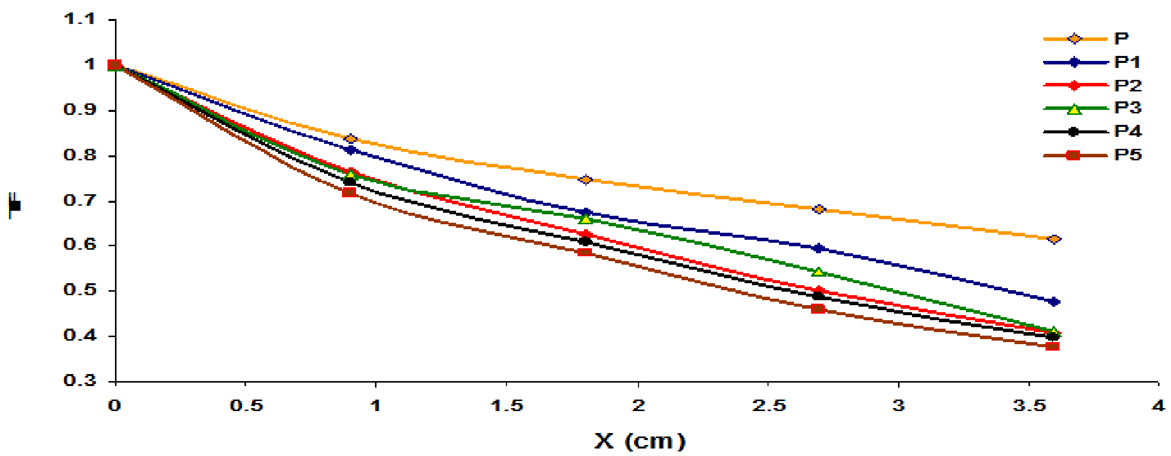

Fig. 2 - The relationship between TF values as a function of the shield thickness (X) using Co-60 radioactive isotope for all types of shields.

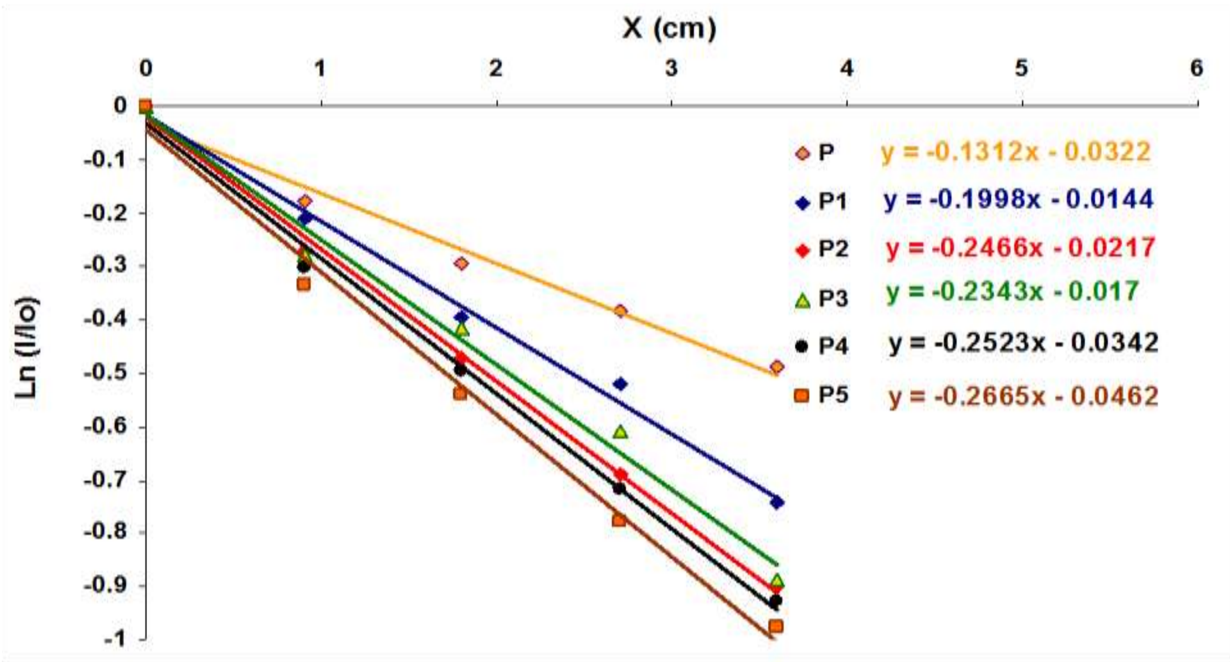

Fig. 3 - The relationship between Ln(I/Io) and the shield thickness (X) using Co-60 radioactive isotope for all types of shields.

Fig. 4 shows a diagram of the linear attenuation coefficient (μ) values for all the types of shields that used in this study. It is concluded from this diagram an increase in μ for sample in which the ferrite powder has a higher concentration and is sintered at higher sintering temperature .

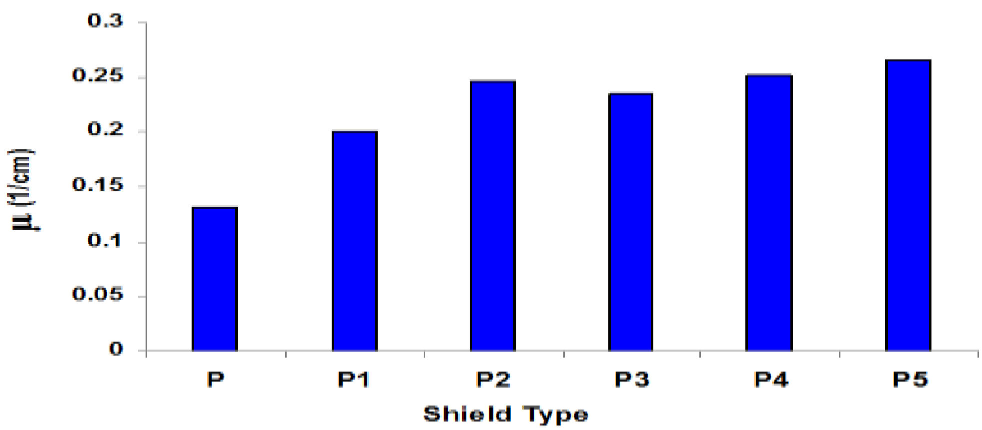

Fig. 4 - A diagram of the μ values as a function of the shield type using Co-60 radioactive isotope.

This indicates that the increasing of the sintering temperature degree and the concentration of the reinforcement material have a significant role in the attenuation process and the reason is to increase the particle size with increasing the temperature degree of sintering and therefore the cross section of the γ-rays interaction with the matter of shield is large causing attenuation and weakening of the incident photons, and this is consistent with previous researches [17.[

Fig. 5 shows a diagram of the mean free path values (λ), the half value layer (HVL), and the tenth value layer (TVL) as a function of the shield type. The diagram shows that the values of these quantities gradually decrease as the concentration and sintering temperature degree of the reinforcement powder increases. These quantities will be as low as the shield P5, which contains a concentration of 15% of the reinforcement powder that sintered at temperature degree of 1200Co, where the density of the shield material and granular size of the reinforcement powder in this type of shield is greater than the other shields because the relationship between the density of the material and granular size and the sintering temperature of the powder is a direct relationship and this makes the beam of photons suffer more attenuation for each length unit by increasing the concentration of matter because of the large probability of interaction with the substance which leads to decreasing the length path during the shield material and this is consistent with the results of previous studies [16, 18].

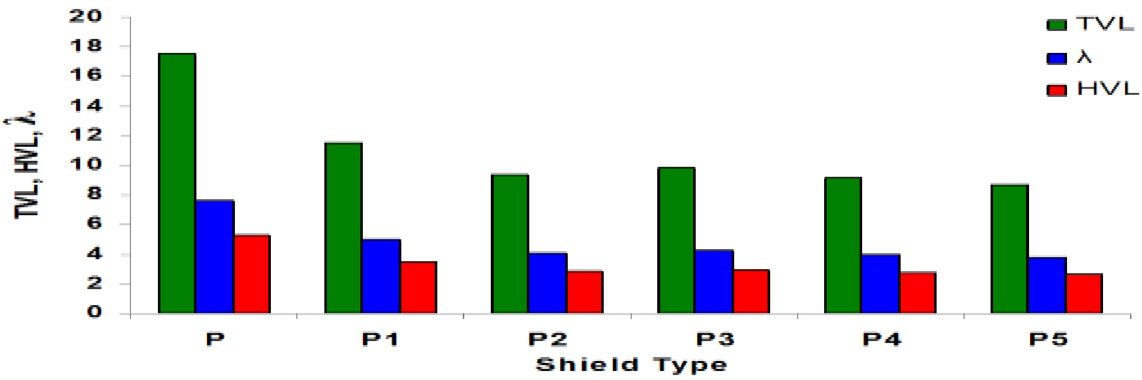

Fig. 5 - A diagram of HVL, TVL and λ as a function of shield type using Co-60 radioactive isotope.

Fig. 6 shows the relationship between HVL, TVL and λ of the used shields as a function of the linear attenuation coefficient. From this figure, we observe that the values of these quantities decrease by increasing the linear attenuation coefficient of γ-rays.

The reason for this difference in data which also affects the accuracy of shield calculations is the change in the radiation spectrum that occurs with increased depth in materials, depending on the composition of the photon spectrum of radionuclides and materials [16, 18]

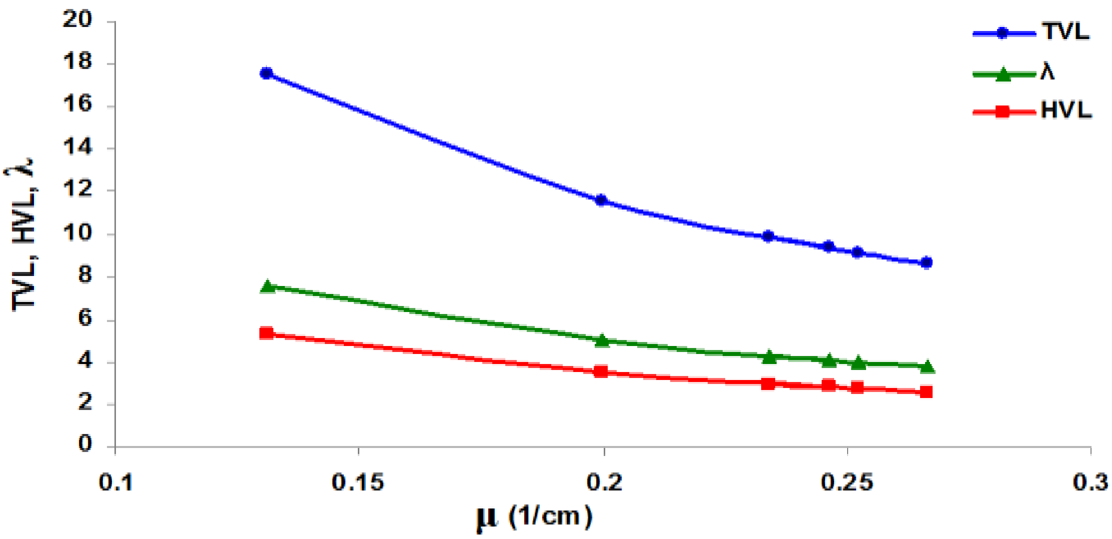

Fig. 6 - The relationship between HVL, TVL and λ as a function of the μ for all used shields using Co-60 radioactive isotope.

5.CONCLUSIONS:

One can gets some important conclusions as following:

The sintering temperature degree of the prepared ferrite has a very important effect in the formation of the pure ferrite phase free of the secondary phases as well as increasing the granular volume of the ferrite material and thus producing a pure material with high absorption.

The value of the linear attenuation coefficient increases with increasing of the sintering temperature degree of the ferrite material as well as increasing the its concentration in the polyester.

The most successful shield is the shield that has highest value of the attenuation coefficient (μ) and lowest value of the transmission factor (TF). It was achieved at shield type of P5 that containing the powder of ferrite prepared at the sintering temperature degree of 1200Co with the 15% concentration.

The composite shield that consists of Polyester reinforced by 15% of CaFe2O4 powder that is sintered with temperature of 1200Co have the lowest values of the half value layer (HVL), tenth value layer (TVL), and mean free path (λ) parameters, which indicates that this type of shield is the best among other studied shields in the use as a nuclear shields .

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المستخلص :

في الدراسة الحالية ، تم إعداد الدروع المتراكبة النووية من البوليستر (PES) كمادة أساس وتقويتها بمسحوق الإسبنيل فرايت (CaFe2O4) المعد بثلاث درجات حرارة تلبد مختلفة (800 ، 1000 وCo1200) باستخدام الطريقة السيراميكية للحصول على مسحوق مختلف الحجم الحبيبي. تمت دراسة معلمات التوهين للأشعة المنبعثة من نظير Co-60 المشع باستخدام أنبوبة عداد كايكر (GM) لستة أنواع من الدروع. النوع الأول هو درع البوليستر النقي (PES)، و درعان متراكبان مكونان من نوعين من البوليستر معزّز بنسبة تركيز15% من مسحوق التقوية المحضر بدرجات حرارة تلبد مختلفة (800 و (Co1000، وثلاثة أنواع بتراكيز مختلفة (2% ، 7% و 15%) من مسحوق مادة التقوية تم اعداده بدرجة حرارة تلبد Co1200. أظهرت النتائج أن قيمة عامل النفاذ (TF) انخفض مع زيادة درجة حرارة التلبد لمسحوق التقوية وتركيزه في الدروع المتراكبة، وزادت مع زيادة سمك الدرع. أيضا ، أظهرت حسابات معامل التوهين الخطي (μ) زيادة قيمه مع زيادة التركيز ودرجة حرارة التلبد لمسحوق التقوية. بالإضافة إلى ذلك، لوحظ أنه عند زيادة كل من التركيز ودرجة حرارة التلبيد لمسحوق التقوية فإن قيم طبقة السمك النصف(HVL) ، وطبقة السمك العشري (TVL) ، ومعدل المسار الحر (λ) قد تناقصت قيمها. أظهرت النتائج أن درع المتراكب PES/15%CaFe2O4 التي أعدت في درجة حرارة تلبيد Co1200 كان أفضل درع لكونه قد حقق أعلى قيمة لمعامل التوهين الخطي (μ) وأدنى قيم من HVL و TVL و λ مقارنة بالدروع الأخرى.

الكلمات المفتاحية: اشعة كاما، الدروع المتراكبة، سبينل فرايت، معامل التوهين، عامل النفاذ