Gamma Ray Buildup Factor for Finite Media in Energy Range (4-10) MeV for Al and Pb

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Abstract

A computer program based on Monte Carlo method had been designed and written in visual basic computer language and utilized for simulating the classic problem of gamma ray beam incident on finite plane slabs of absorbing materials. The source geometry adopted in this program is plane normal source. Dose buildup factor of gamma photons in the absence and presence pair production effect have been calculated in the energy range (4-10) MeV for Aluminum and Lead up to 5 mean free path thickness. Dose buildup factor in the presence of pair production is higher than dose buildup factor in the absence of pair production effect. The deviation between the values of dose buildup factor in the presence and absence pair production is increased when the energy is increased within the studied energy range because the cross section for pair production is increased within the studied energy range.

Keywords**:** Dose buildup factor, Simulation, Monte Carlo method.

Introduction

The concept of a gamma ray buildup factor was initially introduced by White early in 1950, after that the importance in gamma ray attenuation studies was confirmed by Fano in 1953 [1]. Since Goldstein and Wilkins provided the comprehensive data in 1954 [2], the buildup factor has been the most important datum among the fields relevant to gamma ray shielding. The buildup factor is usually studied either by theoretical calculation based on the attenuation coefficient table hubble1969 [3] or by experimental measurements. The first approach, which appears continuously in the literature, is more advanced due to the use of highly efficient computers and the possibilities of handling large number of data. The experimental studies of gamma rays buildup factor face many difficulties; highly active sources are needed and the absorber thickness is limited to no more than a few mean free paths, under such circumstances the researchers may be at the risk of exposure to a high ionizing gamma radiation Laith 2001 [4]. For these reasons it is better to use theoretical tools which enable researchers to study in details gamma rays buildup factor Binder 1979 [5]. Monte Carlo method is conventional methodology to solve the gamma transport equation. Many efforts in the study of gamma ray buildup factor have been made during the last four decades. Since the eighties Musilik et al 1980 [6], Hirayama in 1987 [7] and Fong et al 1989 [8], during the nineties Brismeister in 1993 [9] and Kadotani and Shimizu in 1998 [10], from 2000 ,till now, Al-Samaraey in 2002 [11], and Sardari et al 2009 [12], Alamatsaz and Morkari in 2011 [13], and Shirani and Alamatsaz in 2013 [14]. All those researchers calculate buildup factor as a function of shielding thickness for different materials and different energies based on Monte Carlo method.

Theory

The basic idea of Monte Carlo is to create a series of life histories of the source particles by using random number sampling techniques to sample the probability laws that describe the real particle's behavior and to trace out the particles random number movement through the medium.

When Monte Carlo method is used, the particles histories are generated by simulating the random nature of the particles interactions with medium. Life history of a particle is built up from acknowledge of its trajectory through the particular system of interest. Consider the path of the particle as it travels through some homogenous medium. Since the typical particle scatters frequently the path is zig-zag rather in the manner indicated in the Fig.(1).

Here the particle originates at A with known direction and energy. It has a free flight until it has a collision with an atom of the medium. This collision could result in the absorption of the particle and the immediate termination of its history, but it is assumed to be scattering interactions and the particle continues with a new direction and the change of energy (or wavelength). This change of energy and direction is a statistical process which mean that no unique energy and direction after a scattering; rather, there is a probability distribution for each of these variables. After the first scattering the same particle makes another free flight and experiences another collision and so on.

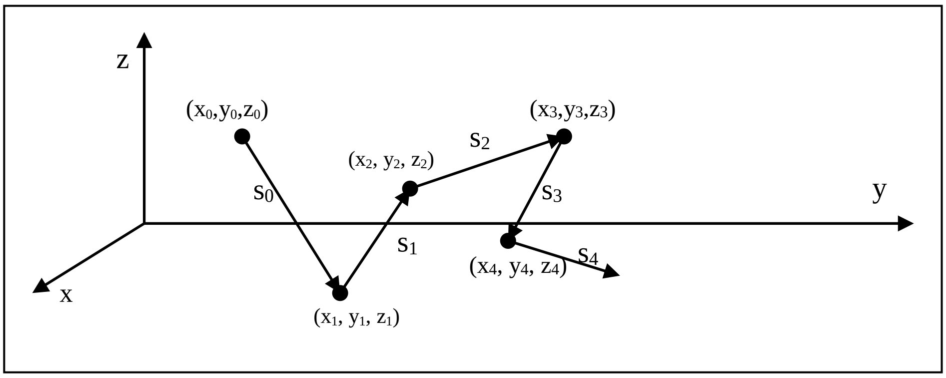


Fig. (1) A typical particle's "random walk" through a medium [15].

In order to track the particle during its journey it is necessary to know: its spatial coordinates(x,y,z), the spherical coordinates (θ,ϕ) of its direction, and its energy E. These variables are sufficient to define the state α of the particle where:

$$\alpha = \alpha\,(x, y, z;\ E;\ \theta,\phi) \quad \text{.............................. (1)}$$

The spherical coordinate system for defining the particle's direction is illustrated in Fig.(2).

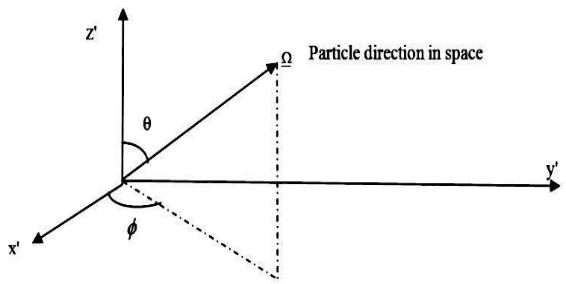


Fig. (2) Particle's direction in spherical coordinates (θ, ϕ), the orthogonal coordinate system (x',y',z') is parallel to the basic reference system (x,y,z) shown in Fig.(2).

A particles trajectory from collision to collision can be constructed as a succession of states α_0, α_1, α_2 and α_n, where i_{th} state is

$$\alpha_i = \alpha_i(x_i, y_i, z_i;\ E_i;\ \theta_i, \phi_i) \quad \text{....................... (2)}$$

That is in the i_{th} state, a particle has the spatial coordinates of the i_{th} collision point and the energy and direction of the particle after the i_{th} collision. With the exception of the initial state each successive state is a function only of the previous state, and scattering laws obeyed by the particle in the material of interest. Thus one could commence with initial or source conditions which define α_0 choosing by random sampling from the relevant probability distributions, the new values of the variable which determine α_1, and so on. In this way, individual life history can be constructed. If we denote by s the path length of the particle to the next collision point, the probability of a particle traveling a distance without having an interaction is

$$\text{Probability } P = e^{-\Sigma s}\, ds \quad \text{............................... (3)}$$

where Σ is the particle's total macroscopic cross section (denoted by μ in the case of photon).

For a moment, it should be assumed that such a procedure is available and that a particular value of s is selected to assign to s_i. Once the value of s_i is determined, the coordinates of the next collision point are readily found from,

$$X_{i+1} = x_i + s_i(\sin\theta_i\cos\emptyset_i)$$
$$Y_{i+1} = y_i + s_i(\sin\theta_i\sin\emptyset_i) \quad \text{.................... (4)}$$
$$Z_{i+1} = z_i + s_i(\cos\theta_i)$$

The energy and direction of particle after scattering is obtained by sampling from the appropriate scattering function. For example, in the case of a photon, the scattering process is Compton scattering and the probability function is given by the Klien-Nishina theory [15].

Program Design

In this study a computer is designed and written to calculate gamma ray dose buildup factor for single layer shield of different materials. The program is written by using visual basic language and utilized for simulating the classical problem of gamma rays beam incident on finite plane slabs of different absorbing materials. The geometry of source used in this program is plane normal source as illustrated in Fig.(3).

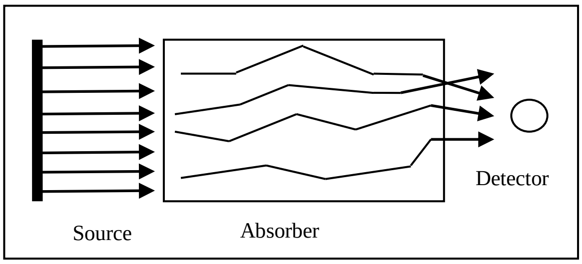


Fig. (3) Geometry of plane normal source and shielding slabs considered by modified program.

The computer program is designed to treat gamma ray penetration through the matter taking into an account the interaction of Compton scattering and pair production in a single layer shield.

The penetration of radiation proceeds by compiling life histories of individual gamma ray as they move about, from the point where they are either absorbed in the shield or pass through it. The basic idea in the program is to compose a series of life histories of the source particles by using random sampling techniques to sample the probability laws that describe the real particle behavior, and to trace out the steps of the particles "random movement" through the medium.

The history of the particle is followed until it can no longer contribute information of interest to the problem in hand. The life history is then terminated and a new particle is started from the source. The applicability of the Monte Carlo technique arises from the fact that the macroscopic cross section may be regarded as the probability of the specific interaction per unit distance traveled by gamma photon.

To start the history of the first photon, it is necessary to determine where the photon has its photon collision. This is done by sampling the first collision probability distribution function $\rho(x) = \Sigma_t\, e^{\Sigma_t\, x}$ where Σ_t (total macroscopic cross section) is evaluated at energy E_o. Suppose that the selected value of (x) is x_i, and the thicknesses of (n) shield layers of different material are ($t_1, t_2, t_3,$ ……t_n), then if (a) represent the total shield thickness, it is necessary to test x_i thus:

1- If x_1> a, then the photon has penetrated the shield without collision, this journey is registered, and the history is terminated.

2- If x_1 < a, a collision occurred within the shield at the point x_1. Now to determine in which layer x_i lies, another comparison is made with different layer thickness, if $x_1 \leq t_1$ then the photon is travelling in the first layer but if $x_1 > t_1$ it doesn't , and the same thing for remaining layers till the position of collision point is determined.

In the particular form of the Monte Carlo method used here, there is a close analogy between the physical particles and the mathematical particles followed by the program. The only sophistication employed is the concept of survival weights. Thus, absorption of the photons is not allowed as such, all collisions are forced to be Compton scattering or pair production. The effect of absorption is accounted for by modifying the weight of the particle after each collision. That is, a particle weight after a collision is obtaining by multiplying the weight before collision by survival ratio, $\mu_c > \mu$ (E) (if we only take the effect of Compton scattering) which is of course the probability that a collision will be a Compton scattering. The applied strategy to account the effect of pair production interaction in this study can be summarized as follows, assuming that the pair production event can occur (i.e. E ≥ 1.022 MeV), then pair production is considered to occur if $\xi > \mu_c / (\mu_c + \mu_{pp})$, where ξ is a random number lying between 0 and 1, otherwise, a Compton scattering take place. In either event, the survival weight factor is given by SURV $= (\mu_c + \mu_{pp})/\mu(\mathrm{E})$. If pair production occurs, the original gamma photon is completely removed and replaced by 2 annihilation gamma photon of 0.511 MeV.

The history of each particle is traced until the particle either escapes from the system, or its energy drops below some preset minimum due to successive scatters. In either event, a new photon is started with an initial weight of unity. The position and direction of a photon are defined by 4-variables (**y**, **z**, **θ**, **φ**), which are referred to as the coordinate system shown in Fig. (2).

The principal quantity computed and output by the program is dose buildup factor, which is a measure of how the transmitted photons are enhanced by Compton and pair production interactions.

Results and Discussion

Dose buildup factor for single layer shield for Aluminum and Lead is calculated using the modified computer program which based on Monte Carlo method, the buildup factor was calculated with thickness in the range (1-5) mfp, and with energy range (4-10) MeV. The parameters that will be studied represent the physical parameters affecting the result of buildup factor (i.e., shield thickness, atomic number of the shield and the energy). Before presenting the results, we will demonstrate the input data of the simulated program which is built and applied in this research.

Physical Parameters

The following physical parameters were considered:

1. Aluminum (Z= 13) and, Lead (Z= 82) are chosen as a shielding materials with density 2.7g/cm^3 and 11.34g/cm^{3}respectively.
2. Cutoff energy; when photon energy isless than cutoff energy, its life history is terminated. The cutoff energy is taken to be 0.019MeV for Aluminum and 0.025 for Lead.
3. Conservation factor for the slab materials =N_A*10^{-24}/A; for Aluminum =0.022379, Lead = 0.0029065.
4. Mass absorption coefficient data, for air in (cm^2/g) which corresponding to the energies values these coefficient are listed in Table (1).
5. Mass attenuation coefficients data in (cm^2/g) for all materials studied in this work which corresponding to the energies values were tabulated in Table (2).

Table (1)
Mass absorption coefficient data, for air in (cm^2/g) corresponding to the energies values [15].

Energy in MeV	μ_{air}	Energy in MeV	μ_{air}	Energy in MeV	μ_{air}	Energy in MeV	μ_{air}
30	0.0146	4	0.0195	0.5	0.0297	0.06	0.0305
20	0.0145	3	0.0211	0.4	0.0295	0.05	0.0406
15	0.0155	2	0.0237	0.3	0.0287	0.04	0.0668
10	0.0156	1.5	0.0256	0.2	0.0268	0.03	0.148
8	0.0163	1	0.028	0.15	0.025	0.02	0.512
6	0.0173	0.8	0.0289	0.1	0.0234	0.015	1.27
5	0.0182	0.6	0.0296	0.08	0.0243	0.01	4.63

Table (2)
The mass attenuation coefficient μ (cm^2/g) for Compton scattering μ_c and pair production μ_{pp} for Aluminum and Lead corresponding to energy interval in (MeV) mesh data [16].

Energy in MeV	Al			Pb		
	μ_c	μ_{pp}	μ_{total}	μ_c	μ_{pp}	μ_{total}
0.5	0.0837	0	0.0837	0.0673	0	0.0673
0.6	0.0775	0	0.0775	0.0626	0	0.0626
0.8	0.0681	0	0.0681	0.0553	0	0.0553
1	0.0612	0	0.0612	0.0499	0	0.0499
1.022	0.0606	0	0.0606	0.0494	0	0.0494
1.25	0.0548	0.000031	0.05483	0.0447	0.00037	0.0450
1.5	0.0498	0.000170	0.0499	0.0407	0.00180	0.0425
2	0.0425	0.000674	0.04317	0.0348	0.00545	0.04025
3	0.0334	0.001918	0.03531	0.0274	0.01192	0.03932
4	0.0279	0.003102	0.03280	0.0229	0.01712	0.04002
5	0.0241	0.004154	0.2825	0.0197	0.02148	0.04118
6	0.0213	0.005098	0.02639	0.0174	0.02523	0.04263
7	0.0191	0.005937	0.02503	0.0157	0.02853	0.04423
8	0.0174	0.006694	0.02409	0.0143	0.03151	0.04581
9	0.0160	0.007377	0.02337	0.0131	0.03421	0.04731
10	0.0148	0.007999	0.02279	0.0121	0.03671	0.04881

Energy Effect

Four energy values (4,6,8,10) MeV is applied in our simulation program for the selected shielding materials and for thicknesses up to 5 mfp. This range of energy was chosen to ensure that the effect of pair production was included in the calculation, and this is one of the most important goals in this study.

The test results as presented in Figs. (4), and (5) for Al and Pb respectively showed that gamma ray buildup factor is inversely proportional with increasing energy. This behavior can be explained that when the energy increased, the penetrating ability for gamma ray is also increase and this led us that the probability of scattering is increased and finally reflected on the buildup calculation, since the scattering play an important role in increasing buildup factor.

The results as also indicates that the rate of increase in the values of buildup factor in Pb more than Al. This is due to the effect of the interaction of the pair production is directly proportional with the atomic number square.

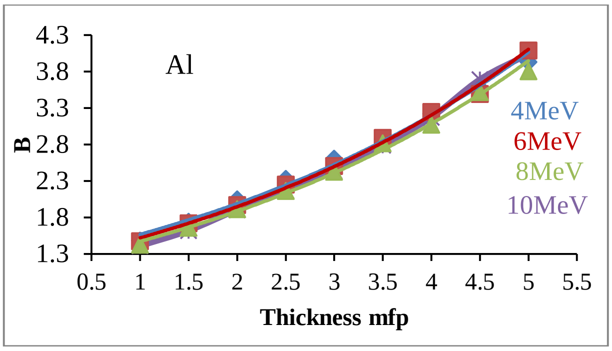


Fig. (4) Effect of source energy on Buildup factor for Al layer.

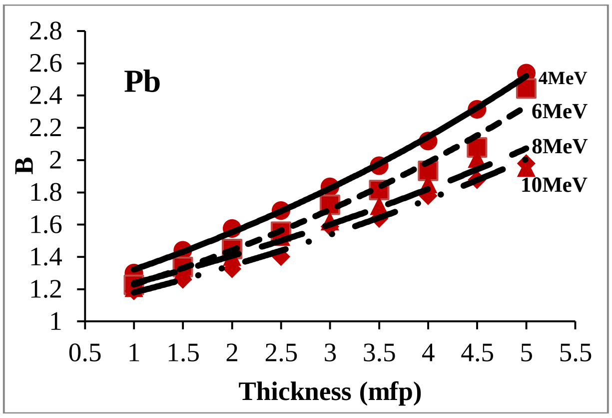
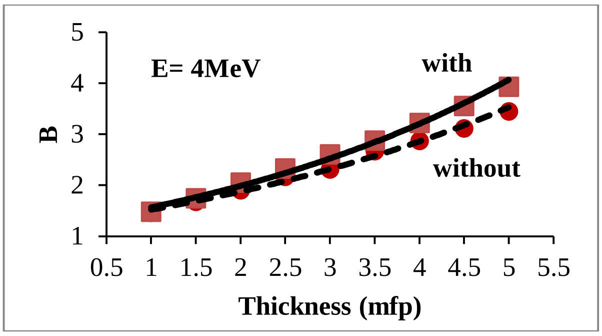


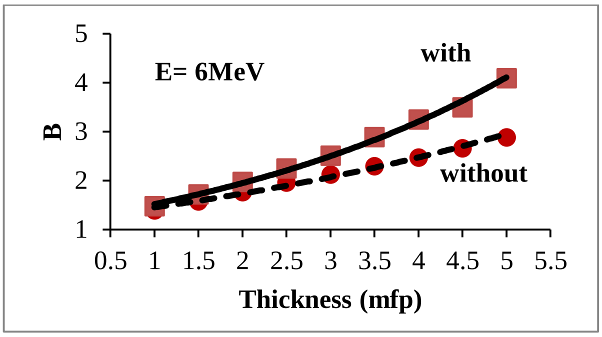
Fig. (5) Effect of source energy on Buildup factor for Pb layer.

To investigate the comparison between gamma ray buildup factor values in the absence and presence the effect of pair production, the simulated program was exacted in the absence of pair production effect (considering the effect of Compton scattering only) by excluding the pair production routine that take the conditions specialized for this type of interaction and in the presence of pair production effect (considering the effect Compton scattering in addition to pair production effect simultaneously).

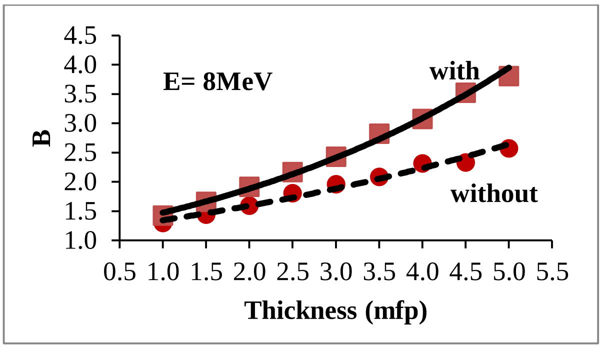
It is clear from Figs. (6) and (7), the calculated values of buildup in the presence of pair production is higher than the calculated value of buildup factor in the absence of the effect of pair production.



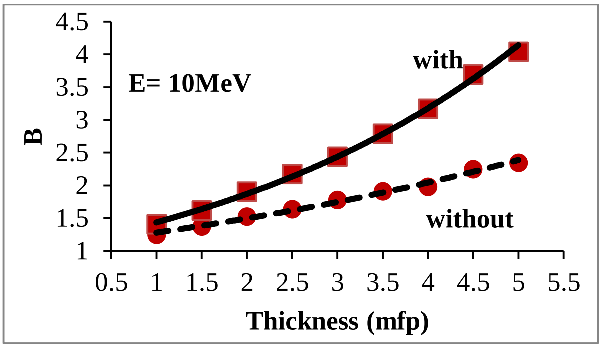
(A)



(B)

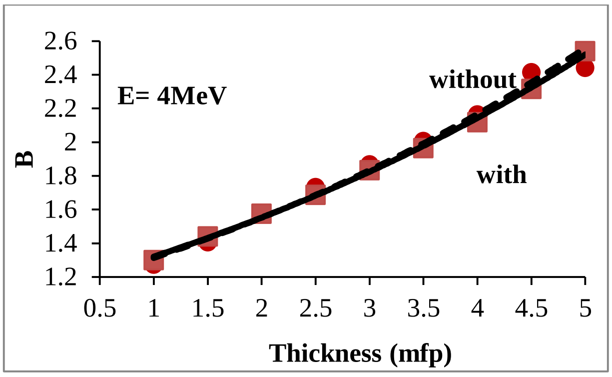


(C)

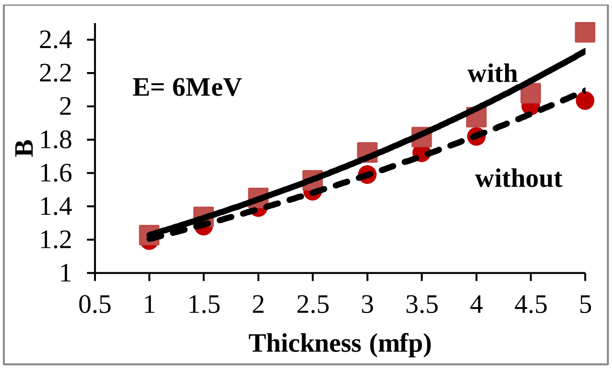


(D)

Fig.(6) The Buildup factor with effect of Pair Production and without it, in Al layer when energy.



(A)



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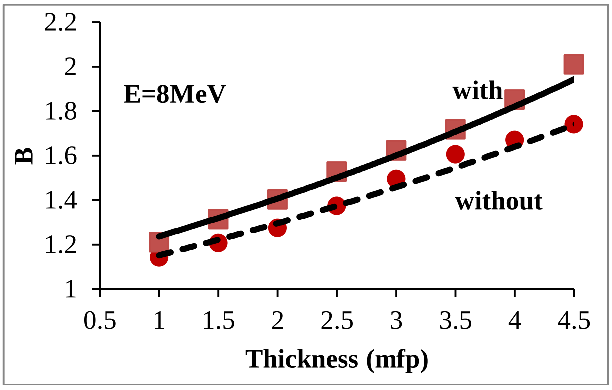

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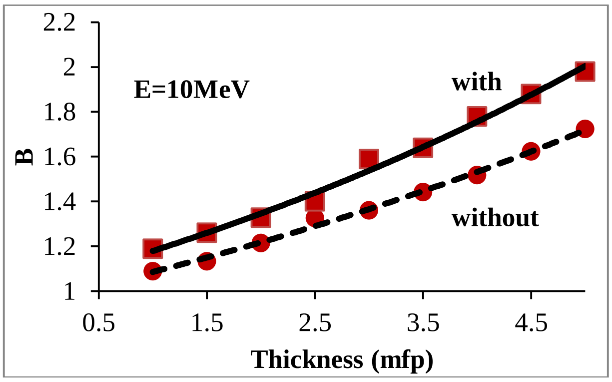
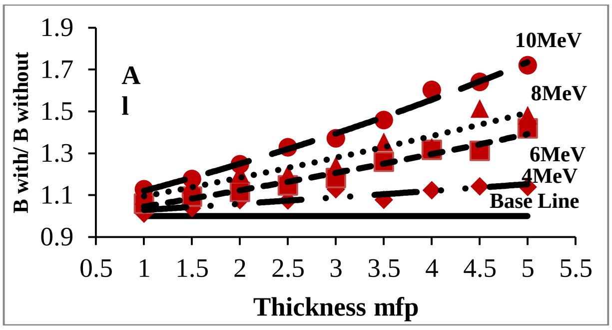


(D)

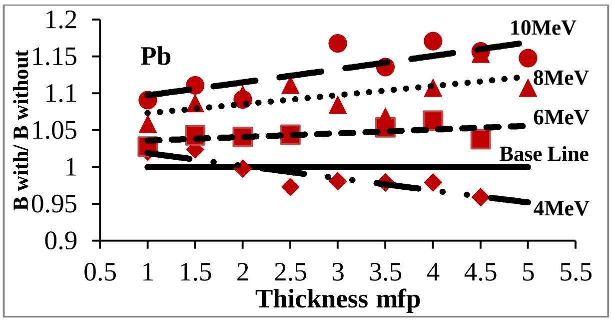
Fig.(7) The Buildup factor with effect of Pair Production and without it, in Pb layer when energy (A) 4MeV (B) 6MeV (C) 8MeV and (D) 10MeV.

This means that the contribution the pair production interaction causes to increase in the value of buildup factor. We can also notice from these figures that the deviation between the two curves (with and without the effect of pair production) is increased when the energy increased within the studied energy range (4-10) MeV and for all the three material chosen up to 5 mfp thickness. We can interpret these results that; the cross section for pair production is increased with the energy is increased within the studied energy range.

The ratio between gamma ray buildup factor in case of with and without pair production effect as a function of material thickness for Al, and Pb for energy (4,6,8, 10) MeV are demonstrated in Fig.(8). It's clear from this figure that the deviation from the Base line is increased with increase of source energy for all the studied material. Also, we can note from this figure that this deviation, more rapidly increased when the atomic number decreased.



(A)



(B)

Fig.(8) The ratio between gamma ray buildup factor in case with and without pair production effect as a function of material thickness for (A) Al and (B) Pb.

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الخلاصة

تم تصميم وكتابة برنامج حاسوبي باعتماد طريقة مونتي كارلو باستخدام لغة بيسك المرئية (الاصدار G) حيث وضفت هذه الطريقة لمحاكاة المسألة التقليدية (الكلاسيكية) في سقوط حزمة اشعة كاما على شريحة مستوية تعمل كمادة موهنة لاشعة كاما. ان الشكل الهندسي للمصدر المشع الذي تم اعتماده في هذه الدراسة وتوظيفه في بناء البرنامج هو المصدر العمودي المستوي. في هذا البحث تم حساب عامل تراكم الجرعة لفوتونات كاما بوجود وعدم وجود تاثير انتاج الزوج ضمن مدى الطاقة (4-10) م.أ.ف لكل من الالمنيوم والرصاص ولغاية سمك 5 معدل مسار حر. ان عامل تراكم الجرعه بوجود تاثير انتاج الزوج يكون اكبر من عامل تراكم الجرعه بغياب تاثير انتاج الزوج حيث وجد ان الانحراف في قيم عامل تراكم الجرعه بوجود وعدم وجود تاثير انتاج الزوج يزداد بزيادة الطاقة ضمن مدى الطاقة المدروس وذلك لان المقطع العرضي لانتاج الزوج يزداد ضمن هذا المدى من الطاقة.