Vol 18 No 6, June 2009
1674-1056/2009/18(06)/2217-06

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

Monte Carlo simulation of the exposure factor*

Zhang Tao(张 涛)[a)b)], Liu Yi-Bao(刘义保)[a)b)†], Yang Bo(杨 波)[b)],
Wu He-Xi(吴和喜)[b)], and Gu Jin-Hu(顾金虎)[b)]

[a)] *Key Laboratory of Nuclear Resources and Environment (East China Institute of Technology), Ministry of Education, Nanchang* 330013, *China*

[b)] *School of Nuclear Engineering and Technology, East China Institute of Technology, Fuzhou* 344000, *China*

(Received 8 October 2008; revised manuscript received 7 November 2008)

In this paper, we simulate the exposure factor by a simple model of a free-air ionization chamber with the Monte Carlo programme Geant4. Special emphasis is placed on the discussion of the exposure factor related to parameters of the chamber model. The reason for the variation in exposure factor with incident ray energy is also analysed in terms of reaction cross section for different types of reactions. The obtained results indicate that our simulation is accurate in the calculation of the exposure factor and can serve as a reference in designing air ionization chambers.

Keywords: exposure factor, Geant4, Monte Carlo simulation, free-air ionization chamber
PACC: 2841, 2850

1. Introduction

The exposure dose is used to describe the ionization power of x or gamma rays in air. In actual work, the ionization power is usually evaluated by the fluence and exposure factor, which should be accurately measured in advance and tabulated. A lot of work has been done on the exposure dose and the associated measurement instrument, i.e. the ionization chamber. But the measured exposure dose is inaccurate and usually needs correction due to the influence of the geometry structure of the ionization chamber.[1−3] Monte Carlo simulation can save the cost of measurement instruments and overcome some physical difficulties, but it still can ensure that accurate results are obtained and offer some guidance in designing measurement instruments.[4]

The remainder of the present paper is organized as follows. In Section 2, the measurement of exposure dose and the calculation of the exposure factor are presented. In Section 3, the simulation system and the Monte Carlo program are described. The simulations and analyses are given in Section 4. Finally, the conclusions drawn from the present study are provided in Section 5.

2. Measurement of exposure dose and calculation of exposure factor

2.1. Free air ionization chamber

The exposure dose is used to describe the ionization power of x or gamma rays in air and is defined as $X = \mathrm{d}Q/\mathrm{d}m$, where $\mathrm{d}Q$ is the absolute value of the total charge of the like-sign ions produced in air when all the electrons (+ or −) liberated by photons in air of mass $\mathrm{d}m$ are completely stopped in air.[5]

The free-air ionization chamber serves as a standard instrument to measure the exposure dose, and is widely used in standards laboratories.[6] Its structure is schematically shown in Fig.1.

The light fence D is the cross section with area ε, which restricts the x or gamma rays incident into the air parallel plates of the chamber. A and B are the high voltage electrode and the collecting electrode of the ionization chamber respectively, and B1 and B2 are the protection electrodes. To insure that secondary electrons do not reach the electrode and that the electron balance condition holds, the vertical distance from the edge of the x or gamma ray bundle to

*Project supported by the National Natural Science Foundation of China (Grant No 10647109), the Foundation for Key Program of Ministry of Education, China (Grant No 208067).
†Corresponding author. E-mail: liuyb01@mails.tsinghua.edu.cn

the electrode, the distance L1 from the front edge of electrode plate B to the light fence D, and the distance L2 from the rear edge of the electrode plate B to the exit of the rays should be at least longer than the maximum range that the secondary electrons can reach in air. Under those conditions, all the ions that are engendered in the collecting volume bounded by protecting wire and electrodes A and B, are produced by the electrons that are liberated by x or gamma rays in the measuring volume V (shaded area in Fig.1).

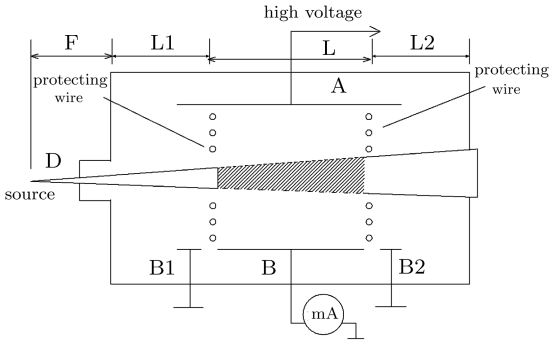


Fig.1. Schematic of free-air ionization chamber structure.

The cross section of the incident ray bundle is inversely proportional to the square of the distance from the measuring spot to the source and the exposure dose. So, the total charge of like-sign ions in the ionization chamber, liberated by the secondary electrons produced in the measuring volume, Q, is given by $Q = X\varepsilon L\rho$, thus

$$X = \frac{Q}{\varepsilon L\rho}, \tag{1}$$

where X in CKg^{-1} is the exposure dose produced by x or gamma rays at the light fence D, ε (in m^2) is the cross section of the light fence, L (in m) is the effective length of the collecting electrode, ρ (in kgm^{-3}) is the density of air under standard atmospheric pressure.

The free-air ionization chamber can be used to measure x or gamma ray exposure dose very well. But when the energy of the incident rays is high, thus the maximum range of the secondary electrons is large (the simulation later shows that when the energy is 3 MeV, the maximum range of the secondary electron can reach 14 m, which means that a huge chamber with a vertical height of at least 28 m is needed), a very large free-air ionization chamber or high-pressure ionization is needed to satisfy the electron balance condition. It is technically difficult to make such a huge ionization chamber. However, when the energy of the incident rays is low, a great error will occur due to the absorption by air. Owing to these factors, the actual energy range of the measured rays is usually limited to a range of 50 keV–3 MeV. However, the physical limitation can be eliminated in Monte Carlo simulations, and in the low energy region, effective incident ray counting can be used to remove the absorption effect.

2.2. Exposure factor

The exposure dose of monoenergetic x or gamma rays has a relationship with its fluence as follows:

$$X = E \cdot \phi \cdot \left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{air}} \cdot \left(\frac{e}{W_{\mathrm{air}}}\right) = f_{\mathrm{x}} \cdot \phi, \tag{2}$$

where E is the energy of the radiation; ϕ is its fluence; $\left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{air}}$ is the energy absorption coefficient of air for the given monoenergetic x or gamma rays in units of $\mathrm{m}^2\mathrm{kg}^{-1}$; e is the electron charge 1.602×10^{-19} C; W_{air} is the average energy absorption that leads to the formation of a pair of ions, which is equal to 33.85 eV; $f_{\mathrm{x}} = E \cdot \left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{air}} \cdot \left(\frac{e}{W_{\mathrm{air}}}\right)$ is the exposure factor, which is equal to the exposure dose corresponding to a unit fluence, in units of $\mathrm{Ckg}^{-1}\mathrm{m}^2$.

Using expressions (1) and (2) and the definition of the fluence $\phi = N/a$[5] yields

$$f_{\mathrm{x}} = \frac{X}{\phi} = \frac{Q}{\rho \cdot L \cdot N} = \frac{E_{\mathrm{d}} \cdot 1.602 * 10^{-19}}{33.85 \cdot \rho \cdot L \cdot N}, \tag{3}$$

where E_{d} is the total energy deposition of the incident rays in the free-air ionization chamber, in units of eV; N is the number of x ray or gamma ray photons incident into the chamber through the light fence.

3. Simulation system and Monte Carlo program

This simulation is performed on the operation system ScientificLinux 4.3.2. The gcc version is 4.3.5. The simulation program is Geant4.[7] The Monte Carlo program Geant4 is developed by the RD44 and Geant4 collaborations.[8] It is flexible and easy to modify for an open source compared with other large Monte Carlo programs, such as MCNP.[9] It is the first Monte Carlo simulation program that adopts object-oriented technology for the simulation of the particles passing through matter. It has been used in a large number of areas, such as high energy physics,

astrophysics and space science, medical physics and radiation protection. Its functionality and modeling capabilities will continue to be extended, and its performance will be further enhanced correspondingly.[10]

4. Simulation and analysis

4.1. Free-air ionization chamber model

According to the above discussion, a simple free-air ionization chamber is built as shown schematically in Fig.2, where F is the distance from the source to the effective volume of the ionization chamber; L is the effective length (the effective electrode length) of the chamber; H is the distance between electrodes of the ionization chamber.

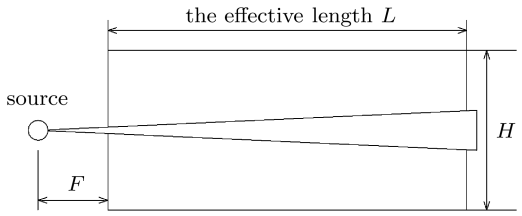


Fig.2. Schematic of the ionization chamber model.

As shown in formula (3), the exposure factor is independent of the light fence, for the exposure dose and the fluence are both inversely proportional to the distance between the source and the light fence, the net effect is independent of the exposure dose in the presence of the light fence (the fence dose influences the exposure dose, and its effect has been discussed in Ref.[11]). According to formula (3), the exposure factor is a function of total energy deposited in the effective region of the chamber, incident particle number, and effective length of the ionization chamber, with the other parameters being constant.

4.2. Relation between energy deposition and effective length

For a given number of incident ray photons, the curves for the simulation relation between the effective length of the chamber and the energy deposited in the effective volume of the ionization chamber for different ray energies are shown in Fig.3.

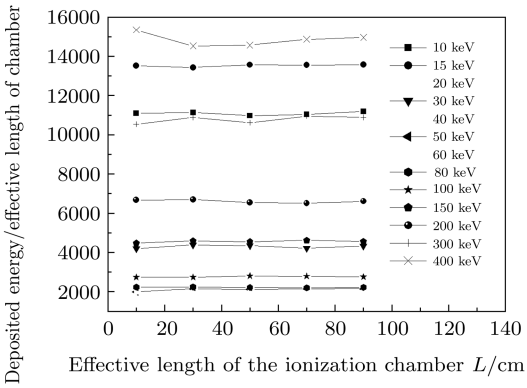


Fig.3. Curves for the ratio between energy deposited in the ionization chamber and the effective length of the chamber as a function of the effective length of the ionization chamber for different energies of incident rays.

In Fig.3, the vertical axis represents the ratio of deposited energy to the effective length of chamber (in units of MeV/cm), the horizontal axis refers to the effective length of the ionization chamber (in units of cm). It is apparent that the deposited energy changes slightly with the energy of the incident rays, which is caused by the stability of the exposure factor and represents that for a given number of incident ray photons, the energy deposited in unit length in air is constant. So, the exposure factor is independent of the effective length of the ionization chamber, and this factor can be ignored in the simulation of the exposure factor.

4.3. Maximum track length of secondary electrons

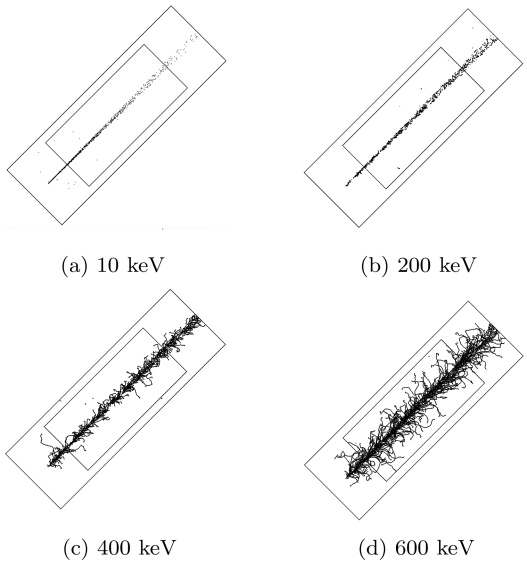
According to the working principle of the free-air ionization chamber, the dimensions of the chamber should be at least larger than the maximum range of secondary electrons (Fig.2), which means that F should be at least larger than the maximum range of secondary electrons in air to maintain the electron balance and that H should be at least larger than twice the maximum range to avoid electrons touching the electrodes. So, the maximum range of secondary electrons in air must be considered. With the powerful simulation and the detailed step information of Geant4, several simulations of the maximum track length of secondary electrons have been carried out, and the results are listed in Table 1.

Table 1. Maximum track length of secondary electrons produced in the chamber (a million injection rays).

ray energy/keV	10	15	20	30	40	50	60	80	100	150
maximum track length	4.048 mm	8.297 mm	1.273 cm	2.485 cm	3.880 cm	6.122 cm	7.298 cm	12.343 cm	16.728 cm	31.718 cm
ray energy/keV	200	300	400	500	600	800	1000	1500	2000	3000
maximum track length	44.213 cm	82.382 cm	1.273 m	1.998 m	2.178 m	3.022 m	4.545 m	6.418 m	9.101 m	14.468 m

It can be seen from Table 1 that the maximum track length of secondary electrons varies significantly as the energy of the incident rays increases, the higher the incident energy is, the longer the track length is. For instance, when incident energy is 10 keV, the track length of the secondary electrons is merely 4.05 mm, but when the incident energy increases to 3 MeV, the track length reaches 14.47 m, and accordingly the electrode distance should be at least larger than 29 m. It is not easy to make such a big ionization chamber when its cost is considered. Here, the Monte Carlo simulation can manifest its advantage.

Figure 4 shows the tracks of secondary electrons for different incident energies in air, with the incident gamma rays hidden. The lines in the rectangle are the actual tracks of electrons.



(a) 10 keV (b) 200 keV

(c) 400 keV (d) 600 keV

Fig.4. Tracks of secondary electrons produced in air by incident rays with energies: 10 (a), 200 (b), 400 (c), and 600 keV (d), where the initial rays are hidden.

Figure 4 shows the vertical views of the secondary electrons generated by gamma rays with different energies. The number of incident gamma ray photons is 10000 (hidden). Comparing panel (a) with panel (d), it is easy to find a great difference in track. So it is urgently necessary to select an appropriate model size in the exposure factor simulation to consider both the electron balance and computing time, because the larger the model size is, the longer the computation time will be in the simulation.

4.4. Simulation of exposure factor

The above discussion indicates that the effective length of the ionization chamber has little influence on the exposure factor, while the effective distance H between the electrodes should be larger than twice the maximum range of the secondary electrons (it is known from formula (3) that under this condition, H is independent of the exposure factor) and the distance F between the source and the effective volume of the chamber should be also larger than the maximum range.

With all the above factors taken into consideration, we adopt 1.3 times the maximum electron track length as the distance between the source and the chamber, and double the maximum electron track length as the effective length of the chamber. The distance between the electrodes is just required to be larger than double the maximum track length of the secondary electrons.

The actual track of electrons in the air cannot be a straight line, so the maximum range of an electron in air is actually shorter than its maximum track length. Here, 1.3 times the maximum electron track length is adopted as a conservative estimation. It is found that the simulation results of the exposure factor are in good agreement with the real values[12] in high energy parts, but less than the real values due to the absorption of the air in the low energy region. To correct this error, the number of real incident ray photons is used to replace the number of ray photons emitted by the source. The value for the low energy part fits well after the improvement. The results are shown in Fig.5.

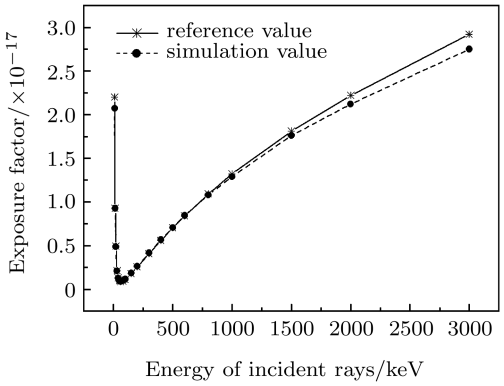


Fig.5. Comparison between simulated value and real value of the exposure factor.

Figure 5 shows the exposure factor as a function of energy of incident rays. It can be seen that the exposure factor first decreases and then increases as the energy of the incident rays increases. A minimum exposure factor is obtained when the incident ray energy is about 50 keV, which results from the changes of cross sections of the interactions involved.

Figure 6 shows the curves for interaction time as a function of incident energy for different types of interactions, i.e. Compton effects, photoelectric effects and pair production. The inset in the upper left corner displays the magnified parts of the curves in the low energy region. It is clear that in the low energy region the photoelectric effect is a dominant interaction, but its interaction cross section first decreases and then increases slightly with increasing incident energy. The Compton reaction increases more dramatically than the photoelectric effect, while pair production nearly happens in the low energy region. The total reaction cross section first decreases and then increases with increasing incident energy, which can be used to explain the character of the exposure factor and it is the essential reason for the variation of the exposure factor with energy.

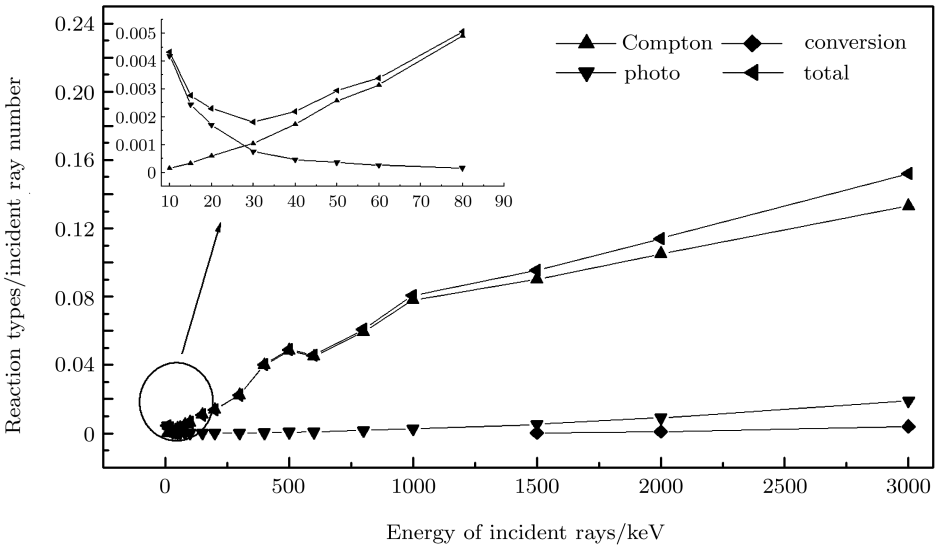


Fig.6. Curves for ratio between the number of ray photons emitted in reactions and the number of total injection ray photons versus the energy of the incident rays for three types of interactions.

5. Conclusion

A simple free-air ionization chamber model is developed to simulate the exposure factor when incident ray energy changes between 10 keV and 3 MeV. The effective length of the ionization chamber and the maximum track length of the secondary electrons in air are taken into consideration in the model. The reason for the variation of exposure factor with incident energy is also analysed primarily by the interaction cross section term. It is found that the simulation results are in good agreement with the real values.

References

[1] Yasushi S, Akira Y, Yoshio H and Takahiro Y 2006 *Appl. Rad. Iso.* **64** 1211

[2] Takata N, Kurosawa T, Begum A and Sugita T 2007 *Nucl. Instrum. Meth.* **580** 346

[3] Lin U T and Chu C H 2006 *Appl. Rad. Iso.* **64** 608

[4] Nariyama N, Kishi N, Itoh T, Taniguchi S and Moriya T 2002 *KEK Proc.* **18** 19

[5] Mahesh K and Vij D R 1985 *Techniques of Radiation Dosimetry* (New York: John Wiley & Sons, Inc.) 74

[6] Lin U T, Sheu R D and Hwang W S 2005 *KEK Proc.* **3** 245

[7] Geant4 introduction, Available at http://geant4.web.cern.ch/geant4/UserDocumentation/Welcome/Introduction To Geant 4/html/introduction To Geant4.html#1

[8] Agostinelli S, Allison J, Amako K, Apostolakis J, Araujo H, Arce P, Asai M, Axen D, Banerjee S, Barrand G, Behner F, Bellagamba L, Boudreau J, Broglia L, Brunengo A, Burkhardt H, Chauvie S, Chuma J, Chytracek R, Cooperman G, Cosmo G, Degtyarenko P, Dell'Acqua A, Depaola G, Dietrich D, Enami R, Feliciello A, Ferguson C, Fesefeldt H, Folger G, Foppiano F, Forti A, Garelli S, Giani S, Giannitrapani R, Gibin D, Gomez Cadenas J J, Gonzalez I, Gracia Abril G, Greeniaus G, Greiner W, Grichine V, Grossheim A, Guatelli S, Gumplinger P, Hamatsu R, Hashimoto K, Hasui H, Heikkinen A, Howard A, Ivanchenko V, Johnson A, Jones F W, Kallenbach J, Kanaya N, Kawabata M, Kawabata Y, Kawaguti M, Kelner S, Kent P, Kimura A, Kodama T, Kokoulin R, Kossov M, Kurashige H, Lamanna E, Lampen T, Lara V, Lefebure V, Lei F, Liendl M, Lockman W, Longo F, Magni S, Maire M, Medernach E, Minamimoto K, Mora de Feitas P, Morita Y, Murakami K, Nagamatu M, Nartallo R, Nieminen P, Nishimura T, Ohtsubo K, Okamura M, O'Neale S, Oohata Y, Paech K, Perl J, Pfeiffer A, Pia M G, Ranjard F, Rybin A, Sadilov S, di Salvo E, Santin G, Sasaki T, Savvas N, Sawada Y, Scherer S, Sei S, Sirotenko V, Smith D, Starkov N, Stoecker H, Sulkimo J, Takahata M, Tanaka S, Tcherniaev E, Safai Tehrani E, Tropeano M, Truscott P, Uno H, Urban L, Urban P, Verderi M, Walkden A, Wander W, Weber H, Wellish J P, Wenaus T, Williams D C, Wright D, Yamada T, Yoshida H and Zschiesche D 2003 *Nucl. Instrum. Meth.* A **506** 250

[9] Liu L P, Liu Y B, Wang J, Yang B and Zhang T 2008 *Chin. Phys.* B **17** 896

[10] Allison J, Amako K, Apostolakis J, Araujo H, Dubois P A, Asai M, Barrand G, Capra R, Chauvie S, Chytracek R, Cirrone G A P, Cooperman G, Cosmo G, Cuttone G, Daquino G G, Donszelmann M, Dressel M, Folger G, Foppiano F, Generowicz J, Grichine V, Guatelli S, Gumplinger P, Heikkinen A, Hrivnacova I, Howard A, Incerti S, Ivanchenko V, Johnson T, Jones F, Koi T, Kokoulin R, Kossov M, Kurashige H, Lara V, Larsson S, Lei F, Link O, Longo F, Maire M, Mantero A, Mascialino B, Mclaren I, Mendez Lorenzo P, Minamimoto K, Murakami K, Nieminen P, Pandola L, Parlati S, Peralta L, Perl J, Pfeiffer A, Pia M G, Ribon A, Rodrigues P, Russo G, Sadilov S, Santin G, Sasaki T, Smith D, Starkov N, Tanaka S, Tcherniaev E, Tome B, Trindade A, Truscott P, Urban L, Verderi M, Walkden A, Wellisch J P, Williams D C, Wright D and Yoshida H 2006 *IEEE Trans. Nucl. Sci.* **53** 270

[11] Tadahiro Kurosawa and Nobuhisa Takata 2005 *CCRI(I)* **05** 27

[12] *International Commission on Radiation Units and Measurements, Average Energy Required to Produce an Ion Pair, ICRU Report 31* (International Commission on Radiation Units and Measurements, Washington, 1979)