PHOTON SCATTERING AND REFLECTION IN MEDICAL DIAGNOSTIC ENERGY DOMAIN

by

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The dependence of reflected photons angular and energy distributions on parameter *c*' – the probability for large-angle scattering – is treated in this paper. The simulation of photon reflection was performed by the FOTELP code for a normal incidence of photons into infinite slabs of common shielding materials, and for the photon initial energies of 20 keV up to 100 keV.

Key words: photon reflection, reflection coefficients, Monte Carlo simulation, FOTELP code, water, aluminum, iron, lead

INTRODUCTION

Radiological protection of the medical team performing X-ray diagnostic techniques is based on the knowledge and data collected from a number of fundamental and rigorous studies of the low-energy photon reflection fenomenon. Research work in this field is focused on theoretical investigation of radiation transport (diffusion, transmission, and reflection) [1, 2], application of basic data on photon interaction with the materials used [2, 3] and calculations based on deterministic methods and Monte Carlo simulations [4, 5]. The syntagm "low-energy reflection" is related to the processes in the energy range bellow 100 keV and to the fenomenon of reflected radiation, *i. e.* to photon reflection from the patient's body and the surrounding objects.

At low energies, photoelectric absorption is dominant among the photon interactions with materials. Photon scattering appears as a coherent and incoherent (Compton) scattering, where the contribution of one or the other process depends on the energy of the initial photon beam and on the target material which causes the scattering process. These three interaction types define the values of linear coefficients for photon interactions and for the mean free path in materials. In this paper, a new parameter *c*' [6] is used for photon reflection analyses, giving us the possibility to establish the relation between the number of large-angle photon scatterings (which happen before final photon reflection) and the angular and energy distribution of the albedo coefficient.

The results presented in this paper are an outcome of a systematic research of low-energy photon reflection carried out over the last several years at the Vinča Institute of Nuclear Sciences. Some results have already been partly published [7-9]. The values for the number and spectral albedo used in this paper have been determined by Monte Carlo simulations of photon reflection and done by the FOTELP code [10]. The normal incidence of a monoenergetic photon beam (in the energy range of 20 keV to 100 keV) to the homogenious plane shield has been simulated and the dependence of angular and energy distributions of the albedo coefficients on the number of consequtive scatterings before the final photon reflection analysed.

INFLUENCE OF SCATTERING ON PHOTON REFLECTION IN THE LOW-ENERGY DOMAIN

In the energy range of up to 100 keV, the probability for a photon to undergo scattering during the in-

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teraction with material is determined by the sum of linear interaction coefficients for coherent scattering μ_{coh} and incoherent scattering μ_{C}, divided by the total interaction coefficient μ (the sum of linear coefficients for the photoelectric effect μ_{ph}, coherent and incoherent scattering)

$$c = \frac{\mu_{\mathrm{coh}} + \mu_{\mathrm{C}}}{\mu} = \frac{\mu_{\mathrm{coh}} + \mu_{\mathrm{C}}}{\mu_{\mathrm{coh}} + \mu_{\mathrm{C}} + \mu_{\mathrm{ph}}} \qquad (1)$$

As the photon undergoing a coherent scattering changes its direction by a small angle and the energy of the scattered photon only slightly decreases in relation to the incident photon energy, in the first approximation, it is acceptable to neglect the coherent scattering process in the analysis of photon interactions because the consequences of such an interaction on photon diffusion are rather small. In this case, the probability for photon scattering can be defined as

$$c = \frac{\mu_{\mathrm{C}}}{\mu} = \frac{\mu_{\mathrm{C}}}{\mu_{\mathrm{C}} + \mu_{\mathrm{ph}}} \qquad (2)$$

In eq. (2), the linear interaction coefficient μ' represents the sum of coefficients for the photoelectric effect and for Compton's scattering. Parameter *c*' can also be understood as a probability for photon scattering at a large angle.

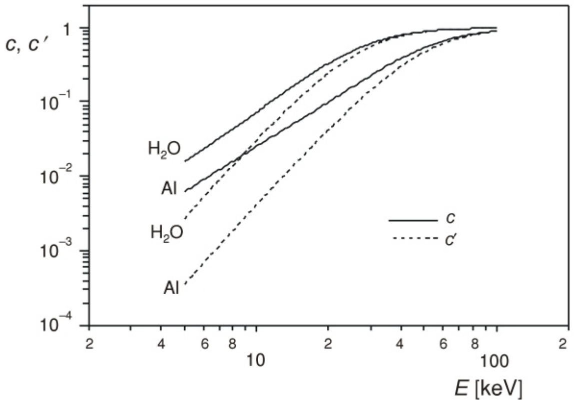

Figure 1. Parameters *c* and *c*' for water and aluminum

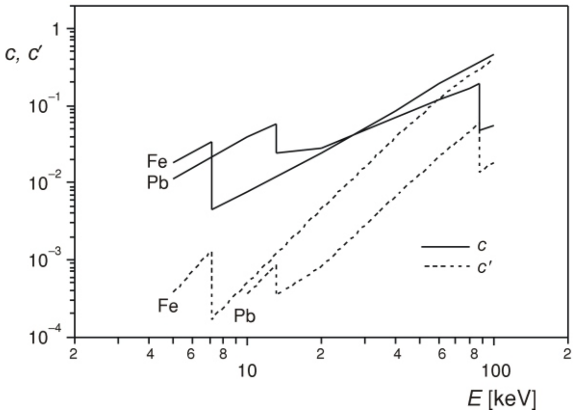

Figure 2. Parameters *c* and *c*' for iron and lead

Energy dependence of the parameters *c* and *c*' for water, aluminum, iron, and lead is shown in figs. 1 and 2.

Parameters *c* and *c*' for water tend to the value of 1 when the photon energy is close to100 keV, while the maximal value for aluminum is 0.9. Water at photon energies higher than 30 keV and aluminum at energies above 50 keV, behave as predominantly scaterring materials. The main consequence of this behaviour is a higher total photon reflection from these materials. The contribution of the photons that survive more than one collision to total reflection causes additional isotropization of the angular distribution of the reflected photons and makes its spectrum flatter. The values of coefficients *c* and *c*' for iron and lead are significantly lower, meaning that a dominant fraction of the reflected photons undergoes a small number of collisions. As a consequence, a strong peak appears in the reflected photon spectrum at an energy close to the initial one, as well as a fast downfall of the distribution towards lower photon energies. Water and aluminum are strong scattering materials for photons having energies close to 100 keV, while iron and lead behave as strong absorption materials in the entire energy range up to 100 keV.

Coherent photon scattering does not involve significant changes, neither in the direction of the primary photon beam, nor in their energy distribution. If the initial photon beam is directed normally towards the iron or lead target, such scattering cannot cause significant reflection due to the dominant photoelectric absorption of the photons. In this case, only photons which have survived very few collisions can be found among the reflected ones. Thus, the intensity of photon reflection from shielding materials of high density is determined by Compton scattering at large angles, *i. e.* photon reflection depends on the parameter *c*'. For iron, this parameter grows from very low values for energies bellow and arround 10 keV, to about 0.4 for photon energies of 100 keV. Parameter *c*' behaves in a similar fashion when lead is concerned, but its maximal value does not exceed several hundredths. Thus, for lead in energy range of our interest there is almost no photon scattering at large angles. The main consequence of coherent photon scattering predomination in lead at low energies is very low photon reflection. In literature, photon reflection from lead is usually considered from high (several MeV) initial photon energies, down to lower energies of up to 100 keV, neglecting the reflection at initial energies bellow this boundary. As this paper is focused on X-ray diagnostics which apply a normal incidence of photons on the target and X-ray energies bellow 100 keV, simulations of photon reflection from the lead target are not considered here.

DEPENDENCE OF THE REFLECTION COEFFICIENT ON THE NUMBER OF PHOTON SCATTERINGS

In order to determine how many photon scatterings preceded the final photon reflection from the target material, we have used the FOTELP code [10] for the simulation of photon reflection from water, aluminum, and iron. More detailed results of these simulations, as well as the results of simulations performed by other codes, are presented in the Ph. D. thesis of one of the authors [6]. Here, only values for water with initial photon energies of 20 keV, 50 keV, and 100 keV, for aluminum and iron with energies of 40 keV and 100 keV, are considered – grouped according to the number of scatterings preceding final photon reflection from the material slab.

The relative contributions of photons finally reflected after *n* scatterings in relation to the contribution of photons reflected after only one scattering are given in tab. 1. The data represents the angular-energy interval in which the maximum of the distribution of reflected photons appears (width of the energy intervals equaling one tenth of the initial photon energy E_0, width of the polar angle interval 10°). This maximum always belongs to the polar angle interval $\theta \in$ (40°, 50°), where θ is measured from the outward normal of the incident target plane. Looking at the energy variable, the peak of the reflected photon distribution is shifted from higher to lower energies with the increase in the number of scatterings *n* survived before the final photon reflection. From tab. 1, it can be seen that the number of scatterings *n* depends on both the target material and the initial photon energy: in light materials and for higher energies, photons are mainly reflected after a larger number of scatterings than in heavy materials and at lower initial photon energies.

Taking into consideration the dominant physical process for photon reflection, *i. e*, large-angle photon scattering for which the probability is given by parameter *c*', it is possible to formulate the following universal rule for all materials and all incident photon energies (in the range of interest of bellow 100 keV): for the higher values of parameter *c*', a higher number of photon scatterings *n* before the reflection are registered. If we compare the results for reflection from water at 20 keV of initial photon energy and from aluminum at 40 keV, the values of corresponding relative contributions which come from the twice, three, and four times scattered photons are rather close. Aditionally, for both materials at these two different initial photon energies, approximately 99% of the total reflection is caused by the photons that survived up to three collisions. Looking at fig. 1 and comparing the values of parameter *c*' calculated from the tables of the X-ray coefficients [3], one can find the approximate numbers: for water at 20 keV *c*' is equal to 0.245, while for aluminum at 40 keV, the value is 0.298. (More precisely, it can be found that for aluminum at 40 keV of initial photon energy, the probability for the reflection of photons collided more than once is slightly higher than the same probability for water at 20 keV, which corresponds to the slightly higher value of parameter *c*' for aluminum than for water at mentioned initial photon energies). In a similar fashion, it can be concluded (tab. 1) that the parameter *c*' for iron at 100 keV has to be approximately the same as for water at 20 keV as for aluminum at 40 keV of the initial photon energy (figs. 1 and 2).

Table 1. Relative contributions of the photon groups (groupped according to the number of scattering events) to the total photon reflection

n	Water E_0 [keV]			Aluminum E_0 [keV]		Iron E_0 [keV]	
	20	50	100	40	100	40	100
1	1	1	1	1	1	1	1
2	0.201	0.484	0.434	0.232	0.398	0.060	0.194
3	0.038	0.193	0.209	0.052	0.144	0.004	0.036
4	0.06	0.093	0.134	0.011	0.076		0.006
5		0.054	0.105	0.002	0.036		
6		0.030	0.072		0.019		
7		0.020	0.065		0.009		
8		0.011	0.049				
9		0.006	0.033				
10			0.020				
11			0.016				
12			0.012				

The previous consideration is limited to the normal incidence of the photon beam on the planar target, the said condition being a good model for radiological diagnostics and therapy. Here, we did not analyse the behaviour of photon beams impinging into the target under sharp angles. In such a case, the contribution of once scattered photons to total reflection is higher, while the contribution of photons scattered more than once decreases.

Influence of the number of scatterings on the angular distribution of the albedo coefficient

Every further scattering event causes further isotropization of the angular photon distribution and, thus, the isotropization of the angular distribution of the reflected photons. This is a quick process, so even three scaterings may decide the final shape of the angular distribution of reflected photons. Figure 3 shows angular distributions of the photon number albedo $a_N(E_0, \theta_0 \quad 0^\circ; \theta)$ obtained from once, twice, and three times scattered photons, as well as the angular distribution of all reflected photons with a 100 keV initial energy, after an normal incidence on the plane water target. The photon number albedo is defined as a ratio of the currents of reflected and incident photons [6]. From fig. 3, a clear idea about the contribution of once, twice, and three times scattered photons in the total reflection can be obtained. A common characteristic of the angular distribution of the number albedo

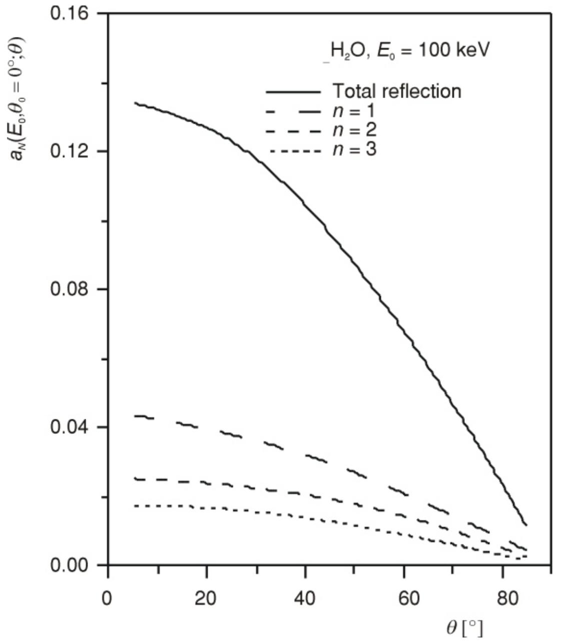

Figure 3. Number albedo – the angular distribution of reflected photons

that can also be observed is that it corresponds to the cosine function of the polar angle of the reflected photons. However, from fig. 3, it is not so evident how much the angular distributions corresponding to the photons which undergo a small number of scatterings deviate from the angular distribution of total reflection.

Figure 4 presents the angular distributions of the number albedo which are normalized against the value for the polar angle $\theta = 0°$. From this representation, one can conclude that the values of the angular distribution of photons scattered only once are bellow the corresponding values for all reflected photons, while normalized values for twice scattered photons are above the values for total reflection. The angular distribution of the number albedo of photons scattered three times deviates from the total distribution of all reflected photons insignificantly, from the practical point of view. The relative differences between the two distributions are less than 3%.

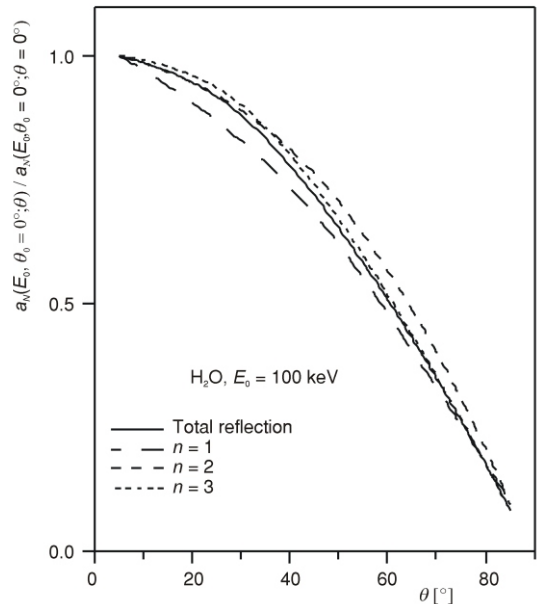

Figure 4. Normalized number albedo – the normalized angular distribution of reflected photons

Influence of the number of scatterings on the spectral albedo shape

For the analysis of the dependence of energy distribution on the number of collisions we have used the same set of photon reflection simulation results as when investigating their influence on the angular distribution. The analyses have been performed using the calculated values for the spectral photon albedo $a_N(E_0,\theta_0 \quad 0^\circ; E)$.

The values of the photon spectral albedo for a water target at the initial photon energy of 100 keV after one, two, and three scatterings, as well as for the total reflection, are shown in fig. 5. This is a typical example of photon reflection where the multiple scattered photons contribute significantly to the shape of energy distribution. (From tab. 1 it can be seen that even photons with ten or more scattering events in their tracking history contribute by more than 1% to the total reflection). Distributions of the photons scattered once and twice have their maximums in the energy range of 70-80 keV, while the maximum of the distribution of three times scattered photons is located in the 60-70 keV interval. With the increasing number of scatterings, the contribution of this group of photons to the total reflection becomes lower and the maximums of their particular energy distributions shifts towards lower energies. The resulting total energy distribution has a maximum between 70 keV and 80 keV, then it declines slowly towards lower energies, still having only a ten times lower value for energies of 30-40 keV than in the maximum.

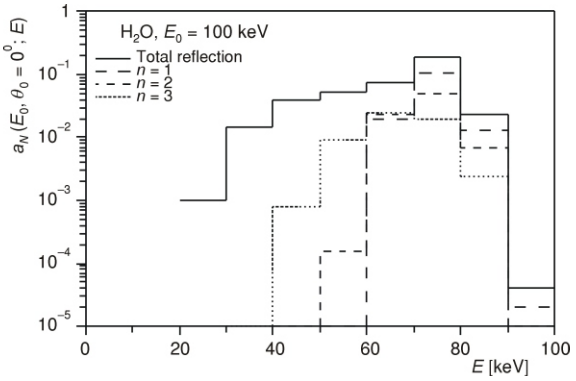

Figure 5. Photon spectral albedo for water

The energy distribution presented in fig. 6 (iron target, initial photon energy of 40 keV) is an example of the strong peak distribution with the absolute domination of the first photon collision. The contribution of the photons collided two times is not large enough to change significantly the total reflection spectrum.

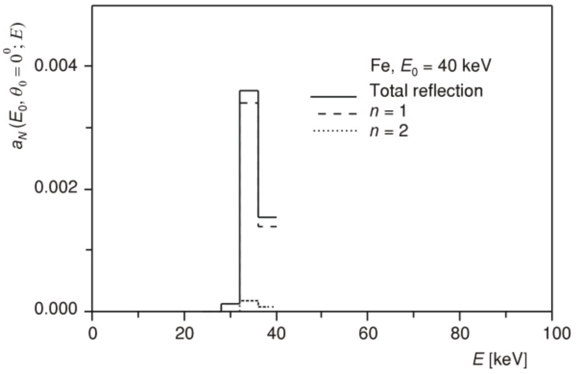

Figure 6. Photon spectral albedo for iron

CONCLUSIONS

It has been demonstrated in this paper that with the increase of the parameter c', which represents the probability for large-angle photon scattering, the number of photon collisions before the final reflection also increases and the value of parameter c' defines the angular and energy distributions of the albedo coefficient.

If among the reflected photons the ones which survive one or two collisions dominate (as is the case for iron and the initial photon energy of 40 keV, where once collided photons contribute to the total reflection with 94% and twice collided photons with about 5% – see tab. 1), then the shape of the angular distribution of the total albedo has to be determined strongly by these two particular distributions. Nevertheless, the angular distribution of the total number albedo does not differ significantly from the cosine function. This is because of the perpendicular incident angle of the initial photon beam towards the target material surface. Only for the non-perpendicular photon incidence there will appear significant non-simetry in the angular distribution of the total photon reflection determined by the distributions of once and twice collided photons [5].

The shape of energy distribution of reflected photons is also predictable if the multiplication factor c' for the selected material and for the initial photon energy is known. Namely, when c' 1, energy distribution has a maximum immediately bellow the initial photon energy and then slowly decreases towards lower energies; if c' 0, the distribution is narrow, with fast decreasing tails arround the characteristic peak. The first distribution is a result of multiple collided photon contributions, while the second one is formed by once collided photons. The first distribution appears when the Compton scattering is the dominant effect, while the second one is a consequence of the dominant share of photoelectric absorption.

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РАСЕЈАЊЕ И РЕФЛЕКСИЈА ФОТОНА У ДОМЕНУ МЕДИЦИНСКИХ ДИЈАГНОСТИЧКИХ ЕНЕРГИЈА

У раду је разматрана зависност угаоне и енергетске расподеле рефлектованих фотона од параметра c' – вероватноће расејања фотона на велики угао. За симулацију рефлексије фотона, при нормалном упаду на бесконачне плоче уобичајених заштитних материјала и при почетним енергијама фотона од 20 keV до 100 keV, коришћен је домаћи програм FOTELP.

Кључне речи: рефлексија фотона, коефицијенти рефлексије, Монте Карло симулација, програм FOTELP, вода, алуминијум, гвожђе, олово