UNIVERSAL DEPENDENCE OF THE TOTAL NUMBER ALBEDO OF PHOTONS ON THE MEAN NUMBER OF PHOTON SCATTERINGS

by

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This paper presents the results of research on photon reflection from plane targets based on Monte Carlo simulations performed by the MCNP code. Five materials (water, concrete, aluminum, iron, and copper) are examined in the area of initial photon energies of up to 200 keV. The values of the total number albedo for photons dependent on the initial photon energy or the mean number of photon scatterings are calculated and graphically presented. We have shown that the values of the total number albedo for different target materials, expressed as a function of the mean number of photon scatterings, are in good agreement with each other and can be approximated by simple, universal analytic functions obtained by the least squares method. The accuracy of these analytic appoximations is confirmed by their comparison with the results of PENELOPE and FOTELP Monte Carlo codes.

Key words: photon, total number albedo, Monte Carlo simulation, MCNP code, FOTELP code, PENELOPE code

INTRODUCTION

In recent times, the possibility of representing differential and integral reflection coefficients in the form of universal functions has been in the focus of researchers engaged in the applied transport theory of various particles such as ions, electrons, neutrons, and photons, for example [1-3]. The results of their studies are significant both methodologically and from a practical point of view. From a theoretical standpoint, the search for a universal definition of the reflection coefficient is conducive to finding common methodical means for studying and defining the heterogeneous processes of physical transport. From a practical point of view, the determination of universal reflection coefficients would result in the reduction of voluminous technical data now needed, tables presently used in engineering manuals and overall simplification of their use [4].

In the domain of medical diagnostics, *i. e*. the initial photon energy range of up to 100 keV, the reflection of photons has been the subject of extensive research, primarily by Monte Carlo simulation techniques aimed at calculating reflection coefficients and, to the same extent, of semianalytical procedures, for the most part applied in the analyses of common properties of the reflection phenomena [5, 6]. Over the course of these investigations, intial steps in formulating reflection coefficients in the form of universal analytic functions which would apply to all initial photon energies, as well as a number of materials used in radiation protection, have been made [7, 8]. By selecting an appropriate argument for the reflection coefficient (for example, the energy of initial photons, the probability of large-angle photon scattering, or the mean number of photon scatterings), the various possibilities of expressing particle and energy total reflection coefficients have been examined. It turns out that if the mean number of photon scatterings is chosen as an argument, then the total reflection coefficient becomes a nearly universal function [9].

This paper is a continuation of our previous studies and a more complete formulation of the universal properties of photon reflection. In comparison to our earlier works, the list of treated materials is expanded with concrete and copper and the range of photon initial energies is extended up to 200 keV. The calculations were performed by the MCNP code [10], and based on them, the results for the total number albedo and the mean number of photon scatterings as functions of pho-

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ton initial energies generated. Then the total number albedo was presented as a function of the mean number of photon scatterings, approximated by two fitting functions, using the least squares method. These functions have a universal shape and their accuracy was verified by comparison with the results of FOTELP and PENELOPE Monte Carlo codes [11, 12].

TOTAL NUMBER ALBEDO OF PHOTONS FOR ENERGIES UP TO 200 keV

The values of the total number albedo for photons are obtained by numerical simulations of photon reflections for energies of inital photons up to 200 keV, determined by the MCNP code. Typical materials that appear in the medical application of hundred keV-energy photons are treated: water, concrete, aluminum, iron, and copper. Complete data on the definitions of relevant physical values, numerical simulations, calculations of difference number albedo, and procedures of particle albedo calculation – can be found in our previous papers [6-9]. Here, we give only the graphical representations of the total number albedo in order to illuminate the concept of a new analysis of photon reflection as a function of the mean number of photon scatterings.

Total number albedo dependent on initial photon energy

The total number albedo for five selected materials is shown in fig. 1 as a function of the initial photon energy. It is evident that in the range of initial photon energies up to 200 keV, albedo coefficients depend strongly on this argument and have continual-growing forms, reaching a weak maximum at higher energies for water. However, from fig. 1, we can also see that the albedo coefficients are highly dependent on the type of material, with a general tendency of photon reflection decreasing with the increase in the density of the material. This dependence is not precisely defined and, in the appropriate literature, albedo coefficients are for the most part displayed in the form of tables. In other words, it is difficult to find a unique function within the energy variable capable to describe photon reflection for different materials.

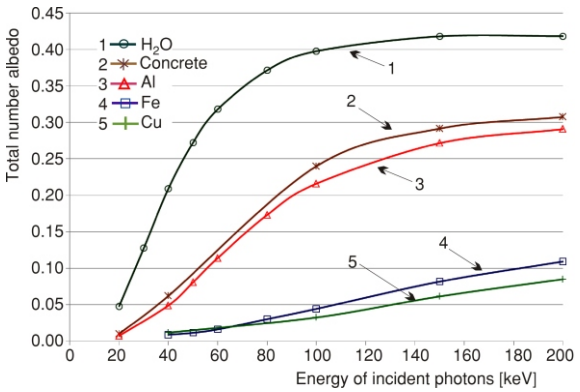

Figure 1. Total number albedo of selected materials as a function of the energy of incident photons

Mean number of photon scatterings dependent on initial photon energy

In our previous work, the mean number of photon scatterings was calculated by the FOTELP code for three shielding materials (water, aluminum, and iron) and a limited number of initial photon energies in the range of 20 keV to 100 keV [8, 9]. Moreover, the mean number of scatterings was determined from the energy-angle distributions of reflected photons, from data corresponding to the absolute peaks of these distributions.

In this study, the mean number of photon scatterings is determined by the MCNP code for the five selected materials and refers to the total photon reflection for specific initial photon energies in the range of 20 keV to 200 keV. These results are shown in fig. 2.

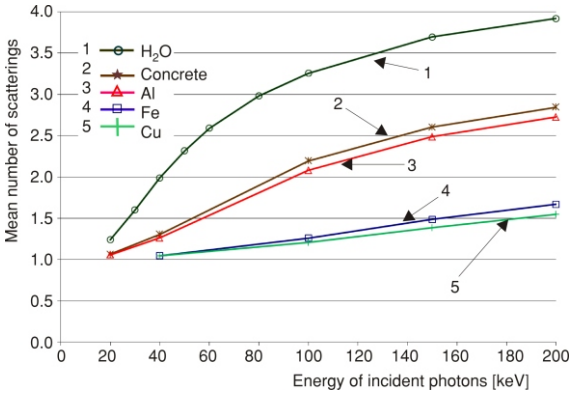

Figure 2. Mean number of photon scatterings for selected materials prior to reflection

Concerning the dependence of the mean number of photon scatterings on the initial energy and materials, the obtained results confirm previous conclusions regarding the total number albedo. Looking at the energy variable, graphics are slow-growing functions with a tendency to enter saturation at higher initial energies. As it might be expected when these types of materials are concerned, for low density materials the mean number of photon scatterings has higher values than for higher density materials. In short: for lighter materials and higher energies, photons are reflected after a larger number of scatterings than for heavier materials or at lower initial photon energies.

Total number albedo dependent on the mean number of photon scatterings

The similarity in grafics of the total number albedo and the mean number of scatterings of low-energy photons, both drawn *vs*. the initial photon energy and different types of target material (see figs. 1 and 2), suggests that the dependence of the total number albedo on the mean number of scatterings should be investigated. This dependence is shown in fig. 3.

The abscissa in fig. 3 represents the mean number of photon scatterings corresponding to the interval of initial energies of 20 keV to 200 keV, while the values of total number albedo are placed in the figure

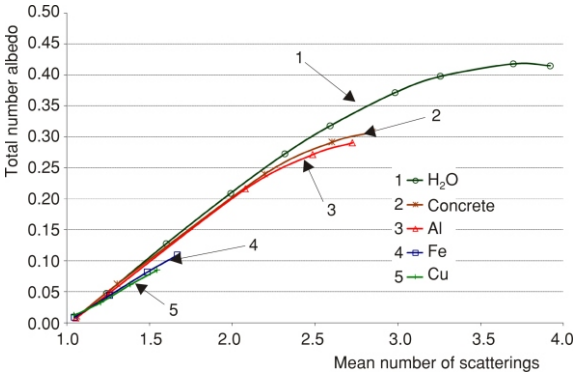

Figure 3. Total number albedo for selected materials as a function of the mean number of photon scatterings prior to reflection

ordinate. For example, the endpoint in the graph for water shows the value of the total number albedo for water (0.415), corresponding to the mean number of photon scatterings in water before leaving the target (3.92); both of these values being obtained by the MCNP simulation for the initial energy of 200 keV. From fig. 3, we can see that the values of the total number albedo for the five selected materials largely coalesce in almost a single line or a narow track, especially for lower energies. This common shape of the total number albedo for all treated materials refers to the possibility of describing photon reflection by an universal function over the mean number of scatterings.

Two fitting functions of the total number albedo

The values of the total number albedo calculated from MCNP simulation results are fitted by the usual least squares method in the form of the second order polynomials over the mean number of photon scattering

$$a_N(\bar{n}) \quad 0.02632\bar{n}^2 \quad 0.29466\bar{n} \quad 0.27632 \quad (1)$$

$$a_N(\bar{n}) \quad 0.03111\bar{n}^2 \quad 0.30513\bar{n} \quad 0.28687 \quad (2)$$

Here, a_N is the total number albedo and $\bar{n}$ – the mean number of photon scatterings.

The first fit – Fit 100, eq. (1) – refers to the interval of energies from 20 keV to 100 keV, while the second one – Fit 200, eq. (2) – is computed for the energy interval of 20 keV to 200 keV. Figure 4 shows both fits in the form of solid and dashed lines and the results of MCNP simulations of photon reflection by different symbols for selected materials.

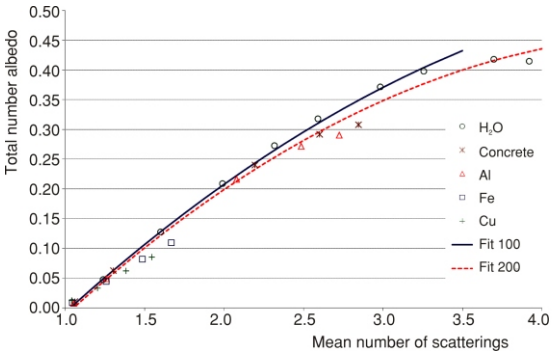

Figure 4. Two fits of the total number albedo simulation data in the form of second order polynomials

In a common interval of two fits of up to 100 keV, the maximum of absolute deviation between them is found for water at the value of abscissa of 3.26, corresponding to the value of 100 keV in the energy of the initial photons. It amounts to 0.027 measured in units of the total number albedo, which is equivalent to 6.85% of the relative deviation.

The maximum absolute deviation of the MCNP results and the Fit 100 values in the interval of up to 100 keV is found for water at an energy of 50 keV, *i. e.* at the abscissa value of 2.32, approximately. It amounts to 0.008 measured in units of the total number albedo, corresponding to 2.77% of the relative deviation.

Similarly, the maximum absolute deviation of the MCNP results and the Fit 200 values in the interval of up to 200 keV is found for water at an energy of 80 keV (at the abscissa value of 2.98) and amounts to 0.025 in units of the total number albedo, or 6.75% of the relative deviation.

For all other materials analysed, maximal absolute deviations are lower than for water. However, at lower limits of the mean number of scatterings (at the graphic's left end), due to the small values of the total number albedo, relative deviations have higher values.

Figure 5 shows the same Fit 100 and Fit 200 curves based on MCNP calculations (full and dashed line, respectively) and the values for the total number

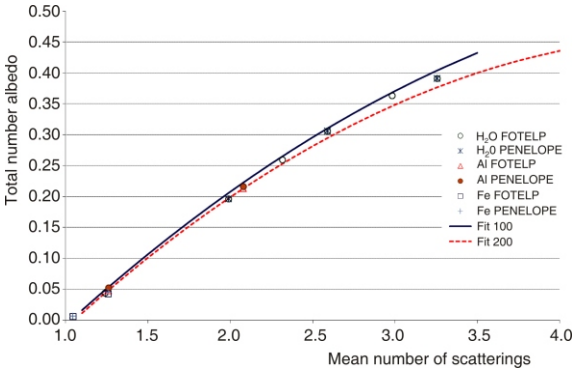

Figure 5. Comparison of the total number albedo values obtained by FOTELP and PENELOPE codes and the two fits based on the least squares method

albedo, based on Monte Carlo calculations for water, aluminum, and iron (different symbols) previously performed by the FOTELP and PENELOPE codes for the interval of initial energies up to 100 keV.

Comparison of the results previously calculated on the basis of data obtained by other Monte Carlo codes and the values determined by the analytical fits of the total number albedo, shows that the simple polynomial fits formulated in this paper (eqs. 1 and 2) are good universal functions, at least in the interval of initial photon energy up to 100 keV and for selected target materials.

CONCLUSIONS

A new concept of expressing the total number albedo of photons as a function of the mean number of photon scatterings is elaborated in detail. Compared to the views on the same topic published earlier, the list of shielding materials treated here by hte MCNP code is expanded by concrete and copper and the interval of initial photon energy enlarged up to 200 keV. The two fits of the total number albedo in the form of simple polynomials of second degree over the mean number of photon scatterings are determined by the ordinary least squares method. The comparison of values for the total number albedo calculated by the fitting functions and PENELOPE and FOTELP Monte Carlo simulation codes, confirms that the analytical reflection functions derived here have universal forms for materials tested and energy interval selected. This is a major contribution of the concept developed in this paper, *i. e.* of the method of analysis of photon reflection which transfers the albedo argument from the energy to the mean number of scatterings.

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УНИВЕРЗАЛНИ ОБЛИК УКУПНОГ ЧЕСТИЧНОГ АЛБЕДА ФОТОНА ПРИКАЗАН У ЗАВИСНОСТИ ОД СРЕДЊЕГ БРОЈА РАСЕЈАЊА ФОТОНА

У раду су приказани резултати истраживања рефлексије фотона од равних мета добијени на основу Монте Карло симулација програмом MCNP. Разматрано је пет материјала (вода, бетон, алуминијум, гвожђе и бакар) у области енергија иницијалних фотона до 200 keV. Израчунате су и графички приказане вредности тоталног бројног албеда фотона у зависности од енергије иницијалних фотона или од средњег броја расејања фотона. Показано је да вредности тоталног бројног албеда, представљене у функцији од средњег броја расејања фотона, мало одступају једне од других за различите материјале мете, те да се могу апроксимирати једноставним универзалним аналитичким функцијама добијеним методом најмањих квадрата. Поређењем са резултатима Монте Карло програма FOTELP и PENELOPE потврђена је тачност аналитичких апроксимација.

Кључне речи: фотон, укупни честични албедо, Монте Карло симулација, MCNP програм, FOTELP програм, PENELOPE програм