Nuclear Technology & Radiation Protection: Year 2014, Vol. 29, No. 4, pp. 274-278

INTEGRAL PARTICLE REFLECTION COEFFICIENT FOR OBLIQUE INCIDENCE OF PHOTONS AS UNIVERSAL FUNCTION IN THE DOMAIN OF INITIAL ENERGIES UP TO 300 keV

by

Vladan L. LJUBENOV [1*] ***and Rodoljub D. SIMOVIĆ*** [2, 3]

[1] International Atomic Energy Agency, Vienna International Centre, Vienna, Austria
[2] Faculty of Ecology and Environmental Protection, Union – Nikola Tesla University, Belgrade, Serbia
[3] Public Company Nuclear Facilities of Serbia, Belgrade, Serbia

Scientific paper
DOI: 10.2298/NTRP1404274L

In this paper we present the results of calculations and analyses of the integral particle reflection coefficient of photons for oblique photon incidence on planar targets, in the domain of initial photon energies from 100 keV to 300 keV. The results are based on the Monte Carlo simulations of the photon reflection from water, concrete, aluminum, iron, and copper materials, performed by the MCNP code. It has been observed that the integral particle reflection coefficient as a function of the ratio of total cross-section of photons and effective atomic number of target material shows universal behavior for all the analyzed shielding materials in the selected energy domain. Analytical formulas for different angles of photon incidence have been proposed, which describe the reflection of photons for all the materials and energies analyzed.

Key words: photon, particle reflection coefficient, oblique incidence, MCNP code

INTRODUCTION

In studying particle reflection from larger objects (such as walls, floors, *etc.*), the concept of particle albedo can be used [1-4]. In this view, reflection is not strictly defined as the reflection from a surface (surface backscattering), but as a complete process of particle penetration into a target material, its scattering and absorption in the object, and finally, backward emission of a part of radiation from the boundary surface of the material, with the decreased energy and from a point on the surface dislocated regarding the point of the primary beam incidence. This concept includes several basic and quite acceptable simplifications of the physical problem, thus enabling spatial, energy, and angular distribution of reflected radiation to be determined in a simpler way than required originally by the totality of the transport task.

Integral reflection coefficients for different kinds of particles can be presented as universal functions within specified ranges of incident particle energies. This means that a single function can describe reflection of one type of particles from different target materials and for different particle energies. Number of papers have been published on this topic [3, 5-11]. The results of these 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 [12].

In the previous ten years the authors published several papers [7-11, 13], in which analyses of photon reflection were done and the universal behavior of the integral reflection coefficients was explored, based on the results of the Monte Carlo simulations of photon transport in a set of materials of interest. Those analyses covered the domain of incident photon energies up to 300 keV and were limited to normal photon incidence only. There are no systematic results for the integral reflection coefficients for oblique photon incidence in the low energy interval available in the literature. Some results can be found in [12], but they do not systematically cover the range of incident photon energies and angles for different target materials, which is the subject of this paper.

* Corresponding author; e-mail: v.ljubenov@iaea.org

METHODOLOGY

We have made an attempt to analyze the oblique photon incidence using the approach and methodology applied for the normal incidence, described in [7, 10, 11, 13]. It is based on a three dimensional model of a planar thick slab of material which is a target for a narrow beam of monoenergetic photons. The photon incidence angle has been varied from 0° (normal incidence) up to 90° (extreme grazing angle, beam direction very close to the target surface) in the steps of 10°. The photon incidence under 90° has been modeled using 89.5° in the simulations, in order to enable photons to enter the target material.

In this paper we analyze the integral particle reflection coefficient (total number albedo) of photons for reflection from different shielding materials (water, concrete, aluminum, iron, and copper) for three values of the initial photon energies: 100 keV, 200 keV, and 300 keV. The total number albedo has been calculated based on the results of Monte Carlo simulations of the photon transport, performed using MCNP4C code [14]. MCNP simulations were run with 10^7 photon histories, which ensured statistical uncertainty of the results far less than 1% in all cases (different materials, different initial photon energies, different incidence angles). The number of reflected photons leaving the material in all directions and with all energies was determined using the surface current tally (type F1).

Monte Carlo results for total number albedo of photons for oblique photon incidence were analyzed using the parameter μ/Z_{eff}, (where μ is the total cross-section of photons and Z_{eff} is the effective atomic number of target material), *i. e*., the albedo coefficients are presented as functions of the μ/Z_{eff} parameter, as it was done for normal photon incidence in ref. [11].

RESULTS OF THE MCNP CALCULATIONS

The total number albedo for a given initial photon energy has been presented as a function of the photon incidence angle. The values of the total number albedo of photons for five selected target materials, for three initial photon energies and for four selected angles of photon incidence are presented in tab. 1. Values of the parameter μ/Z_{eff}, which correspond to the given target material and initial photon energy, as described in [11], are also presented in tab. 1.

Values of the total number albedo of photons a_{N} for all the materials analyzed and for three incident photon energies E_0, presented as functions of the angle of photon incidence θ_0, are presented in figs. 1-3.

The results presented in tab. 1 and in figs. 1-3 show that the total number albedo increases with the increase of the photon incidence angle for a given target material and for a constant initial photon energy E_0. This is because photons entering into the target medium under a small angle to the surface (large angle to the surface normal) are not penetrating into the material deeply, so if scattered towards the surface, they have a higher probability to leave the material without undergoing another collision.

UNIVERSAL FUNCTIONS FOR TOTAL NUMBER ALBEDO OF PHOTONS FOR OBLIQUE INCIDENCE

In our previously published papers [10, 11] it was shown that for normal photon incidence it was possible to present the number and energy albedo of photons as functions of the mean number of photon collisions in the material or as functions of the parameter μ/Z_{eff}, and that these functions were universal for

Table 1. Total number albedo of photons for four different angles of oblique incidence θ_0

Material	E_0 [keV]	μ/Z_{eff} [cm^{-1}]	Total number albedo a_{N}			
			$\theta_0 = 10°$	$\theta_0 = 30°$	$\theta_0 = 60°$	$\theta_0 = 90°$
Water	100	0.165	0.40072	0.42514	0.52111	0.74195
	200	0.136	0.41828	0.44569	0.55216	0.77810
	300	0.118	0.40200	0.43078	0.54415	0.78297
Concrete	100	0.382	0.24204	0.26085	0.34287	0.59276
	200	0.285	0.31051	0.33520	0.43872	0.70311
	300	0.246	0.31081	0.33766	0.44889	0.72427
Aluminum	100	0.424	0.21814	0.23547	0.31351	0.56259
	200	0.321	0.29114	0.31513	0.41751	0.68792
	300	0.278	0.29659	0.32279	0.43334	0.71372
Iron	100	2.600	0.04485	0.04975	0.07522	0.22036
	200	1.060	0.11077	0.12465	0.19294	0.46991
	300	0.833	0.13997	0.15826	0.24532	0.56110
Copper	100	3.660	0.03292	0.03660	0.05604	0.19349
	200	1.280	0.08627	0.09797	0.15704	0.42138
	300	0.946	0.11437	0.13067	0.21066	0.52543

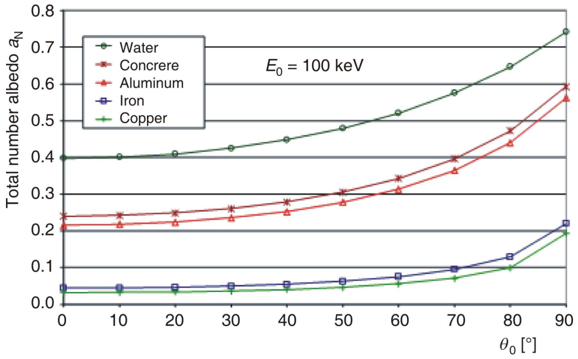

Figure 1. Total number albedo for 100 keV photons

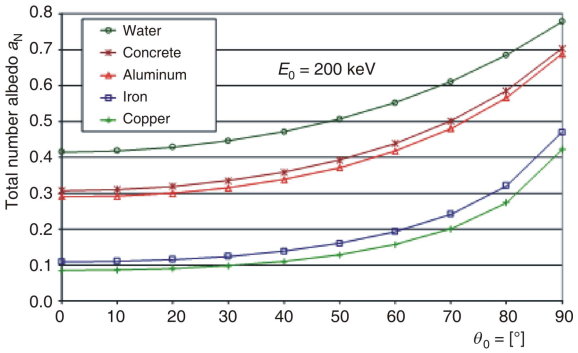

Figure 2. Total number albedo for 200 keV photons

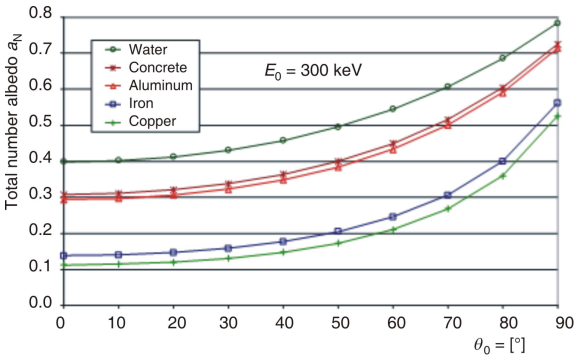

Figure 3. Total number albedo for 300 keV photons

several target materials. In this paper we explore the possibility to present the total number albedo of photons for oblique incidence as universal function of the ratio of total cross-section of photons and effective atomic number of target material μ/Z_{eff}.

Figures 4 to 7 present graphically the dependence of the total number albedo on the parameter μ/Z_{eff} for several different angles of photon incidence (θ_0 = = 10°, 30°, 60°, and 90°). The energy dependent values for μ are taken from the reference [12].

Figures 4 to 7 generally confirm the universal behavior of the total number albedo of photons a_N for oblique incidence, when presented as a function of μ/Z_{eff}.

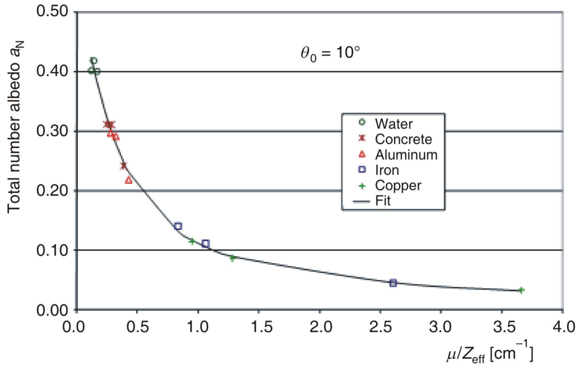

Figure 4. Total number albedo of photons as a function of μ/Z_{eff} for incident angle of 10°

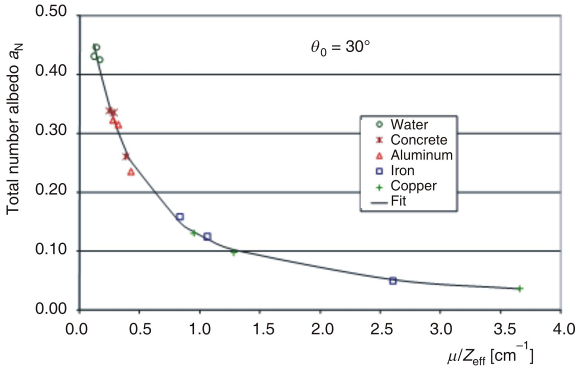

Figure 5. Total number albedo of photons as a function of μ/Z_{eff} for incident angle of 30°

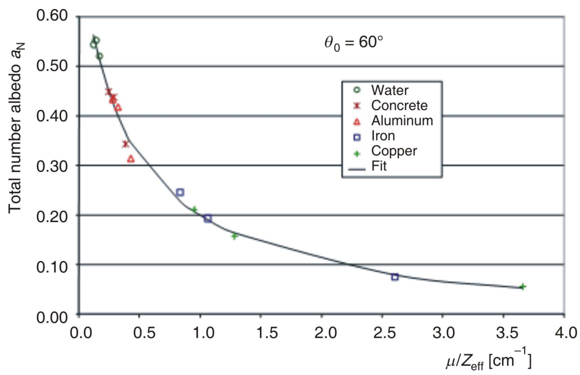

Figure 6. Total number albedo of photons as a function of μ/Z_{eff} for incident angle of 60°

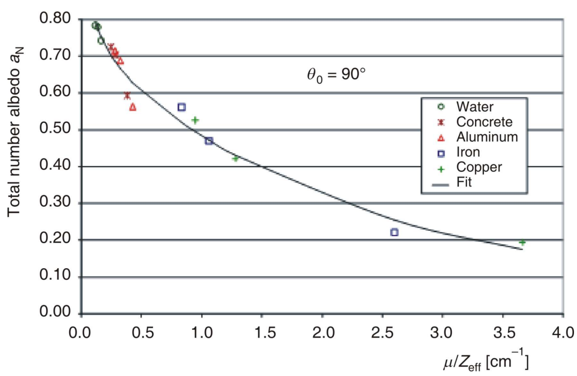

Figure 7. Total number albedo of photons as a function of μ/Z_{eff} for incident angle of 90°

Universal functions, which successfully describe the total number albedo of photons for all the materials and initial photon energies E_0 analyzed, have been proposed. The common form of these universal functions for all the analyzed angles of photon incidence θ_0 is presented in eq. (1), while the coefficients of the function for different angles of photon incidence θ_0, determined by fitting the results of the numerical MCNP simulations to a sum of exponential terms, are given in tab. 2,

$$a_{\mathrm{N}} \quad C_1 \quad C_2 \mathrm{e}^{\frac{\mu/Z_{\mathrm{eff}} \quad C_3}{C_4}} \quad C_5 \mathrm{e}^{\frac{\mu Z_{\mathrm{eff}} \quad C_3}{C_6}} \qquad (1)$$

Table 2. Coefficients C_1 to C_6 of the universal functions for total number albedo for different angles of photon incidence θ_0

θ_0 [°]	C_1	C_2	C_3	C_4	C_5	C_6
10	0.0171	0.3978	–0.00292	0.3148	0.1460	1.6077
30	0.0213	0.3887	–0.00160	0.3012	0.1841	1.4317
60	0.0311	0.3356	0.00855	0.2578	0.3385	1.3343
90	0.0499	0.1360	0.04905	0.1434	0.6784	2.1307

Agreement of the MCNP results (points presented by different symbols) and the values predicted by the universal "fit" curves is better for smaller angles of oblique incidence, but is quite good even for very large angles. Almost all the MCNP results are within 5% discrepancy from the exponential "fit" curve for the photon incidence angles up to 60°. For larger incidence angles discrepancies are higher, but again within 10% for most of the points. The maximal discrepancy is 15% for iron at E_0 = 100 keV and θ_0 = 90°.

CONCLUSIONS

Based on the Monte Carlo simulations of photon transport, integral particle reflection coefficient of photons (total number albedo) was determined for different target materials and for oblique photon incidence in the domain of initial photon energies up to 300 keV. Universal behavior of this coefficient was demonstrated when it is presented as a function of the parameter μ/Z_{eff}. Universal functions that successfully describe the particle reflection for all the materials, angles of incidence and initial photon energies have been found. This confirmed that the universal behavior of the total number albedo of photons, previously found for normal photon incidence, is also valid for oblique incidence.

AUTHOR CONTRIBUTIONS

The selection of materials and the domain of initial photon energies for analyses was done by R. D. Simović. Monte Carlo simulations were prepared, carried out and post-processed by V. L. Ljubenov. The fitting parameter was proposed by V. L. Ljubenov, who performed the fitting as well. The manuscript was prepared jointly by both authors. The figures and tables were prepared by V. L. Ljubenov.

REFERENCES

[1] Berger, M. J., Raso, D. J., Monte Carlo Calculations of Gamma-Ray Backscattering, *Radiation Research, 12* (1960), 1, pp. 20-37

[2] Chilton, A. B., Shultis, J. K., Faw, R. E., Principles of Radiation Shielding, Prentice-Hall Inc., Englewood Cliffs, N. J., USA, 1984

[3] Vicanek, M., Urbassek, N. M., Reflection Coefficient of Low-Energy Light Ions, *Phys. Rev., B 44* (1991), 14, pp. 7234-7242

[4] Diop, C. M., Elhamzaoui, B., Nimal, J. C., Determination of the Double Angular and Energy Differential Gamma-Ray Albedo for Iron Material by Using the Monte Carlo Method, *Nucl. Sci. Eng., 117* (1994), 4, pp. 201-226

[5] Luo, Z., Hou, Q., Can the Light Ion Transport in Heavy Targets be Characterized by a Single Parameter, *Nucl. Instr. and Meth., B 95* (1995), 1, pp. 1-6

[6] Marković, S., Backscattered Radiation Field in Diagnostic Radiology Contrast Techniques, Ph. D. Thesis, Faculty of Electrical Engineering, University of Belgrade, Belgrade, 2008

[7] Ljubenov, V., et *al*., Total Reflection Coefficients of Low-Energy Photons Presented as Universal Functions, *Nucl Technol Radiat, 25* (2010), 2, pp. 100-106

[8] Simović, R. D., Vukanić, J., Reflection Coefficients of Low-Energy Light Ions for the Power Form of the Interaction Potential, *Radiat. Phys. Chem., 80* (2011), 3, pp. 310-317

[9] Vukanić, J., Simović, R., Ljubenov, V., Interpolation Formula for Particle Reflection Coefficient of keV Light Ions Obliquely Incident on Heavy Solids, *Nucl. Instr. and Meth., B 269* (2011), 2, pp. 89-93

[10] Ljubenov, V., Simović, R., Universal Dependence of the Total Number Albedo of Photons on the Mean Number of Photon Scatterings, *Nucl Technol Radiat, 26* (2011), 3, pp. 249-253

[11] Ljubenov, V., Simović, R., Photon Albedo Coefficients as Functions of μ/Z_{eff} Parameter, *Nucl Technol Radiat, 28* (2013), 3, pp. 247-253

[12] Mashkovich, V. P., Ionizing Radiation Shielding – Manual (in Russian), Energoatomizdat, Moscow, 1982

[13] Ljubenov, V., *et al*., Photon Scattering and Reflection in Diagnostic Energy Domain, *Nucl Technol Radiat, 23* (2008), 1, pp. 31-36

[14] ***, MCNP™ – A General Monte Carlo N-Particle Transport Code, Version 4C, LA-13709-M, Manual, (Ed. J. E. Briesmeister), LANL, Los alamos, N. Mex., USA, 2000

Received on June 15, 2014
Accepted on December 8, 2014

Владан Љ. ЉУБЕНОВ, Родољуб Д. СИМОВИЋ

ИНТЕГРАЛНИ ЧЕСТИЧНИ КОЕФИЦИЈЕНТ РЕФЛЕКСИЈЕ ЗА КОСИ УПАД ФОТОНА КАО УНИВЕРЗАЛНА ФУНКЦИЈА У ОБЛАСТИ ПОЧЕТНИХ ЕНЕРГИЈА ДО 300 keV

У раду су приказани резултати прорачуна и анализа интегралног честичног коефицијента рефлексије фотона при косом упаду на равне мете, у области почетних енергија фотона од 100 keV до 300 keV. Резултати се заснивају на Монте Карло симулацијама рефлексије фотона од воде, бетона, алуминијума, гвожђа и бакра, обављеним MCNP програмом. За све анализиране заштитне материјале у изабраној енергетској области, уочено је да се интегрални честични коефицијент рефлексије универзално понаша – када је приказан као функција односа тоталног пресека фотона и ефективног атомског броја материјала мете. Одређене су аналитичке формуле за различите углове упада фотона које описују рефлексију фотона од свих анализираних материјала и за све одабране енергије.

Кључне речи: фотон, честични коефицијент рефлексије, кос упад, MCNP програм