Reflection Ratios of Electrons and Photons from Solids

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Reflection Ratios of Electrons and Photons from Solids

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Electron and photon reflection ratios (in number and energy) for absorbers bombarded by electrons have been computed with the ITS Monte Carlo system version 3, and results are given in the form of tables. Electrons of energies from 0.1 to 100 MeV have been assumed normally incident on an effectively semi-infinite absorber. The absorbers considered are elemental solids of atomic numbers from 4 to 92 (Be, C, Al, Cu, Ag, Au and U). An empirical equation for the electron number-reflection ratio has been formulated, by least-squares fit to experimental data collected from literature. Values of parameters derived from the Monte Carlo data on photon number- and energy-reflection ratios are graphically presented.

1. Introduction

When fast electrons impinge on a solid absorber, some of them leave it from the incident surface. Some of bremsstrahlung photons generated in the absorber also emerge from the surface. We call these phenomena "reflection" of electrons and photons. Knowledge on reflection is important in the use and measurement of electron beams, especially in dose evaluation in electron-beam processing. An example is given by the semiempirical algorithm developed by Tabata and Ito[1,2] to calculate the depth-dose distribution of electrons in multilayer absorbers. This algorithm gives good estimates of doses, comparable to Monte Carlo calculation[3], on the assumption that the effect on the dose of the presence of a different material-layer is mainly caused by the difference in electron reflection through boundaries between media.

For a quantitative description of reflection, the following parameters are used:

(1) The electron number-reflection ratio η_{eN} defined as the number of reflected electrons per incident electron.

(2) The electron energy-reflection ratio η_{eE} defined as the ratio of the sum total of the energy of reflected electrons to the sum total of incident-electron energy.

(3) The phonton number-reflection ratio η_{pN} defined as the number of reflected

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photons per incident electron.

(4) The photon energy-reflection ratio η_{pE} defined as the ratio of the sum total of the energy of reflected photons to the sum total of incident-electron energy.

The ratio η_{eN} is commonly called the backscattering coefficient of electrons, and has been studied extensively up to the incident-electron energy of 22 MeV. However, data on the other three reflection ratios have been quite scarce.

We have computed the four reflection ratios for electrons with initial energies from 0.1 to 100 MeV incident on elemental solid absorbers. A brief account of results was given in a previous paper[4]. In the present paper, numerical data are presented for completeness. An empirical equation for η_{eN} and parameters derived from η_{pN} and η_{pE} are also given.

2. Method

The computation of the reflection ratios has been made with the Integrated TIGER Series (ITS) Monte-Carlo system version 3 (Halbleib *et al.*[5]). Plane-parallel electron beams have been assumed to be normally incident on an effectively semi-infinite absorber. The absorber materials considered are Be, C, Al, Cu, Ag, Au and U. The number of primary-electron histories simulated has been 10^5. The transport of all generations of electrons has been followed down to a cutoff energy, which is the minimum of 5% of the initial energy and 0.5 MeV. Photon transport has been simulated down to 10 keV (for more details, see Andreo *et al.*[6]).

The formulation of the empirical equation for η_{eN} has been made by least-squares fit to a total of 1093 experimental data points collected in the energy region from 1 keV to 22 MeV. The functional form of the equation used is a modification of the empirical equation of Tabata *et al.*[7]

3. Results and Discussion

Values of the reflection ratios η_{eN}, η_{eE}, η_{pN} and η_{pE} obtained from the output of the Monte Carlo calculation are given in Table 1.

In Fig. 1 values of η_{eN} obtained with ITS are shown along with experimental data. The experimental data have been taken from the references cited by Tabata *et al.*[7] and from additional papers by Bishop[8], Bronshtein and Denisov[9], Drescher *et al.*[10], Hunger and Küchler[11] and Neubert and Rogaschewski[12]. Curves represent the empirical equation obtained.

The empirical equation is yet tentative; it is given by

Table 1 Values of the electron number-reflection ratio η_{eN}, electron energy-reflection ratio η_{eE}, the photon number-reflection ratio η_{pN} and the photon energy-reflection ratio η_{pE}. Errors attached are statistical uncertainties. Values without an error have an uncertainty greater than 100%.

T_0 (MeV)	η_{eN}	η_{eE}	η_{eN}	η_{eE}
Z=4				
0.1	$(1.94\pm0.05)\times10^{-2}$	$(9.37\pm0.26)\times10^{-3}$	3.07×10^{-4}	6.61×10^{-5}
0.2	$(1.75\pm0.05)\times10^{-2}$	$(7.83\pm0.20)\times10^{-3}$	$(9.81\pm0.90)\times10^{-4}$	1.40×10^{-4}
0.5	$(1.26\pm0.04)\times10^{-2}$	$(5.03\pm0.19)\times10^{-3}$	$(2.72\pm0.11)\times10^{-3}$	$(2.23\pm0.18)\times10^{-4}$
1	$(9.00\pm0.35)\times10^{-3}$	$(3.22\pm0.14)\times10^{-3}$	$(6.85\pm0.29)\times10^{-3}$	$(3.72\pm0.23)\times10^{-4}$
2	$(4.78\pm0.20)\times10^{-3}$	$(1.55\pm0.67)\times10^{-3}$	$(1.90\pm0.05)\times10^{-2}$	$(6.02\pm0.22)\times10^{-4}$
5	$(1.61\pm0.12)\times10^{-3}$	$(4.95\pm0.48)\times10^{-4}$	$(6.91\pm0.08)\times10^{-2}$	$(1.11\pm0.02)\times10^{-3}$
10	5.30×10^{-4}	1.47×10^{-4}	$(1.77\pm0.01)\times10^{-1}$	$(1.46\pm0.02)\times10^{-3}$
20	3.00×10^{-4}	9.02×10^{-5}	$(3.92\pm0.02)\times10^{-1}$	$(1.58\pm0.01)\times10^{-3}$
50	1.60×10^{-4}	2.99×10^{-5}	$(7.46\pm0.02)\times10^{-1}$	$(1.18\pm0.01)\times10^{-3}$
100	1.20×10^{-4}	9.86×10^{-6}	$(9.39\pm0.03)\times10^{-1}$	$(7.63\pm0.05)\times10^{-4}$
Z=6				
0.1	$(4.06\pm0.04)\times10^{-2}$	$(2.05\pm0.02)\times10^{-2}$	5.43×10^{-4}	1.35×10^{-4}
0.2	$(3.68\pm0.07)\times10^{-2}$	$(1.75\pm0.03)\times10^{-2}$	$(1.46\pm0.09)\times10^{-3}$	$(2.29\pm0.20)\times10^{-4}$
0.5	$(2.98\pm0.05)\times10^{-2}$	$(1.25\pm0.03)\times10^{-2}$	$(4.45\pm0.26)\times10^{-3}$	$(3.81\pm0.27)\times10^{-4}$
1	$(2.18\pm0.05)\times10^{-2}$	$(7.81\pm0.22)\times10^{-3}$	$(1.05\pm0.03)\times10^{-2}$	$(6.52\pm0.26)\times10^{-4}$
2	$(1.26\pm0.03)\times10^{-2}$	$(4.14\pm0.17)\times10^{-3}$	$(2.42\pm0.05)\times10^{-2}$	$(1.04\pm0.03)\times10^{-3}$
5	$(3.71\pm0.20)\times10^{-3}$	$(1.11\pm0.08)\times10^{-3}$	$(8.40\pm0.07)\times10^{-2}$	$(1.71\pm0.02)\times10^{-3}$
10	$(1.32\pm0.13)\times10^{-3}$	3.73×10^{-4}	$(1.96\pm0.01)\times10^{-1}$	$(2.05\pm0.03)\times10^{-3}$
20	6.60×10^{-4}	1.49×10^{-4}	$(3.96\pm0.02)\times10^{-1}$	$(2.09\pm0.02)\times10^{-3}$
50	3.50×10^{-4}	4.80×10^{-5}	$(6.95\pm0.02)\times10^{-1}$	$(1.46\pm0.01)\times10^{-3}$
100	3.60×10^{-4}	1.73×10^{-5}	$(8.82\pm0.03)\times10^{-1}$	$(9.59\pm0.08)\times10^{-4}$
Z=13				
0.1	$(1.34\pm0.01)\times10^{-1}$	$(7.74\pm0.05)\times10^{-2}$	$(4.27\pm0.18)\times10^{-3}$	$(3.88\pm0.23)\times10^{-4}$
0.2	$(1.29\pm0.01)\times10^{-1}$	$(7.07\pm0.06)\times10^{-2}$	$(4.75\pm0.19)\times10^{-3}$	$(5.97\pm0.30)\times10^{-4}$
0.5	$(1.15\pm0.01)\times10^{-1}$	$(5.62\pm0.06)\times10^{-2}$	$(9.96\pm0.38)\times10^{-3}$	$(1.10\pm0.05)\times10^{-3}$
1	$(9.27\pm0.08)\times10^{-2}$	$(4.10\pm0.04)\times10^{-2}$	$(1.91\pm0.04)\times10^{-2}$	$(1.75\pm0.05)\times10^{-3}$
2	$(5.95\pm0.08)\times10^{-2}$	$(2.21\pm0.03)\times10^{-2}$	$(4.32\pm0.07)\times10^{-2}$	$(2.78\pm0.08)\times10^{-3}$
5	$(2.16\pm0.04)\times10^{-2}$	$(6.32\pm0.16)\times10^{-3}$	$(1.21\pm0.01)\times10^{-1}$	$(4.28\pm0.06)\times10^{-3}$
10	$(6.44\pm0.26)\times10^{-3}$	$(1.72\pm0.09)\times10^{-3}$	$(2.37\pm0.01)\times10^{-1}$	$(4.81\pm0.06)\times10^{-3}$
20	$(2.44\pm0.19)\times10^{-3}$	4.48×10^{-4}	$(4.09\pm0.02)\times10^{-1}$	$(4.06\pm0.04)\times10^{-3}$
50	1.46×10^{-3}	1.42×10^{-4}	$(6.41\pm0.03)\times10^{-1}$	$(2.54\pm0.02)\times10^{-3}$
100	$(1.09\pm0.10)\times10^{-3}$	2.95×10^{-5}	$(8.25\pm0.02)\times10^{-1}$	$(1.66\pm0.01)\times10^{-3}$
Z=29				
0.1	$(2.96\pm0.02)\times10^{-1}$	$(2.00\pm0.01)\times10^{-1}$	$(1.28\pm0.03)\times10^{-2}$	$(1.57\pm0.05)\times10^{-3}$
0.2	$(2.89\pm0.01)\times10^{-1}$	$(1.89\pm0.01)\times10^{-1}$	$(1.82\pm0.03)\times10^{-2}$	$(1.83\pm0.05)\times10^{-3}$
0.5	$(2.63\pm0.02)\times10^{-1}$	$(1.59\pm0.01)\times10^{-1}$	$(2.51\pm0.03)\times10^{-2}$	$(2.85\pm0.08)\times10^{-3}$
1	$(2.34\pm0.02)\times10^{-1}$	$(1.31\pm0.01)\times10^{-1}$	$(3.29\pm0.06)\times10^{-2}$	$(4.59\pm0.12)\times10^{-3}$
2	$(1.81\pm0.01)\times10^{-1}$	$(8.85\pm0.06)\times10^{-2}$	$(7.12\pm0.09)\times10^{-2}$	$(7.55\pm0.14)\times10^{-3}$
5	$(8.85\pm0.12)\times10^{-2}$	$(3.40\pm0.05)\times10^{-2}$	$(1.91\pm0.01)\times10^{-1}$	$(1.33\pm0.01)\times10^{-2}$
10	$(3.53\pm0.07)\times10^{-2}$	$(1.06\pm0.03)\times10^{-2}$	$(3.23\pm0.02)\times10^{-1}$	$(1.43\pm0.01)\times10^{-2}$
20	$(1.14\pm0.03)\times10^{-2}$	$(2.29\pm0.07)\times10^{-3}$	$(4.73\pm0.02)\times10^{-1}$	$(1.16\pm0.01)\times10^{-2}$
50	$(5.57\pm0.25)\times10^{-3}$	$(5.02\pm0.46)\times10^{-4}$	$(6.83\pm0.03)\times10^{-1}$	$(6.27\pm0.05)\times10^{-3}$
100	$(4.17\pm0.18)\times10^{-3}$	$(1.03\pm0.09)\times10^{-4}$	$(9.16\pm0.03)\times10^{-1}$	$(4.05\pm0.02)\times10^{-3}$
Z=47				
0.1	$(3.91\pm0.02)\times10^{-1}$	$(2.85\pm0.01)\times10^{-1}$	$(7.23\pm0.25)\times10^{-3}$	$(1.93\pm0.06)\times10^{-3}$
0.2	$(3.89\pm0.02)\times10^{-1}$	$(2.78\pm0.01)\times10^{-1}$	$(1.65\pm0.04)\times10^{-2}$	$(2.93\pm0.10)\times10^{-3}$
0.5	$(3.67\pm0.01)\times10^{-1}$	$(2.48\pm0.01)\times10^{-1}$	$(3.58\pm0.04)\times10^{-2}$	$(4.88\pm0.09)\times10^{-3}$
1	$(3.32\pm0.01)\times10^{-1}$	$(2.09\pm0.01)\times10^{-1}$	$(6.06\pm0.07)\times10^{-2}$	$(7.79\pm0.17)\times10^{-3}$
2	$(2.71\pm0.02)\times10^{-1}$	$(1.52\pm0.01)\times10^{-1}$	$(1.09\pm0.01)\times10^{-1}$	$(1.31\pm0.02)\times10^{-2}$
5	$(1.56\pm0.01)\times10^{-1}$	$(7.03\pm0.05)\times10^{-2}$	$(2.49\pm0.01)\times10^{-1}$	$(2.34\pm0.02)\times10^{-2}$
10	$(7.11\pm0.10)\times10^{-2}$	$(2.49\pm0.04)\times10^{-2}$	$(3.95\pm0.02)\times10^{-1}$	$(2.62\pm0.02)\times10^{-2}$
20	$(2.52\pm0.06)\times10^{-2}$	$(5.86\pm0.15)\times10^{-3}$	$(5.34\pm0.03)\times10^{-1}$	$(2.08\pm0.01)\times10^{-2}$
50	$(1.02\pm0.03)\times10^{-2}$	$(9.70\pm0.59)\times10^{-4}$	$(7.46\pm0.02)\times10^{-1}$	$(1.12\pm0.01)\times10^{-2}$
100	$(7.80\pm0.26)\times10^{-3}$	$(2.25\pm0.20)\times10^{-4}$	1.04 ± 0.03	$(7.45\pm0.04)\times10^{-3}$
Z=79				
0.1	$(5.01\pm0.02)\times10^{-1}$	$(3.94\pm0.01)\times10^{-1}$	$(7.58\pm0.23)\times10^{-3}$	$(2.23\pm0.10)\times10^{-3}$
0.2	$(5.17\pm0.02)\times10^{-1}$	$(4.02\pm0.01)\times10^{-1}$	$(1.59\pm0.04)\times10^{-2}$	$(4.22\pm0.14)\times10^{-3}$
0.5	$(5.04\pm0.01)\times10^{-1}$	$(3.77\pm0.01)\times10^{-1}$	$(4.27\pm0.04)\times10^{-2}$	$(8.70\pm0.11)\times10^{-3}$
1	$(4.61\pm0.02)\times10^{-1}$	$(3.28\pm0.01)\times10^{-1}$	$(8.59\pm0.07)\times10^{-2}$	$(1.40\pm0.02)\times10^{-2}$
2	$(3.94\pm0.01)\times10^{-1}$	$(2.57\pm0.01)\times10^{-1}$	$(1.62\pm0.01)\times10^{-1}$	$(2.23\pm0.02)\times10^{-2}$
5	$(2.54\pm0.01)\times10^{-1}$	$(1.38\pm0.01)\times10^{-1}$	$(3.40\pm0.01)\times10^{-1}$	$(3.98\pm0.03)\times10^{-2}$
10	$(1.32\pm0.01)\times10^{-1}$	$(5.66\pm0.05)\times10^{-2}$	$(5.05\pm0.02)\times10^{-1}$	$(4.65\pm0.02)\times10^{-2}$
20	$(5.56\pm0.07)\times10^{-2}$	$(1.60\pm0.03)\times10^{-2}$	$(6.43\pm0.03)\times10^{-1}$	$(3.80\pm0.02)\times10^{-2}$
50	$(2.22\pm0.05)\times10^{-2}$	$(2.61\pm0.11)\times10^{-3}$	$(8.19\pm0.03)\times10^{-1}$	$(2.01\pm0.01)\times10^{-2}$
100	$(1.66\pm0.04)\times10^{-2}$	$(5.85\pm0.27)\times10^{-4}$	1.08 ± 0.003	$(1.29\pm0.01)\times10^{-2}$
Z=92				
0.1	$(5.27\pm0.02)\times10^{-1}$	$(4.20\pm0.01)\times10^{-1}$	$(6.77\pm0.28)\times10^{-3}$	$(2.37\pm0.14)\times10^{-3}$
0.2	$(5.43\pm0.02)\times10^{-1}$	$(4.30\pm0.01)\times10^{-1}$	$(1.53\pm0.04)\times10^{-2}$	$(4.51\pm0.14)\times10^{-3}$
0.5	$(5.32\pm0.02)\times10^{-1}$	$(4.08\pm0.01)\times10^{-1}$	$(4.37\pm0.06)\times10^{-2}$	$(9.83\pm0.17)\times10^{-3}$
1	$(4.94\pm0.01)\times10^{-1}$	$(3.61\pm0.01)\times10^{-1}$	$(9.07\pm0.06)\times10^{-2}$	$(1.65\pm0.02)\times10^{-2}$
2	$(4.24\pm0.02)\times10^{-1}$	$(2.85\pm0.01)\times10^{-1}$	$(1.79\pm0.01)\times10^{-1}$	$(2.63\pm0.02)\times10^{-2}$
5	$(2.85\pm0.02)\times10^{-1}$	$(1.62\pm0.01)\times10^{-1}$	$(3.76\pm0.01)\times10^{-1}$	$(4.51\pm0.03)\times10^{-2}$
10	$(1.56\pm0.01)\times10^{-1}$	$(7.19\pm0.06)\times10^{-2}$	$(5.42\pm0.02)\times10^{-1}$	$(5.31\pm0.03)\times10^{-2}$
20	$(6.91\pm0.07)\times10^{-2}$	$(2.11\pm0.03)\times10^{-2}$	$(6.69\pm0.03)\times10^{-1}$	$(4.36\pm0.02)\times10^{-2}$
50	$(2.88\pm0.06)\times10^{-2}$	$(3.84\pm0.10)\times10^{-3}$	$(8.12\pm0.02)\times10^{-1}$	$(2.30\pm0.01)\times10^{-2}$
100	$(2.07\pm0.04)\times10^{-2}$	$(7.91\pm0.31)\times10^{-4}$	1.04 ± 0.003	$(1.46\pm0.01)\times10^{-2}$

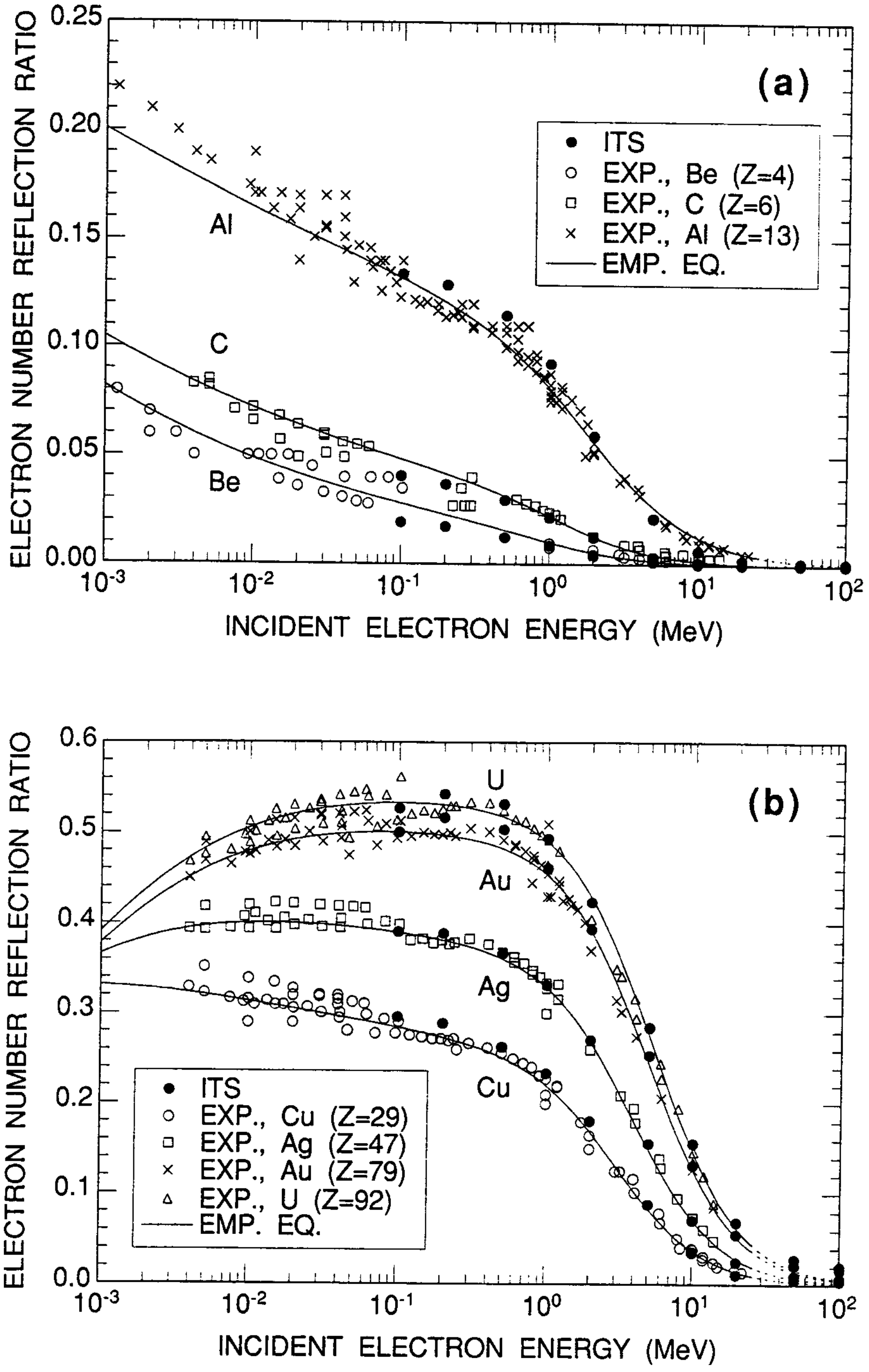

Fig. 1 Electron number-reflection ratio η_{eN}. (a) absorbers of atomic number $Z=4-13$. (b) $Z=29-92$.

$$\eta_{eN}=a_1/\{\tau_0^{a_2}[1+(a_3/\tau_0)^{a_4}]\,[1+(\tau_0/a_5)^{a_6-a_2}]\}, \tag{1}$$

where

$$a_1=b_1+b_2\exp[-(b_3/Z)^{b_4}] \tag{2}$$
$$a_2=b_5/[1+(Z/b_6)^{b_7}] \tag{3}$$
$$a_3=b_8/[1+(b_9/Z)^{b_{10}}] \tag{4}$$
$$a_4=b_{11} \tag{5}$$
$$a_5=b_{12}Z^{b_{13}} \tag{6}$$
$$a_6=b_{14}+b_{15}/[1+(b_{16}/Z)^{b_{17}}] \tag{7}$$

τ_0 is the incident electron energy in units of the rest energy of the electron, Z is the atomic number of absorber material, and the symbols b_i ($i=1, 2, \ldots 17$) denote adjustable coefficients. Values of b_i determined by the least-squares fit mentioned in the previous section are given in Table 2. Equation (1) has two factors, $1/\tau_0^{a_2}$ and $1/[1+(a_3/\tau_0)^{a_4}]$, that were not included in the previous equation[7]. These factors express the behavior of η_{eN} at lower energies for lower and higher Z absorbers. Thus the lower limit to the applicable energy-region has been extended from about 50 keV of the previous equation to about 1 keV. The root-mean-square deviation of the experimental data from the equation is 5.6%.

Table. 2 Values of adjustable coefficients b_i ($i=1, 2, \cdots, 17$) in the empirical equation for the electron number-reflection ratio.

Coefficient	Value
b_1	9.41×10^{-3}
b_2	1.132
b_3	57.1
b_4	0.579
b_5	3.47
b_6	0.163
b_7	0.833
b_8	7.30×10^{-4}
b_9	58.5
b_{10}	5.14
b_{11}	0.574
b_{12}	1.43
b_{13}	0.447
b_{14}	1.108
b_{15}	0.417
b_{16}	13.0
b_{17}	1.76×10^{2}

In addition to η_{pN} and η_{pE}, the following parameters are of interest in relation to photon reflection:
(1) The average energy T_p of reflected photons.
(2) The sum total ΣT_p of the photon energy reflected per incident electron.
(3) The reflected photon-energy R_p per sum total of the energy given to photons.
The parameter T_p is given by $(\eta_{pE}/\eta_{pN})T_0$, where T_0 is the incident electron energy; ΣT_p is given by $\eta_{pE}T_0$; and R_p is given by η_{pE}/Y, where Y is the radiation yeild, i.e., the fraction of the initial energy of an electron that is converted to bremsstrahlung energy as the electron slows down to rest.

In Figs. 2–4, the above three parameters are plotted as a function of the incident-electron energy. The values of the radiation yield used have been taken from ICRU Report 37 (Ref. 13). In Fig. 3 the Monte Carlo results of Lockwood *et al.*[14] and the empirical equation reported in our previous paper[4] are also plotted. The results of Lockwood *et al.* were obtained with a previous version of the TIGER code.

Figure 2 indicates that T_p increases with increasing incident-electron energy, and reaches an almost constant value, which ranges from 0.08 keV to 1.5 MeV depending on Z. The parameter ΣT_p also increases with increasing incident-electron energy, and does not reach a saturation at the highest energy of 100 MeV, as can be seen from Fig. 3. Such behavior of T_p and ΣT_p contrasts with the behavior of the photon energy-reflection ratio η_{pE}, which shows a maximum around the incident-electron energy of 10 MeV as can be seen from Table 1 and

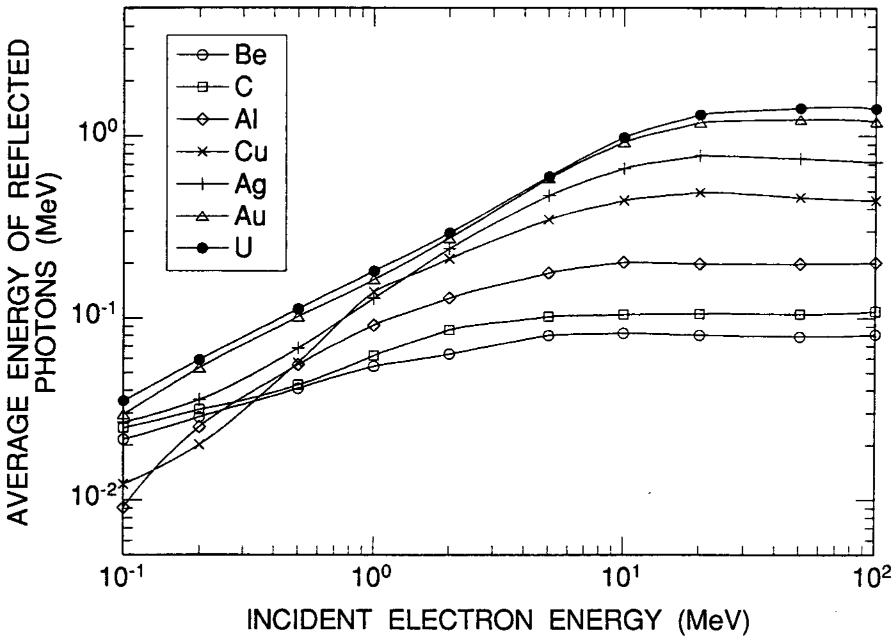

Fig. 2 Average energy T_p of reflected photons.

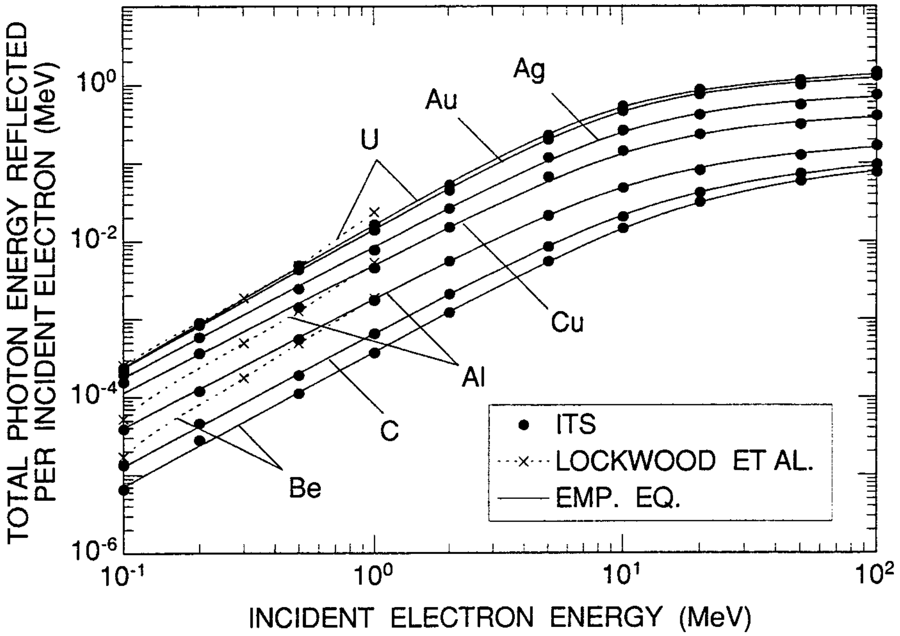

Fig. 3 Sum total ΣT_p of the photon energy reflected per incident electron.

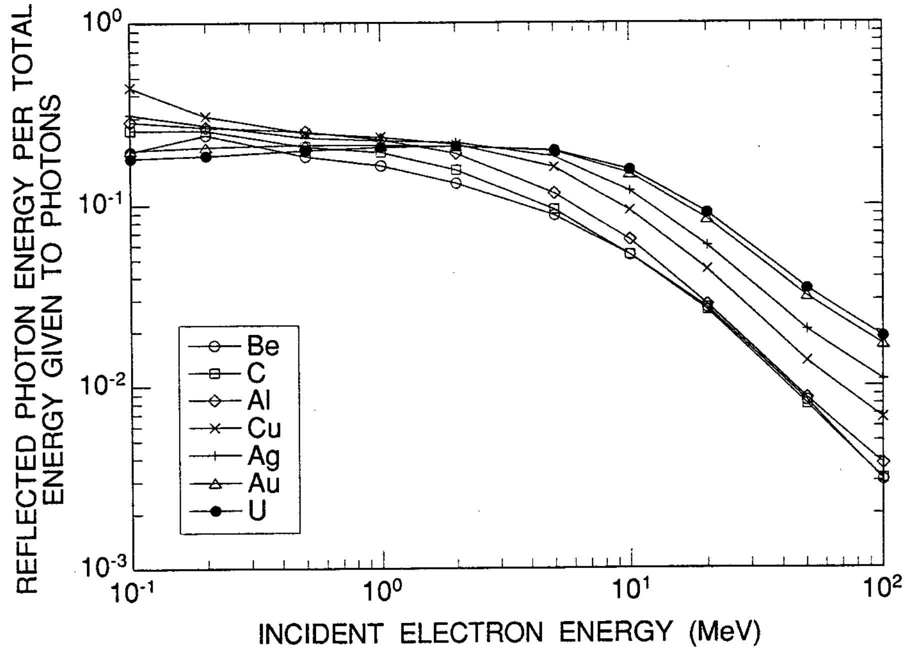

Fig. 4 The reflected photon-energy R_p per sum total of the energy given to photons.

Fig. 4 of Ref. 4.

From Fig. 4 we see that R_p takes on an almost constant value of about 20% at the lowest energies, and starts to show a rapid decrease with increasing incident-electron energy at an intermediate energy.

A final report on the empirical equation for the electron number-reflection ratio η_{eN} will be given elsewhere.

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