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Rinsuke ITO, Pedro ANDREO and Tatsuo TABATA

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# Reflection Ratios of Electrons and Photons from Solids

Rinsuke ITO\*, Pedro ANDREO# and Tatsuo TABATA\*

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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<sup>1,2)</sup> to calculate the depth-dose distribution of electrons in multilayer absorbers. This algorithm gives good estimates of doses, comparable to Monte Carlo calculation<sup>3)</sup>, 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  $\eta_{eN}$  defined as the number of reflected electrons per incident electron.
- (2) The electron energy-reflection ratio  $\eta_{eE}$  defined as the ratio of the sum total of the energy of reflected electrons to the sum total of incident-electron energy.

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\* Research Institute for Advanced Science and Technology

# Department of Radiation Physics, Karolinska Institute and University of Stockholm, Stockholm, Sweden.

- (3) The photon number-reflection ratio  $\eta_{pN}$  defined as the number of reflected photons per incident electron.
- (4) The photon energy-reflection ratio  $\eta_{pE}$  defined as the ratio of the sum total of the energy of reflected photons to the sum total of incident-electron energy.

The ratio  $\eta_{eN}$  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 incident on elemental solid absorbers with initial energies from 0.1 to 100 MeV. A brief account of results was given in a previous paper<sup>4)</sup>. In the present paper, numerical data are presented for completeness. An empirical equation for  $\eta_{eN}$  and parameters derived from  $\eta_{pN}$  and  $\eta_{pE}$  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.*<sup>5)</sup>). 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 cut-off 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.*<sup>6)</sup>).

The formulation of the empirical equation for  $\eta_{eN}$  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.*<sup>7)</sup>

## 3 Results And Discussion

Values of the reflection ratios  $\eta_{eN}$ ,  $\eta_{eE}$ ,  $\eta_{pN}$  and  $\eta_{pE}$  obtained by the Monte Carlo calculations are given in Table 1.

In Fig. 1 values of  $\eta_{eN}$  obtained are shown along with experimental data. The experimental data have been taken from the references cited by Tabata *et al.*<sup>7)</sup> and from additional papers by Bishop<sup>8)</sup>, Bronshtein and Denisov<sup>9)</sup>, Drescher *et al.*<sup>10)</sup>, Hunger and K uchler<sup>11)</sup> and Neubert and Rogaschewski<sup>12)</sup>. Curves represent the empirical equation obtained.

The empirical equation is yet tentative; it is given by

Table 1 Values of  $\eta_{eN}$ ,  $\eta_{eE}$ ,  $\eta_{pN}$  and  $\eta_{pE}$ . Errors attached are statistical uncertainties. Values without an error have an uncertainty greater than 10%.

$T_0$ (MeV)	$\eta_{eN}$	$\eta_{eE}$	$\eta_{pN}$	$\eta_{pE}$
Z = 4				
0.1	(1.94±0.05)E-2	(9.37±0.26)E-3	3.07E-4	6.61E-5
0.2	(1.75±0.05)E-2	(7.83±0.20)E-3	(9.81±0.90)E-4	1.40E-4
0.5	(1.26±0.04)E-2	(5.03±0.19)E-3	(2.72±0.11)E-3	(2.23±0.18)E-4
1	(9.00±0.35)E-3	(3.22±0.14)E-3	(6.85±0.29)E-3	(3.72±0.23)E-4
2	(4.78±0.20)E-3	(1.55±0.67)E-3	(1.90±0.05)E-2	(6.02±0.22)E-4
5	(1.61±0.12)E-3	(4.95±0.48)E-4	(6.91±0.08)E-2	(1.11±0.02)E-3
10	5.30E-4	1.47E-4	(1.77±0.01)E-1	(1.46±0.02)E-3
20	3.00E-4	9.02E-5	(3.92±0.02)E-1	(1.58±0.01)E-3
50	1.60E-4	2.99E-5	(7.46±0.02)E-1	(1.18±0.01)E-3
100	1.20E-4	9.86E-6	(9.39±0.03)E-1	(7.63±0.05)E-4
Z = 6				
0.1	(4.06±0.04)E-2	(2.05±0.02)E-2	5.43E-4	1.35E-4
0.2	(3.68±0.07)E-2	(1.75±0.03)E-2	(1.46±0.09)E-3	(2.29±0.20)E-4
0.5	(2.98±0.05)E-2	(1.25±0.03)E-2	(4.45±0.26)E-3	(3.81±0.27)E-4
1	(2.18±0.05)E-2	(7.81±0.22)E-3	(1.05±0.03)E-2	(6.52±0.26)E-4
2	(1.26±0.03)E-2	(4.14±0.17)E-3	(2.42±0.05)E-2	(1.04±0.03)E-3
5	(3.71±0.20)E-3	(1.11±0.08)E-3	(8.40±0.07)E-2	(1.71±0.02)E-3
10	(1.32±0.13)E-3	3.73E-4	(1.96±0.01)E-1	(2.05±0.03)E-3
20	6.60E-4	1.49E-4	(3.96±0.02)E-1	(2.09±0.02)E-3
50	3.50E-4	4.80E-5	(6.95±0.02)E-1	(1.46±0.01)E-3
100	3.60E-4	1.73E-5	(8.82±0.03)E-1	(9.59±0.08)E-4
Z = 13				
0.1	(1.34±0.01)E-1	(7.74±0.05)E-2	(4.27±0.18)E-3	(3.88±0.23)E-4
0.2	(1.29±0.01)E-1	(7.07±0.06)E-2	(4.75±0.19)E-3	(5.97±0.30)E-4
0.5	(1.15±0.01)E-1	(5.62±0.06)E-2	(9.96±0.38)E-3	(1.10±0.05)E-3
1	(9.27±0.08)E-2	(4.10±0.04)E-2	(1.91±0.04)E-2	(1.75±0.05)E-3
2	(5.95±0.08)E-2	(2.21±0.03)E-2	(4.32±0.07)E-2	(2.78±0.08)E-3
5	(2.16±0.04)E-2	(6.32±0.16)E-3	(1.21±0.01)E-1	(4.28±0.06)E-3
10	(6.44±0.26)E-3	(1.72±0.09)E-3	(2.37±0.01)E-1	(4.81±0.06)E-3
20	(2.44±0.19)E-3	4.48E-4	(4.09±0.02)E-1	(4.06±0.04)E-3
50	1.46E-3	1.42E-4	(6.41±0.03)E-1	(2.54±0.02)E-3
100	(1.09±0.10)E-3	2.95E-5	(8.25±0.02)E-1	(1.66±0.01)E-3
Z = 29				
0.1	(2.96±0.02)E-1	(2.00±0.01)E-1	(1.28±0.03)E-2	(1.57±0.05)E-3
0.2	(2.89±0.01)E-1	(1.89±0.01)E-1	(1.82±0.03)E-2	(1.83±0.05)E-3
0.5	(2.63±0.02)E-1	(1.59±0.01)E-1	(2.51±0.03)E-2	(2.85±0.08)E-3
1	(2.34±0.02)E-1	(1.31±0.01)E-1	(3.29±0.06)E-2	(4.59±0.12)E-3
2	(1.81±0.01)E-1	(8.85±0.06)E-2	(7.12±0.09)E-2	(7.55±0.14)E-3
5	(8.85±0.12)E-2	(3.40±0.05)E-2	(1.91±0.01)E-1	(1.33±0.01)E-2
10	(3.53±0.07)E-2	(1.06±0.03)E-2	(3.23±0.02)E-1	(1.43±0.01)E-2
20	(1.14±0.03)E-2	(2.29±0.07)E-3	(4.73±0.02)E-1	(1.16±0.01)E-2
50	(5.57±0.25)E-3	(5.02±0.46)E-4	(6.83±0.03)E-1	(6.27±0.05)E-3
100	(4.17±0.18)E-3	(1.03±0.09)E-4	(9.16±0.03)E-1	(4.05±0.02)E-3
Z = 47				
0.1	(3.91±0.02)E-1	(2.85±0.01)E-1	(7.23±0.25)E-3	(1.93±0.06)E-3
0.2	(3.89±0.02)E-1	(2.78±0.01)E-1	(1.65±0.04)E-2	(2.93±0.10)E-3
0.5	(3.67±0.01)E-1	(2.48±0.01)E-1	(3.58±0.04)E-2	(4.88±0.09)E-3
1	(3.32±0.01)E-1	(2.09±0.01)E-1	(6.06±0.07)E-2	(7.79±0.17)E-3
2	(2.71±0.02)E-1	(1.52±0.01)E-1	(1.09±0.01)E-1	(1.31±0.02)E-2
5	(1.56±0.01)E-1	(7.03±0.05)E-2	(2.49±0.01)E-1	(2.34±0.02)E-2
10	(7.11±0.10)E-2	(2.49±0.04)E-2	(3.95±0.02)E-1	(2.62±0.02)E-2
20	(2.52±0.06)E-2	(5.86±0.15)E-3	(5.34±0.03)E-1	(2.08±0.01)E-2
50	(1.02±0.03)E-2	(9.70±0.59)E-4	(7.46±0.02)E-1	(1.12±0.01)E-2
100	(7.80±0.26)E-3	(2.25±0.20)E-4	1.04±0.03	(7.45±0.04)E-3
Z = 79				
0.1	(5.01±0.02)E-1	(3.94±0.01)E-1	(7.58±0.23)E-3	(2.23±0.10)E-3
0.2	(5.17±0.02)E-1	(4.02±0.01)E-1	(1.59±0.04)E-2	(4.22±0.14)E-3
0.5	(5.04±0.01)E-1	(3.77±0.01)E-1	(4.27±0.04)E-2	(8.70±0.11)E-3
1	(4.61±0.02)E-1	(3.28±0.01)E-1	(8.59±0.07)E-2	(1.40±0.02)E-2
2	(3.94±0.01)E-1	(2.57±0.01)E-1	(1.62±0.01)E-1	(2.23±0.02)E-2
5	(2.54±0.01)E-1	(1.38±0.01)E-1	(3.40±0.01)E-1	(3.98±0.03)E-2
10	(1.32±0.01)E-1	(5.66±0.05)E-2	(5.05±0.02)E-1	(4.65±0.02)E-2
20	(5.56±0.07)E-2	(1.60±0.03)E-2	(6.43±0.03)E-1	(3.80±0.02)E-2
50	(2.22±0.05)E-2	(2.61±0.11)E-3	(8.19±0.03)E-1	(2.01±0.01)E-2
100	(1.66±0.04)E-2	(5.85±0.27)E-4	1.08±0.003	(1.29±0.01)E-2
Z = 92				
0.1	(5.27±0.02)E-1	(4.20±0.01)E-1	(6.77±0.28)E-3	(2.37±0.14)E-3
0.2	(5.43±0.02)E-1	(4.30±0.01)E-1	(1.53±0.04)E-2	(4.51±0.14)E-3
0.5	(5.32±0.02)E-1	(4.08±0.01)E-1	(4.37±0.06)E-2	(9.83±0.17)E-3
1	(4.94±0.01)E-1	(3.61±0.01)E-1	(9.07±0.06)E-2	(1.65±0.02)E-2
2	(4.24±0.02)E-1	(2.85±0.01)E-1	(1.79±0.01)E-1	(2.63±0.02)E-2
5	(2.85±0.02)E-1	(1.62±0.01)E-1	(3.76±0.01)E-1	(4.51±0.03)E-2
10	(1.56±0.01)E-1	(7.19±0.06)E-2	(5.42±0.02)E-1	(5.31±0.03)E-2
20	(6.91±0.07)E-2	(2.11±0.03)E-2	(6.69±0.03)E-1	(4.36±0.02)E-2
50	(2.88±0.06)E-2	(3.84±0.10)E-3	(8.12±0.02)E-1	(2.30±0.01)E-2
100	(2.07±0.04)E-2	(7.91±0.31)E-4	1.04±0.003	(1.46±0.01)E-2

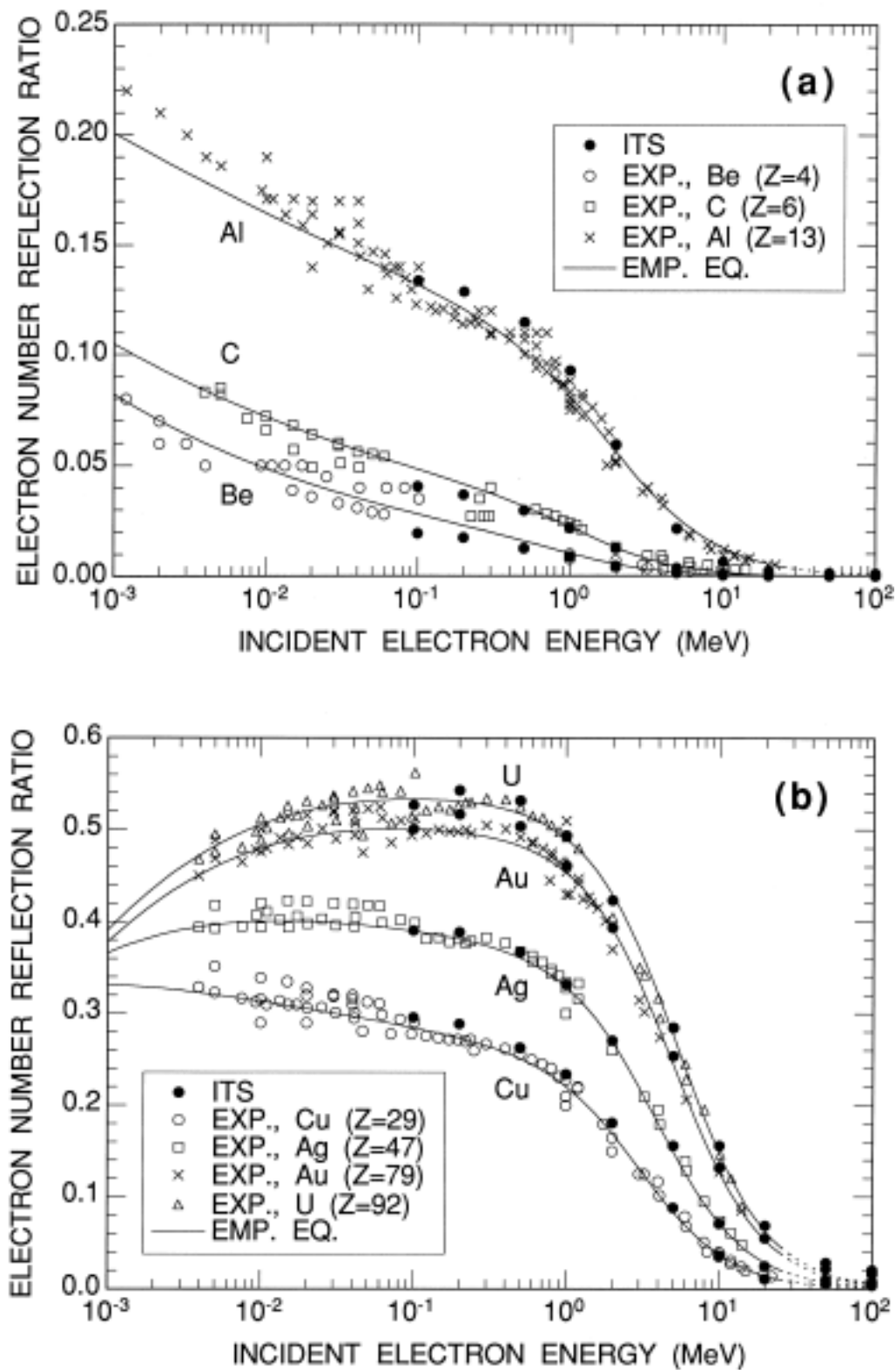


Fig. 1. Electron number-reflection ratio  $\eta_{eN}$ . (a) absorbers of atomic number  $Z=4-13$ ,  
(b)  $Z=29-92$ .

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

where

$$a_1 = b_1 + b_2 \exp\left[-(b_3/Z)^{b_4}\right] \quad (2)$$

$$a_2 = b_5 / \left[ 1 + (Z/b_6)^{b_7} \right] \quad (3)$$

$$a_3 = b_8 / \left[ 1 + (b_9/Z)^{b_{10}} \right] \quad (4)$$

$$a_4 = b_{11} \quad (5)$$

$$a_5 = b_{12} Z^{b_{13}} \quad (6)$$

$$a_6 = b_{14} + b_{15} / \left[ 1 + (b_{16}/Z)^{b_{17}} \right] \quad (7)$$

$r_0$  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  $b_i$  ( $i=1, 2, \dots, 17$ ) 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  $1/\left[1 + (a_3/\tau_0)^{a_4}\right]$ , that were not included in the previous equation<sup>7)</sup>. These factors express the behavior of  $\eta_{eN}$  at lower energies

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

Coefficient	Value
$b_1$	$9.41 \times 10^{-3}$
$b_2$	1.132
$b_3$	57.1
$b_4$	0.579
$b_5$	3.47
$b_6$	0.163
$b_7$	0.833
$b_8$	$7.30 \times 10^{-4}$
$b_9$	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
$b_{17}$	$1.76 \times 10^2$

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%.

In addition to  $\eta_{pN}$  and  $\eta_{pE}$ , the following parameters are of interest in relation to photon reflection:

- (1) The average energy  $T_p$  of reflected photons.
- (2) The sum total  $\Sigma T_p$  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;  $\Sigma T_p$  is given by  $\eta_{pE}T_0$ ; and  $R_p$  is given by  $\eta_{pE}/Y$ , where  $Y$  is the radiation yield, *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.*<sup>14)</sup> and the empirical equation reported in our previous paper<sup>4)</sup> are also plotted. The results of Lockwood *et al.* were obtained with a previous version of the TIGER code.

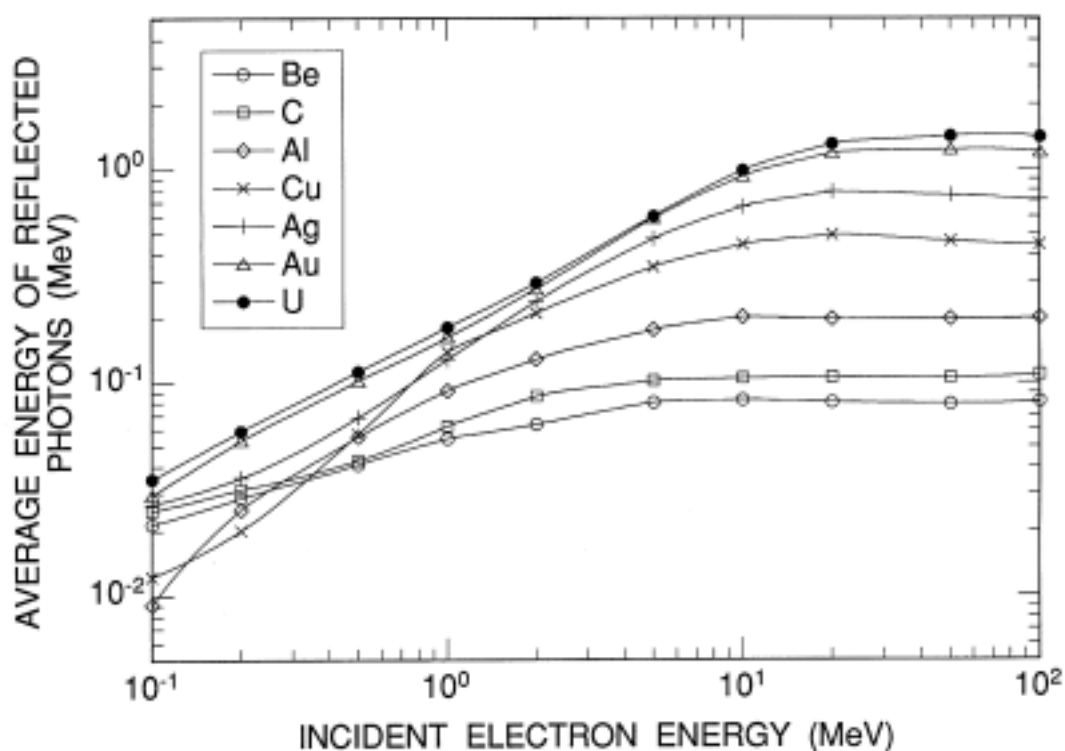


Fig. 2. Average energy  $T_p$  of reflected photons.

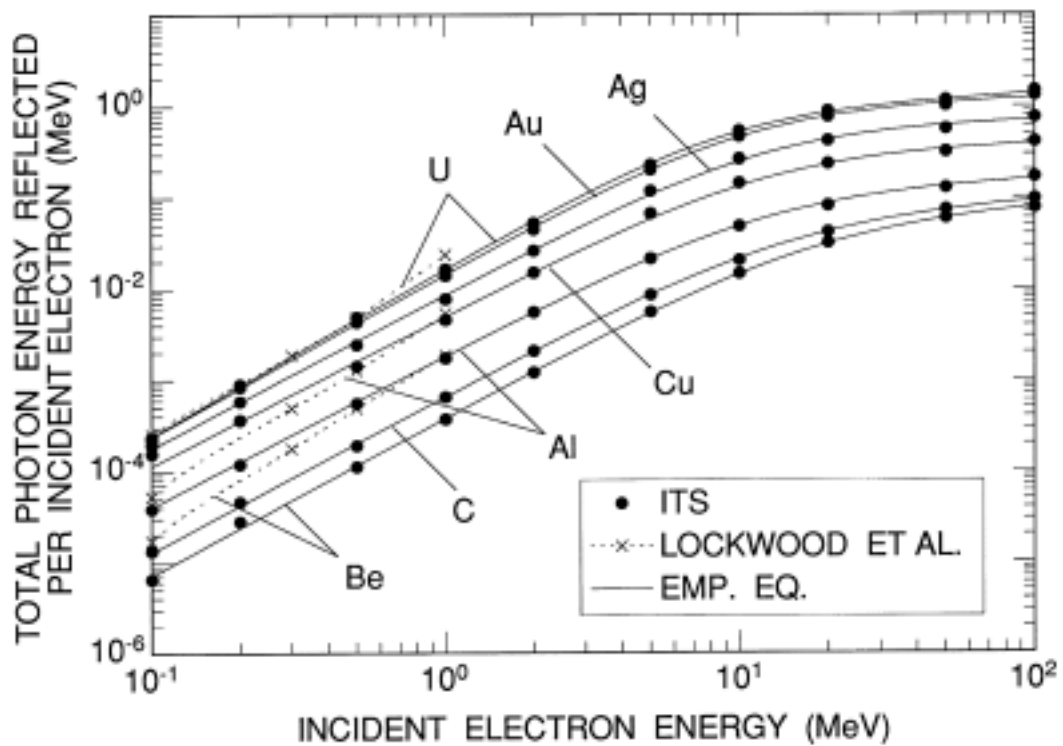


Fig. 3. Sum total  $\Sigma T_p$  of the photon energy reflected per incident electron.

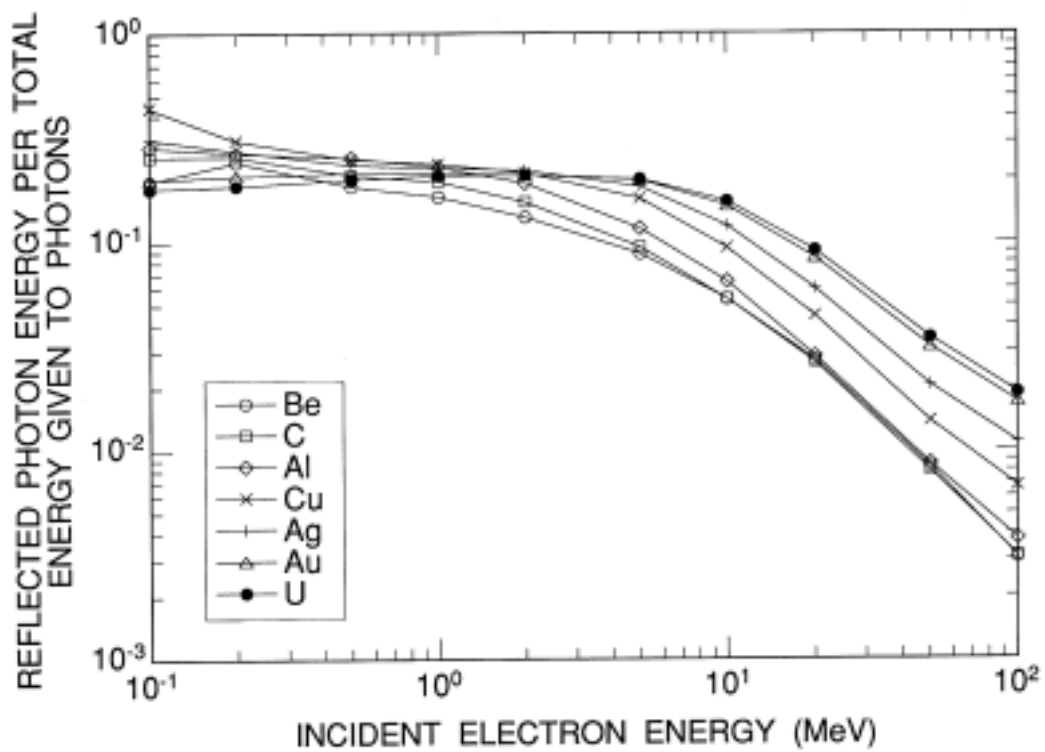


Fig. 4. The reflected photon energy  $R_p$  per sum total of the energy given to photons.

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  $\Sigma T_p$  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  $\Sigma T_p$  contrasts with the behavior of the photon energy-reflection ratio  $\eta_{pE}$ , which shows a maximum around the incident-electron energy of 10 MeV as can be seen from Table 1 and 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  $\eta_{eN}$  will be given elsewhere.

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