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Density Effect for the Ionization Loss of Charged Particles in Various Substances

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ABSTRACT

The density-effect correction $\delta(\beta)$ for the ionization energy loss of charged particles has been evaluated for a total of 278 substances including 98 cases of elements of the Periodic Table (12 gases and 86 condensed materials, including liquid hydrogen and graphite of three different densities) and including also 180 chemical compounds and substances of biological interest (13 gases and 167 liquid or solid substances). In the calculations, up-to-date values of the mean excitation potential I and of the atomic absorption edges $h\nu_i$ were employed as input data for the general equations for $\delta(\beta)$ previously derived by Sternheimer.

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*A version of this report with a shortened text but the same tables will appear in Atomic Data and Nuclear Data Tables.

1. Introduction

The density-effect correction δ for the ionization loss of charged particles [1-12] has been evaluated previously for a large number of substances.[5-12] The last previous extensive effort in this direction was made in the paper of Sternheimer, Seltzer, and Berger[12] in which the density effect was evaluated for a total of 72 substances (34 metallic elements, 26 compounds, 11 gases and liquid hydrogen). In Ref. 12, the basic equations of Sternheimer (Refs. 3 and 5) were used in order to evaluate the density effect, employing up-to-date values of the mean excitation potential[13-14] I, and of the atomic absorption edges[15] $h\nu_i$.

In the present work, the results of Ref. 12 have been extended to a total of 278 substances including 98 cases of elements of the Periodic Table (12 gases and 86 condensed materials including liquid hydrogen and graphite of three different densities) and including also 180 chemical compounds and substances of biological interest (13 gases and 167 liquid or solid compounds). The essential advance of the present calculations over those previously carried out in Refs. 5-12 consists in the development and implementation of a computer algorithm which carries out in a single operation the numerical evaluation of the density effect and the fitting of the numerical results by an approximation formula.

2. Numerical Evaluation of the Density Effect

The calculations of $\delta(\beta)$ are based on the following equations derived by Sternheimer[3,5] in 1945 and 1952:

$$\delta(\beta) = \sum_{i=1}^{n} f_i \ell n \left[(\ell_i^2 + \ell^2)/\ell_i^2\right] - \ell^2(1 - \beta^2) \quad , \qquad (1)$$

where $\beta = v/c$ is the particle velocity divided by the velocity of light, and ℓ is the solution of the equation:

$$\frac{1}{\beta^2} - 1 = \sum_{i=1}^{n} \frac{f_i}{\bar{\nu}_i^2 + \ell^2} \quad . \tag{2}$$

In Eq. (2), $\bar{\nu}_i$ is defined by:

$$\bar{\nu}_i = \nu_i \rho / \nu_p \quad , \tag{3}$$

where $h\nu_i$ is the absorption edge for the i^{th} oscillator of the dispersion model. The quantity $h\nu_p$ is the plasma energy of the electrons of the substance considered as free electrons, and is given by [16]

$$h\nu_p = 28.816 \, (\rho_0 Z/A)^{1/2} \text{ eV} \quad , \tag{4}$$

where ρ_0 is the density of the medium (in g/cm^3), Z is the atomic number and A is the atomic weight. In the case of a compound or molecular gas, Z/A is to be replaced by the ratio of the total number of electrons to the effective molecular weight or the sum of atomic weights of the constituent atoms: $\Sigma Z_i / \Sigma A_i$. As in Ref. 12, a separate dispersion oscillator is used for each subshell of the atom considered, e.g., K, L_I, L_{II}, and L_{III} for neon. The quantity ρ in Eq. (3) is the adjustment factor which was introduced by Sternheimer[5] in 1952 and which is designed to give agreement of the oscillator energies $h\nu_i \rho$ (or rather $h\nu_p \ell_i$) with the observed mean excitation potential I. Specifically, in Eq. (1), the constants ℓ_i are defined by:

$$\ell_i \equiv (\bar{\nu}_i^2 + \frac{2}{3} f_i)^{1/2} \quad \text{for} \quad \bar{\nu}_i > 0 \tag{5}$$

$$\ell_n = f_n^{1/2} \quad \text{for} \quad \bar{\nu}_n = 0 \qquad \text{(conduction electrons in a metal)}. \tag{6}$$

In Eq. (5), the factor 2/3 takes into account the Lorentz-Lorenz correction [see Ref. 5, Eqs. (48)-(52)] in the expression for the polarizability $\alpha(\nu)$; note that this factor does not enter for the case of conduction electrons for which $\ell_n = f_n^{1/2}$, as given above.

The mean excitation potential I of the medium is given by

$$\ell n\ I = \sum_i f_i\ \ell n(h\nu_p \ell_i) \quad . \tag{7}$$

By making use of Eq. (3) for $\bar{\nu}_i$, we obtain the following expression, which is used to determine the value of the Sternheimer adjustment factor ρ:

$$\ell n\ I = \sum_{i=1}^{n-1} f_i\ \ell n\left[(h\nu_i \rho)^2 + \frac{2}{3} f_i (h\nu_p)^2\right]^{1/2} + f_n\ \ell n\ (h\nu_p\ f_n^{1/2}) \quad . \tag{8}$$

For a conductor, f_n is taken as n_c/Z, where n_c is the effective number of conduction electrons per atom of the substance. Note that for a compound (insulator) or for a gas, $n_c = 0$, the sum in Eq. (8) extends from i = 1 to n, and the last term on the right-hand side of Eq. (8) is not present. The values of ρ thus determined from the experimental values of I and $h\nu_i$ lie generally in the range 1.5 - 2.5. Physically the meaning of ρ is that it takes into account the fact that for the excitations of an inner shell with absorption edge $h\nu_i$, the contribution of the excitation (ionization) to continuum states involves energies which are larger than $h\nu_i$. A very approximate estimate of ρ was made in Ref. 12 [Eq. (11)], with the result that ρ is of the order of $e^{1/2} = 1.649$.

In Eqs. (1), (2), and (5)-(8), f_i is the oscillator strength for the i^{th} oscillator, which was taken as n_i/Z for the inner (non-conduction) electrons; here n_i is the number of electrons for the subshell considered, e.g., $n_i = 4$ for the L_{III} subshell. In the case of a metal, n_c was taken to be the lowest chemical valence of the element considered.* The values of the absorption edges $h\nu_i$ for the various subshells of all elements were obtained from the compilation of Carlson.[15] The values of I were obtained from two recent papers of Berger and Seltzer.[13,14]

In Fig. 1, we have plotted the values of the Sternheimer adjustment factor ρ as a function of Z. The solid curve has been drawn through the ρ values for metals as obtained by means of Eq. (8). The ρ values for the 12 gases are shown separately as crosses. It can be seen that except for the four gases O_2, N_2, F, and Ne, the crosses lie very close to the curve determined by the ρ values for condensed substances. The most striking feature of the curve of Fig. 1 is the existence of successive maxima and minima as a function of Z. The maxima and minima reflect the existence of similar features in the curve of I/Z vs. Z, as presented in Fig. 1 of Ref. 12, but in the present case, i.e., for ρ, these fluctuations are much more pronounced. They can be related to the electronic shell structure of the atoms considered.

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*An alternative prescription would be to use as the effective number of conduction electrons the number of electrons participating in plasma excitations in metals. The latter number can be deduced from optical data and from measured electron energy-loss spectra. Effective numbers of plasma electrons have been deduced from the experimental literature by Raether[17] for 27 metals and by Isaacson[18] for 47 metals; see also Mann and Brandt,[19] and Ziegler, Biersack and Littmark.[20] We have made some numerical tests, and have found, for example, that the use of results of Raether or Isaacson would change the density-effect correction such that the electron stopping power in gold would differ by less than 0.3% and that in copper by less than 0.25%, compared to the values obtained when the number of conduction electrons is deduced from the lowest valence state.

Thus the maxima at Z = 11, Z = 30, Z = 47, and Z = 70, correspond approximately to the filling of the $2p^6$, $3d^{10}$, $4d^{10}$, and $4f^{14}$ shells, respectively. In addition, the pronounced shoulder in the neighborhood of Z = 80 can be correlated with the completion of the $5d^{10}$ shell in this region of the Periodic Table.

On the other hand, the minima of ρ at $Z \cong 20$, Z = 39, Z = 57, and Z = 89 correspond approximately to the filling of the ns^2 shell in the alkaline earths Ca (Z = 20), Sr (Z = 38), Ba (Z = 56), and Ra (Z = 88), respectively. We would like to note that these alkaline earths correspond to the closing of the successive supershells[21] of the Periodic Table, where a supershell is defined as the set of all shells $n\ell$ with the same value of the quantum number $k = n + \ell$. Thus both the curves I/Z vs. Z and ρ vs. Z give additional support to the k ordering of atomic structure.[22]

3. Fitting Formula

Using the procedures described above, numerical values of $\delta(\beta)$ were calculated for each material at many points on a logarithmically spaced energy grid. The energy variable used was T/m_0c^2, where T is the kinetic energy and m_0c^2 is the particle rest energy. The grid values were chosen to be $T_{(i)}/m_0c^2$ = 100,000, 80,000, 60,000, 50,000, 40,000, 30,000, 20,000, 15,000, 10,000, and so on, down to $T_{(i)}/m_0c^2 = 0.01$. The numerical values of δ were fitted to the formula proposed by Sternheimer[5] in 1952, namely:

$$\delta(X) = 4.6052X + a(X_1 - X)^m + C, \quad (X_0 < X < X_1) \tag{9}$$

$$\delta(X) = 4.6052X + C, \quad (X > X_1) \tag{10}$$

where $X \equiv \log_{10}(p/m_0c) = \log_{10}(\beta\gamma) = 1/2 \log_{10}[(T/m_0c^2)(T/m_0c^2 + 2)]$, with p the momentum of the incident particle and $\gamma = (1 - \beta^2)^{-1/2}$. X_0 is the value of X below which $\delta(X)$ is zero for the case of an insulator or gas, and the value of X below which $\delta(X)$ for a metal (conductor) is small, i.e., $\delta(X) \leq 0.14$. X_1 is the value of X above which $\delta(X)$ has essentially attained its asymptotic value (to within 0.015). In Eqs. (9) and (10), a and m are adjustable parameters which will be determined below, and C is given by:

$$C = -2 \ln (I/h\nu_p) - 1 \quad , \tag{11}$$

where I is the mean excitation potential of the substance for use in the Bethe-Bloch stopping-power formula.[23,24] In the present paper, we will frequently use the notation $\bar{C}$ for $-C = |C|$.

4. Determination of the Parameters in the Fitting Formula

The experience of Sternheimer[5-10] in fitting $\delta(\beta)$ indicates that X_1 of Eq. (9) can be taken as that value of X for which the deviation of $\delta(X)$ from its asymptotic value [Eq. (10)] is of the order of 0.01, and in particular does not exceed 0.015.

For each grid value $X_{(i)}$, the computer program calculates the values of δ and δ_{as}, the asymptotic value defined by Eq. (10). We define δ_1 as follows:

$$\delta_i \equiv \delta - \delta_{as} \quad . \tag{12}$$

Furthermore we define X_a as follows [see Ref. 10, Eq. (8)]:

$$X_a \equiv \bar{C}/4.6052 \quad . \tag{13}$$

Incidentally, the physical significance of the difference δ_1 is clearly shown (for the case of neon gas at normal temperature and pressure) in Fig. 1 of Ref. 10.

4.1 Non-Conductors

We first consider the case of non-conducting materials for which $\delta(\beta) = 0$ at low velocities $\beta < \beta_0$, where β_0 is the velocity for which $\ell^2 = 0$ according to Eq. (2). We then have $X_0 = \log_{10}(\beta_0\gamma_0)$, where $\gamma_0 = (1 - \beta_0{}^2)^{-1/2}$. After X_0 has been thus determined it is necessary to determine X_1 in Eqs. (9) and (10). Now the numerical values of δ_1, to be denoted by $\delta_{1,num}$ [see Eq. (12)] are approximated by the monomial expression $a(X_1 - X)^m$, as shown by Eq. (9). We will denote the fitted values of $a(X_1 - X)^m$ at the mesh points by $\delta_{1,fit}$.

Thus we have

$$\delta_{1,fit}(X) = a(X_1 - X)^m \quad . \tag{14}$$

The values of X_1, a and m must be so chosen as to minimize the maximum deviations:

$$\Delta\delta_1 \equiv \delta_{1,fit} - \delta_{1,num} \quad . \tag{15}$$

We have one condition relating a, m, X_0, and X_1, namely that $\delta(X_0) = 0$. From Eq. (9) we obtain directly:

$$4.6052X_0 + a(X_1 - X_0)^m - \bar{C} = 0 \quad , \tag{16}$$

where $\bar{C} \equiv - C$. Upon solving for a, and using Eq. (13), one finds that

$$a = \frac{4.6052(X_a - X_0)}{(X_1 - X_0)^m} \quad . \tag{17}$$

The remaining task is to determine the best values of X_1 and m. For each insulator or gas, nine separate calculations were run with X_1 determined by the condition that $\delta_1(X_1)$ [see Eq. (12)] has the values 0.0015, 0.002, 0.003, 0.004, 0.005, 0.006, 0.008, 0.010, and 0.015, respectively. This procedure directly limits the maximum inaccuracy introduced by neglecting the numerical value of $\delta_1 = \delta - \delta_{as}$ for $X \geq X_1$. The resulting errors are certainly tolerable because when the stopping number is ~ 20, an error of 0.015 in $\delta(X)$ introduces a relative error of only 0.015/20 = 0.00075 = 0.075%.

The equation for a and the above procedure for determining a reasonable range of values of X_1 leave only the exponent m undetermined. In the previous fits in Refs. 5, 7-10, and 12, it was found that it is best to require an exact fit of Eq. (9) to the numerical value of $\delta_{1,num}$ at one additional point in the range $X_0 < X < X_1$, preferably for an X value near the value of X_a defined by Eq. (13). This intermediate X value for which the additional fit was made will be denoted by X_2. Trial values of X_2 were chosen to be the ten grid points $X_{(i)}$ immediately below, and the ten grid points $X_{(i)}$ immediately above X_a defined by Eq. (13), subject to the condition that $X_0 < X_2 < X_1$.

We can now solve for m as follows. For a given value of X_2, we have:

$$a(X_1 - X_2)^m = \delta_1(X_2) \quad . \tag{18}$$

In view of the definition of $\delta_1(X_0)$ and the requirement of an exact fit at $X = X_0$, we have also:

$$a(X_1 - X_0)^m = \delta_1(X_0) \quad . \tag{19}$$

Dividing Eq. (19) by Eq. (18),

$$\frac{\delta_1(X_0)}{\delta_1(X_2)} = \left(\frac{X_1 - X_0}{X_1 - X_2}\right)^m , \tag{20}$$

and therefore:

$$m = \frac{\log_{10}[\delta_1(X_0)/\delta_1(X_2)]}{\log_{10}[(X_1-X_0)/(X_1-X_2)]} . \tag{21}$$

With m thus determined** and for the given values of X_1 and X_0, a can now be obtained from Eq. (17).

The following computer algorithm was used for selecting the parameters a and m:

1. For each trial combination X_1 and X_2, a and m were calculated according to Eqs. (17) and (21).
2. These trial values of a and m were used to evaluate $\delta_{1,fit}$ according to Eq. (9) at each grid-point $X_{(i)}$ between X_0 and X_1, and the maximum difference $\Delta_{max} = |\delta_{1,fit} - \delta_{1,num}|$ for the trial was noted.

** It should be noted that δ is a monotonically increasing function of X. This condition is satisfied only when the fitting parameter m is smaller than a maximum value m_{max} which -- for insulators and gases -- is given by[11] $m_{max} = \frac{X_1 - X_0}{X_a - X_0}$. In 26 of the 278 cases considered, the fitting procedure resulted in a value of m somewhat larger than m_{max}, with the result that (for compounds) the value of δ from Eq. (9) was slightly negative in a narrow energy region near threshold. These values of m were nevertheless accepted because the resulting error was negligible, the absolute value of δ in this region being smaller than ~ 0.02.

3. This procedure was repeated in 180 trials, i.e., using the 9 choices of X_1 and 20 choices of X_2 discussed earlier. The values of X_0, X_1, a and m finally selected were those from the trial giving the smallest value of Δ_{max}. Values of these parameters will be given in Tables I and II.

4.2 Conductors

We now proceed to a discussion of the density effect for metallic conductors. In this case, $\delta(\beta)$ does not vanish for arbitrarily small velocities, as already discussed by Sternheimer in Ref. 7. The basic reason is that for substances with conduction electrons, Eq. (2) contains a term with $\bar{\nu}_n = 0$, and this leads to the result that $\xi^2 > 0$ for any nonvanishing β^2. Therefore a suitable value of X_0 must be chosen for which $\delta(X_0)$ is small, but not zero. X_0 cannot be made too small algebraically (e.g., very negative), since this would spoil the overall fit to Eq. (9) at larger values of X. It has been our general experience in obtaining the fits published in Ref. 12 that X_0 must generally be chosen such that $\delta(X_0)$ is close to 0.1 in all cases (see Table I of Ref. 12). In view of this observation, and in order to widen the choice of parameters so as to obtain the smallest values of Δ_{max}, the computer program was run for each of the 180 aforementioned choices with an additional choice of five values of X_0, such that the calculated values of $\delta(X_0)$ were 0.06, 0.08, 0.10, 0.12, and 0.14, respectively. Thus a total of 180 x 5 = 900 possible fits were run for each metallic substance, and again that fit was chosen which gives the smallest value of Δ_{max}.

For the case of metals, the equations for a and m_{max} are slightly changed because $\delta(X_0)$ is not zero. The appropriate equations have been derived in Ref. 11 and are as follows: We define $X_{a,\delta}$ by

$$X_{a,\delta} \equiv \frac{\bar{C} + \delta(X_0)}{4.6052} \quad . \tag{22}$$

In terms of $X_{a,\delta}$ the modified equations for a and m_{max} are given by:

$$a = \frac{4.6052(X_{a,\delta} - X_0)}{(X_1 - X_0)^m} \quad , \tag{23}$$

$$m_{max} = \frac{X_1 - X_0}{X_{a,\delta} - X_0} \quad . \tag{24}$$

Obviously, for insulators [$\delta(X_0) = 0$], $X_{a,\delta}$ reduces to X_a as defined above [Eq. (13)].

For metals we have found that the density effect δ for X below X_0 can be approximated satisfactorily by the formula

$$\delta(X) = \delta(X_0) \times 10^{2(X-X_0)}, \qquad X < X_0 \quad . \tag{25}$$

The error in δ incurred by the use of Eq. (25) is always smaller than the uncertainty Δ_{max} for the fit above X_0.

Before we proceed to a detailed explanation of Tables I and II, we note that in some cases, for the 72 substances considered by us in Ref. 12, although the same values of the mean excitation potential I were used, the new values of a and m are nevertheless appreciably different. For example, for

borosilicate glass (Pyrex) we have $a_1 = 0.2988$ and $m_1 = 2.805$ in the fit of Ref. 12 (with $X_0 = 0.1479$, $X_1 = 2.5$) and we have $a_2 = 0.08270$ and $m_2 = 3.5224$ (with $X_0 = 0.1479$, $X_1 = 2.9933$) in the present fit. For gold, we found $a_1 = 0.1533$ and $m_1 = 2.881$ (with $X_0 = 0.0966$, $\delta(X_0) = 0.0912$; $X_1 = 3.5$) in Ref. 12, and $a_2 = 0.09756$ and $m_2 = 3.1101$ (with $X_0 = 0.2021$, $\delta(X_0) = 0.14$; $X_1 = 3.6979$) in the present work. Even though the parameters a and m are individually quite sensitive to the choices of X_0, X_1, X_2, $\delta_1(X_1)$ (and $\delta_0(X_0)$ in the case of metals), the variations of a and m are correlated so that the fitted values δ_{fit} are quite similar.***

We note that the compositions for the various substances, in particular for the organic compounds and the biological substances, are not listed in Table II. For those compositions, the reader is referred to the recent paper of Seltzer and Berger.[13]

5. Example of the Use of Tables I and II

The density-effect correction δ is to be used in the Bethe stopping-power formula

$$-\frac{1}{\rho_0}\frac{dE}{dX} = \frac{0.153536}{\beta^2}\frac{Z}{A}\left\{F(\beta) - 2\ln I - 2\frac{C}{Z} - \delta\right\} \quad . \tag{26}$$

In this expression, $-\frac{1}{\rho_0}\frac{dE}{dX}$ is the mean energy loss per unit pathlength, in MeV/(g cm^{-2}). The term 2 C/Z is the shell correction, which is generally negligible at energies at which the density-effect correction δ is significant. For heavy charged particles (muons, pions, protons, ...)

*** Examination of our data indicates that the correlation is such that $\frac{a_1}{a_2} = \eta^{(m_2-m_1)}$, where η has a value in the range 4 to 8.

$$F(\beta) = 2\ell n \frac{2m_0c^2\beta^2}{1 - \beta^2} , \qquad (27)$$

and for electrons

$$F(\beta) = \ell n \left|\frac{m_0c^2 T \beta^2}{2(1 - \beta^2)}\right| - (2\sqrt{1-\beta^2} - 1 + \beta^2) \ell n2 + 1 - \beta^2 + \frac{1}{8}(1 - \sqrt{1-\beta^2}). \qquad (28)$$

As an example we consider the case of aluminum. We find $X_0 = 0.1708$, $X_1 = 3.0127$, $\delta(X_0) = 0.12$, $\delta_1(X_1) = 0.0015$, $a = 0.08024$, $m = 3.6345$, $\bar{C} = 4.2395$. As a result, from Eqs. (9) and (10), $\delta(X)$ is given by:

$$\delta(X) = 0.12[10^{2(X-0.1708)}] \qquad (X < 0.1708)$$

$$\delta(X) = 4.6052X + 0.08024(3.0127-X)^{3.6345} - 4.2395 \qquad (0.1708 < X < 3.0127)$$

$$\delta(X) = 4.6052X - 4.2395 \qquad (X > 3.0127).$$

We note that $X_0 = 0.1708$ corresponds to a momentum $p/m_0c = 10^{0.1708} = 1.482$, or a kinetic energy (in units m_0c^2) $T/m_0c^2 = 0.788$.

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Definition of Parameters in Tables I and II

Z	Atomic number
Z/A	Ratio of atomic number to atomic weight
I	Mean excitation energy (in eV)
ρ_0	Density (in g/cm^3)
$h\nu_p$	Plasma energy (in units eV) [Eq. (4)]
ρ	Sternheimer adjustment factor for the atomic excitation energies [Eqs. (3) and (8)].
$-C$	[Eq. (11)].
X_0, X_1, m, a	Parameters in fitting formulas [Eqs. (9) and (10)].
δ_0	Density-effect value used as fitting parameter in Eq. (25).
Δ_{max}	Upper bound for the error inherent in fitting procedure. The absolute value of the difference between the fitted and the numerical value of δ is at all energies smaller than Δ_{max}.

The composition of the compounds and mixtures in Table II, in terms of fractions by weight of the atomic constituents, can be found in Seltzer and Berger.[13] The designation (ICRU) indicates tissue compositions adopted by the International Commission on Radiation Units and Measurements,[25] and the designation (ICRP) indicates tissue compositions adopted by the International Commission on Radiological Protection.[26]

Table I. Density-Effect Parameters for Elemental Substances

Material	Z	Z/A	I (ev)	Density, ρ_o (g/cm^3)	$h\nu_p$ (eV)	ρ	-C	X_0	X_1	a	m	δ_0	Δ_{max}
HYDROGEN	1	0.99216	19.2	8.3748E-05	0.263	1.412	9.5835	1.8639	3.2718	0.14092	5.7273	0.0	0.024
HYDROGEN, LIQUID	1	0.99216	21.8	6.0000E-02	7.031	1.546	3.2632	0.4759	1.9215	0.13483	5.6249	0.0	0.021
HELIUM	2	0.49967	41.8	1.6632E-04	0.263	1.700	11.1393	2.2017	3.6122	0.13443	5.8347	0.0	0.024
LITHIUM	3	0.43221	40.0	5.3400E-01	13.844	1.535	3.1221	0.1304	1.6397	0.95136	2.4993	0.14	0.062
BERYLLIUM	4	0.44384	63.7	1.8480E+00	26.098	1.908	2.7847	0.0592	1.6922	0.80392	2.4339	0.14	0.029
BORON	5	0.46254	76.0	2.3700E+00	30.170	2.320	2.8477	0.0305	1.9688	0.56224	2.4512	0.14	0.024
CARBON (GRAPHITE, DENS 2.265)	6	0.49954	78.0	2.2650E+00	30.652	2.290	2.8680	-0.0178	2.3415	0.26142	2.8697	0.12	0.038
CARBON (GRAPHITE, DENS 2.0)	6	0.49954	78.0	2.0000E+00	28.803	2.376	2.9925	-0.0351	2.4860	0.20240	3.0036	0.10	0.038
CARBON (GRAPHITE, DENS 1.7)	6	0.49954	78.0	1.7000E+00	26.555	2.490	3.1550	0.0480	2.5387	0.20762	2.9532	0.14	0.038
NITROGEN	7	0.49976	82.0	1.1653E-03	0.695	1.984	10.5400	1.7378	4.1323	0.15349	3.2125	0.0	0.086
OXYGEN	8	0.50002	95.0	1.3315E-03	0.744	2.314	10.7004	1.7541	4.3213	0.11778	3.2913	0.0	0.101
FLUORINE	9	0.47372	115.0	1.5803E-03	0.788	2.450	10.9653	1.8433	4.4096	0.11083	3.2962	0.0	0.121
NEON	10	0.49556	137.0	8.3851E-04	0.587	2.577	11.9041	2.0735	4.6421	0.08064	3.5771	0.0	0.110
SODIUM	11	0.47847	149.0	9.7100E-01	19.641	2.648	5.0526	0.2880	3.1962	0.07772	3.6452	0.08	0.098
MAGNESIUM	12	0.49373	156.0	1.7400E+00	26.708	2.331	4.5297	0.1499	3.0668	0.08163	3.6166	0.08	0.073
ALUMINUM	13	0.48181	166.0	2.6989E+00	32.860	2.180	4.2395	0.1708	3.0127	0.08024	3.6345	0.12	0.061
SILICON	14	0.49848	173.0	2.3300E+00	31.055	2.103	4.4351	0.2014	2.8715	0.14921	3.2546	0.14	0.059
PHOSPHORUS	15	0.48428	173.0	2.2000E+00	29.743	2.056	4.5214	0.1696	2.7815	0.23610	2.9158	0.14	0.057
SULFUR	16	0.49906	180.0	2.0000E+00	28.789	2.131	4.6659	0.1580	2.7159	0.33992	2.6456	0.14	0.059
CHLORINE	17	0.47951	174.0	2.9947E-03	1.092	1.734	11.1421	1.5555	4.2994	0.19849	2.9702	0.0	0.041
ARGON	18	0.45059	188.0	1.6620E-03	0.789	1.753	11.9480	1.7635	4.4855	0.19714	2.9618	0.0	0.037
POTASSIUM	19	0.48595	190.0	8.6200E-01	18.650	1.830	5.6423	0.3851	3.1724	0.19827	2.9233	0.10	0.035
CALCIUM	20	0.49900	191.0	1.5500E+00	25.342	1.666	5.0396	0.3228	3.1191	0.15643	3.0745	0.14	0.031
SCANDIUM	21	0.46712	216.0	2.9890E+00	34.050	1.826	4.6949	0.1640	3.0593	0.15754	3.0517	0.10	0.027
TITANIUM	22	0.45948	233.0	4.5400E+00	41.619	1.969	4.4450	0.0957	3.0386	0.15662	3.0302	0.12	0.025
VANADIUM	23	0.45150	245.0	6.1100E+00	47.861	2.070	4.2659	0.0691	3.0322	0.15436	3.0163	0.14	0.024
CHROMIUM	24	0.46157	257.0	7.1800E+00	52.458	2.181	4.1781	0.0340	3.0451	0.15419	2.9896	0.14	0.023
MANGANESE	25	0.45506	272.0	7.4400E+00	53.022	2.347	4.2702	0.0447	3.1074	0.14973	2.9796	0.14	0.021
IRON	26	0.46556	286.0	7.8740E+00	55.172	2.504	4.2911	-0.0012	3.1531	0.14680	2.9632	0.12	0.021
COBALT	27	0.45815	297.0	8.9000E+00	58.188	2.626	4.2601	-0.0187	3.1790	0.14474	2.9502	0.12	0.019
NICKEL	28	0.47708	311.0	8.9020E+00	59.385	2.889	4.3115	-0.0566	3.1851	0.16496	2.8430	0.10	0.020
COPPER	29	0.45636	322.0	8.9600E+00	58.270	2.956	4.4190	-0.0254	3.2792	0.14339	2.9044	0.08	0.019
ZINC	30	0.45886	330.0	7.1330E+00	52.132	3.142	4.6906	0.0049	3.3668	0.14714	2.8652	0.08	0.019
GALLIUM	31	0.44464	334.0	5.9040E+00	46.688	2.747	4.9353	0.2267	3.5434	0.09440	3.1314	0.14	0.019
GERMANIUM	32	0.44083	350.0	5.3230E+00	44.141	2.461	5.1411	0.3376	3.6096	0.07188	3.3306	0.14	0.025
ARSENIC	33	0.44046	347.0	5.7300E+00	45.779	2.219	5.0510	0.1767	3.5702	0.06633	3.4176	0.08	0.030
SELENIUM	34	0.43060	348.0	4.5000E+00	40.112	2.104	5.3210	0.2258	3.6264	0.06568	3.4317	0.10	0.024
BROMINE	35	0.43803	343.0	7.0722E-03	1.604	1.845	11.7307	1.5262	4.9899	0.06335	3.4670	0.0	0.022
KRYPTON	36	0.42959	352.0	3.4733E-03	1.114	1.770	12.5115	1.7158	5.0748	0.07446	3.4051	0.0	0.025
RUBIDIUM	37	0.43291	363.0	1.5320E+00	23.467	1.823	6.4776	0.5737	3.7995	0.07261	3.4177	0.14	0.026
STRONTIUM	38	0.43369	366.0	2.5400E+00	30.244	1.707	5.9867	0.4585	3.6778	0.07165	3.4435	0.14	0.026
YTTRIUM	39	0.43867	379.0	4.4690E+00	40.346	1.649	5.4801	0.3608	3.5542	0.07138	3.4585	0.14	0.027
ZIRCONIUM	40	0.43850	393.0	6.5060E+00	48.671	1.638	5.1774	0.2957	3.4890	0.07177	3.4533	0.14	0.028
NIOBIUM	41	0.44130	417.0	8.5700E+00	56.039	1.734	5.0141	0.1785	3.2201	0.13883	3.0930	0.14	0.036
MOLYBDENUM	42	0.43777	424.0	1.0220E+01	60.951	1.658	4.8793	0.2267	3.2784	0.10525	3.2549	0.14	0.030
TECHNETIUM	43	0.43919	428.0	1.1500E+01	64.760	1.727	4.7769	0.0949	3.1253	0.16572	2.9738	0.14	0.040
RUTHENIUM	44	0.43534	441.0	1.2410E+01	66.978	1.780	4.7694	0.0599	3.0834	0.19342	2.8707	0.14	0.046
RHODIUM	45	0.43729	449.0	1.2410E+01	67.128	1.804	4.8008	0.0576	3.1069	0.19205	2.8633	0.14	0.046
PALLADIUM	46	0.43225	470.0	1.2020E+01	65.683	1.911	4.9358	0.0563	3.0555	0.24178	2.7239	0.14	0.047

Table I. (Continued)

Material	Z	Z/A	I (ev)	Density, ρ_0 (g/cm^3)	$\hbar\nu_p$ (eV)	ρ	-C	X_0	X_1	a	m	δ_0	Δ_{max}
SILVER	47	0.43572	470.0	1.0500E+01	61.635	1.933	5.0630	0.0657	3.1074	0.24585	2.6899	0.14	0.052
CADMIUM	48	0.42701	469.0	8.6500E+00	55.381	1.895	5.2727	0.1281	3.1667	0.24609	2.6772	0.14	0.051
INDIUM	49	0.42676	488.0	7.3100E+00	50.896	1.851	5.5211	0.2406	3.2032	0.23879	2.7144	0.14	0.044
TIN	50	0.42127	488.0	7.3100E+00	50.567	1.732	5.5340	0.2879	3.2959	0.18689	2.8576	0.14	0.037
ANTIMONY	51	0.41889	487.0	6.6910E+00	48.242	1.645	5.6241	0.3189	3.3489	0.16652	2.9319	0.14	0.034
TELLURIUM	52	0.40752	485.0	6.2400E+00	45.952	1.577	5.7131	0.3296	3.4418	0.13815	3.0354	0.14	0.033
IODINE	53	0.41764	491.0	4.9300E+00	41.348	1.498	5.9488	0.0549	3.2596	0.23766	2.7276	0.0	0.045
XENON	54	0.41130	482.0	5.4854E-03	1.369	1.435	12.7281	1.5630	4.7371	0.23314	2.7414	0.0	0.043
CESIUM	55	0.41383	488.0	1.8730E+00	25.370	1.462	6.9135	0.5473	3.5914	0.18233	2.8866	0.14	0.035
BARIUM	56	0.40778	491.0	3.5000E+00	34.425	1.410	6.3153	0.4190	3.4547	0.18268	2.8906	0.14	0.035
LANTHANUM	57	0.41035	501.0	6.1540E+00	45.792	1.392	5.7850	0.3161	3.3293	0.18591	2.8828	0.14	0.036
CERIUM	58	0.41393	523.0	6.6570E+00	47.834	1.461	5.7837	0.2713	3.3432	0.18885	2.8592	0.14	0.040
PRASEODYMIUM	59	0.41871	535.0	6.7100E+00	48.301	1.520	5.8096	0.2333	3.2773	0.23265	2.7331	0.14	0.041
NEODYMIUM	60	0.41597	546.0	6.9000E+00	48.819	1.588	5.8290	0.1984	3.3063	0.23530	2.7050	0.14	0.044
PROMETHIUM	61	0.42094	560.0	7.2200E+00	50.236	1.672	5.8224	0.1627	3.3199	0.24280	2.6674	0.14	0.048
SAMARIUM	62	0.41234	574.0	7.4600E+00	50.540	1.749	5.8597	0.1520	3.3460	0.24698	2.6403	0.14	0.053
EUROPIUM	63	0.41458	580.0	5.2430E+00	42.484	1.838	6.2278	0.1888	3.4633	0.24448	2.6245	0.14	0.060
GADOLINIUM	64	0.40699	591.0	7.9004E+00	51.672	1.882	5.8738	0.1058	3.3932	0.25109	2.5977	0.14	0.061
TERBIUM	65	0.40900	614.0	8.2290E+00	52.865	1.993	5.9045	0.0947	3.4224	0.24453	2.6056	0.14	0.063
DYSPROSIUM	66	0.40615	628.0	8.5500E+00	53.698	2.081	5.9183	0.0822	3.4474	0.24665	2.5849	0.14	0.061
HOLMIUM	67	0.40623	650.0	8.7950E+00	54.467	2.197	5.9587	0.0761	3.4782	0.24638	2.5726	0.14	0.062
ERBIUM	68	0.40655	658.0	9.0660E+00	55.322	2.260	5.9521	0.0648	3.4922	0.24823	2.5573	0.14	0.061
THULIUM	69	0.40844	674.0	9.3210E+00	56.225	2.333	5.9677	0.0812	3.5085	0.24889	2.5469	0.14	0.062
YTTERBIUM	70	0.40453	684.0	6.7300E+00	47.546	2.505	6.3325	0.1199	3.6246	0.25295	2.5141	0.14	0.071
LUTETIUM	71	0.40579	694.0	9.8400E+00	57.581	2.348	5.9785	0.1560	3.5218	0.24033	2.5643	0.14	0.054
HAFNIUM	72	0.40338	705.0	1.3310E+01	66.770	2.174	5.7139	0.1965	3.4337	0.22918	2.6155	0.14	0.035
TANTALUM	73	0.40343	718.0	1.6654E+01	74.692	2.070	5.5262	0.2117	3.4805	0.17798	2.7623	0.14	0.030
TUNGSTEN	74	0.40250	727.0	1.9300E+01	80.315	1.997	5.4059	0.2167	3.4960	0.15509	2.8447	0.14	0.027
RHENIUM	75	0.40278	736.0	2.1020E+01	83.846	1.976	5.3445	0.0559	3.4845	0.15184	2.8627	0.08	0.026
OSMIUM	76	0.39958	746.0	2.2570E+01	86.537	1.947	5.3083	0.0891	3.5414	0.12751	2.9608	0.10	0.023
IRIDIUM	77	0.40058	757.0	2.2420E+01	86.357	1.927	5.3418	0.0819	3.5480	0.12690	2.9658	0.10	0.023
PLATINUM	78	0.39984	790.0	2.1450E+01	84.389	1.965	5.4732	0.1484	3.6212	0.11128	3.0417	0.12	0.021
GOLD	79	0.40108	790.0	1.9320E+01	80.215	1.926	5.5747	0.2021	3.6979	0.09756	3.1101	0.14	0.020
MERCURY	80	0.39882	800.0	1.3546E+01	66.977	1.904	5.9605	0.2756	3.7275	0.11014	3.0519	0.14	0.021
THALLIUM	81	0.39631	810.0	1.1720E+01	62.104	1.814	6.1365	0.3491	3.8044	0.09455	3.1450	0.14	0.019
LEAD	82	0.39575	823.0	1.1350E+01	61.072	1.755	6.2018	0.3776	3.8073	0.09359	3.1608	0.14	0.019
BISMUTH	83	0.39717	823.0	9.7470E+00	56.696	1.684	6.3505	0.4152	3.8248	0.09410	3.1671	0.14	0.020
POLONIUM	84	0.40195	830.0	9.3200E+00	55.773	1.637	6.4003	0.4267	3.8293	0.09282	3.1830	0.14	0.020
RADON	86	0.38736	794.0	9.0662E-03	1.708	1.458	13.2839	1.5368	4.9889	0.20798	2.7409	0.0	0.057
RADIUM	88	0.38934	826.0	5.0000E+00	40.205	1.403	7.0452	0.5991	3.9428	0.08804	3.2454	0.14	0.022
ACTINIUM	89	0.39202	841.0	1.0070E+01	57.254	1.380	6.3742	0.4559	3.7966	0.08567	3.2683	0.14	0.023
THORIUM	90	0.38787	847.0	1.1720E+01	61.438	1.363	6.2473	0.4202	3.7681	0.08655	3.2610	0.14	0.025
PROTACTINIUM	91	0.39388	878.0	1.5370E+01	70.901	1.420	6.0327	0.3144	3.5079	0.14770	2.9845	0.14	0.036
URANIUM	92	0.38651	890.0	1.8950E+01	77.986	1.447	5.8694	0.2260	3.3721	0.19677	2.8171	0.14	0.043
NEPTUNIUM	93	0.39232	902.0	2.0250E+01	81.221	1.468	5.8149	0.1869	3.3690	0.19741	2.8082	0.14	0.043
PLUTONIUM	94	0.39322	921.0	1.9840E+01	80.486	1.519	5.8748	0.1557	3.3981	0.20419	2.7679	0.14	0.057
AMERICIUM	95	0.39085	934.0	1.3670E+01	66.607	1.552	6.2813	0.2274	3.5021	0.20308	2.7615	0.14	0.056
CURIUM	96	0.38855	939.0	1.3510E+01	66.022	1.559	6.3097	0.2484	3.5160	0.20257	2.7579	0.14	0.056
BERKELIUM	97	0.39260	952.0	1.4000E+01	67.557	1.574	6.2912	0.2378	3.5186	0.20192	2.7560	0.14	0.062

Table II. Density-Effect Parameters for Compounds and Mixtures

Material	Z/A	I (ev)	Density, ρ_0 (g/cm^3)	$h\nu_p$ (eV)	ρ	-C	X_0	X_1	a	m	Δ_{max}
A-150 TISSUE-EQUIVALENT PLASTIC	0.54903	65.1	1.1270E+00	22.667	1.950	3.1100	0.1329	2.6234	0.10783	3.4442	0.048
ACETONE	0.55097	64.2	7.8990E-01	19.010	1.976	3.4341	0.2197	2.6928	0.11100	3.4047	0.069
ACETYLENE	0.53768	58.2	1.0967E-03	0.700	1.734	9.8419	1.6017	4.0074	0.12167	3.4277	0.080
ADENINE	0.51803	71.4	1.3500E+00	24.098	1.892	3.1724	0.1295	2.4219	0.20908	3.0271	0.052
ADIPOSE TISSUE (ICRP)	0.55847	63.2	9.2000E-01	20.655	1.987	3.2367	0.1827	2.6530	0.10278	3.4817	0.060
AIR, DRY (NEAR SEA LEVEL)	0.49919	85.7	1.2048E-03	0.707	2.054	10.5961	1.7418	4.2759	0.10914	3.3994	0.090
ALANINE	0.53876	71.9	1.4200E+00	25.204	2.074	3.0965	0.1354	2.6336	0.11484	3.3526	0.056
ALUMINUM OXIDE	0.49038	145.2	3.9700E+00	40.206	2.394	3.5682	0.0402	2.8665	0.08500	3.5458	0.031
AMBER	0.55178	63.2	1.1000E+00	22.450	1.946	3.0701	0.1335	2.5610	0.11934	3.4098	0.053
AMMONIA	0.58719	53.7	8.2602E-04	0.635	1.814	9.8763	1.6822	4.1158	0.08315	3.6464	0.102
ANILINE	0.53689	66.2	1.0235E+00	21.361	1.938	3.2622	0.1618	2.5805	0.13134	3.3434	0.052
ANTHRACENE	0.52740	69.5	1.2830E+00	23.704	1.954	3.1514	0.1146	2.5213	0.14677	3.2831	0.042
B-100 BONE-EQUIVALENT PLASTIC	0.52740	85.9	1.4500E+00	25.199	2.013	3.4528	0.1252	3.0420	0.05268	3.7365	0.043
BAKELITE	0.52792	72.4	1.2500E+00	23.408	2.046	3.2582	0.1471	2.6055	0.12713	3.3470	0.052
BARIUM FLUORIDE	0.42207	375.9	4.8900E+00	41.398	1.727	5.4122	-0.0098	3.3871	0.15991	2.8867	0.034
BARIUM SULFATE	0.44561	285.7	4.5000E+00	40.805	1.893	4.8923	-0.0128	3.4069	0.11747	3.0427	0.030
BENZENE	0.53768	63.4	8.7865E-01	19.806	1.873	3.3269	0.1710	2.5091	0.16519	3.2174	0.052
BERYLLIUM OXIDE	0.47978	93.2	3.0100E+00	34.629	2.296	2.9801	0.0241	2.5846	0.10755	3.4927	0.031
BISMUTH GERMANIUM OXIDE	0.42065	534.1	7.1300E+00	49.904	2.121	5.7409	0.0456	3.7816	0.09569	3.0781	0.023
BLOOD (ICRP)	0.54995	75.2	1.0600E+00	22.001	2.184	3.4581	0.2239	2.8017	0.08492	3.5406	0.088
BONE, COMPACT (ICRU)	0.53010	91.9	1.8500E+00	28.536	2.091	3.3390	0.0944	3.0201	0.05822	3.6419	0.042
BONE, CORTICAL (ICRP)	0.52130	106.4	1.8500E+00	28.298	2.118	3.6488	0.1161	3.0919	0.06198	3.5919	0.040
BORON CARBIDE	0.47058	84.7	2.5200E+00	31.380	2.140	2.9859	0.0093	2.1006	0.37087	2.8076	0.022
BORON OXIDE	0.48838	99.6	1.8120E+00	27.107	2.446	3.6027	0.1843	2.7379	0.11548	3.3832	0.053
BRAIN (ICRP)	0.55423	73.3	1.0300E+00	21.772	2.162	3.4279	0.2206	2.8021	0.08255	3.5585	0.086
BUTANE	0.58497	48.3	2.4934E-03	1.101	1.727	8.5633	1.3788	3.7524	0.10852	3.4884	0.100
N-BUTYL ALCOHOL	0.56663	59.9	8.0980E-01	19.520	1.942	3.2425	0.1937	2.6439	0.10081	3.5139	0.065
C-552 AIR-EQUIVALENT PLASTIC	0.49969	86.8	1.7600E+00	27.023	2.128	3.3338	0.1510	2.7083	0.10492	3.4344	0.053
CADMIUM TELLURIDE	0.41665	539.3	6.2000E+00	46.314	1.935	5.9096	0.0438	3.2836	0.24840	2.6665	0.057
CADMIUM TUNGSTATE	0.42747	468.3	7.9000E+00	52.954	2.289	5.3594	0.0123	3.5941	0.12861	2.9150	0.027
CALCIUM CARBONATE	0.49955	136.4	2.8000E+00	34.080	2.141	3.7738	0.0492	3.0549	0.08301	3.4120	0.037
CALCIUM FLUORIDE	0.48670	166.0	3.1800E+00	35.849	2.127	4.0653	0.0676	3.1683	0.06942	3.5263	0.044
CALCIUM OXIDE	0.49929	176.1	3.3000E+00	36.988	1.973	4.1209	-0.0172	3.0171	0.12128	3.1936	0.024
CALCIUM SULFATE	0.49950	152.3	2.9600E+00	35.038	2.179	3.9388	0.0587	3.1229	0.07708	3.4495	0.021
CALCIUM TUNGSTATE	0.43761	395.0	6.0620E+00	46.934	2.262	5.2603	0.0323	3.8932	0.06210	3.2649	0.021
CARBON DIOXIDE	0.49989	85.0	1.8421E-03	0.874	2.118	10.1537	1.6294	4.1825	0.11768	3.3227	0.091
CARBON TETRACHLORIDE	0.48107	166.3	1.5940E+00	25.234	1.742	4.7712	0.1773	2.9165	0.19018	3.0116	0.041
CELLULOSE ACETATE, CELLOPHANE	0.53040	77.6	1.4200E+00	25.008	2.170	3.2647	0.1580	2.6778	0.11151	3.3810	0.060
CELLULOSE ACETATE BUTYRATE	0.53279	74.6	1.2000E+00	23.041	2.128	3.3497	0.1794	2.6809	0.11444	3.3738	0.056
CELLULOSE NITRATE	0.51424	87.0	1.4900E+00	25.224	2.252	3.4762	0.1897	2.7253	0.11813	3.3237	0.063
CERIC SULFATE DOSIMETER SOLUTION	0.55278	76.7	1.0300E+00	21.743	2.205	3.5212	0.2363	2.8769	0.07666	3.5607	0.095
CESIUM FLUORIDE	0.42132	440.7	4.1150E+00	37.942	1.714	5.9046	0.0084	3.3374	0.22052	2.7280	0.044
CESIUM IODIDE	0.41569	553.1	4.5100E+00	39.455	1.672	6.2807	0.0395	3.3353	0.25381	2.6657	0.067
CHLOROBENZENE	0.51529	89.1	1.1058E+00	21.752	1.889	3.8201	0.1714	2.9272	0.09856	3.3797	0.031
CHLOROFORM	0.48585	156.0	1.4832E+00	24.462	1.734	4.7055	0.1786	2.9581	0.16959	3.0627	0.038

Table II. (Continued)

Material	Z/A	I (ev)	Density, ρ_0 (g/cm^3)	$h\nu_p$ (eV)	ρ	-C	X_0	X_1	a	m	Δ_{max}
CONCRETE, PORTLAND	0.50274	135.2	2.3000E+00	30.986	2.322	3.9464	0.1301	3.0466	0.07515	3.5467	0.024
CYCLOHEXANE	0.57034	56.4	7.7900E-01	19.207	1.861	3.1544	0.1728	2.5549	0.12035	3.4278	0.057
1,2-DICHLOROBENZENE	0.50339	106.5	1.3048E+00	23.354	1.862	4.0348	0.1587	2.8276	0.16010	3.0836	0.029
DICHLORODIETHYL ETHER	0.51744	103.3	1.2199E+00	22.894	1.903	4.0135	0.1773	3.1586	0.06799	3.5250	0.026
1,2-DICHLOROETHANE	0.50526	111.9	1.2351E+00	22.764	1.618	4.1849	0.1375	2.9529	0.13383	3.1675	0.030
DIETHYL ETHER	0.56663	60.0	7.1378E-01	18.326	1.951	3.3721	0.2231	2.6745	0.10550	3.4586	0.070
N,N-DIMETHYL FORMAMIDE	0.54724	66.6	9.4870E-01	20.763	2.005	3.3311	0.1977	2.6686	0.11470	3.3710	0.065
DIMETHYL SULFOXIDE	0.53757	98.6	1.1014E+00	22.173	2.075	3.9844	0.2021	3.1263	0.06619	3.5708	0.030
ETHANE	0.59861	45.4	1.2532E-03	0.789	1.690	9.1043	1.5107	3.8743	0.09627	3.6095	0.097
ETHYL ALCOHOL	0.56437	62.9	7.8930E-01	19.232	2.013	3.3699	0.2218	2.7052	0.09878	3.4834	0.071
ETHYL CELLULOSE	0.54405	69.3	1.1300E+00	22.594	2.065	3.2415	0.1683	2.6527	0.11077	3.4098	0.057
ETHYLENE	0.57034	50.7	1.1750E-03	0.746	1.733	9.4380	1.5528	3.9327	0.10636	3.5387	0.085
EYE LENS (ICRP)	0.54877	73.3	1.1000E+00	22.388	2.154	3.3720	0.2070	2.7446	0.09690	3.4550	0.077
FERRIC OXIDE	0.47592	227.3	5.2000E+00	45.331	2.747	4.2245	-0.0074	3.2573	0.10478	3.1313	0.026
FERROBORIDE	0.46507	261.0	7.1500E+00	52.546	2.726	4.2057	-0.0988	3.1749	0.12911	3.0240	0.022
FERROUS OXIDE	0.47323	248.6	5.7000E+00	47.327	2.769	4.3175	-0.0279	3.2002	0.12959	3.0168	0.022
FERROUS SULFATE DOSIMETER SOLN.	0.55328	76.4	1.0240E+00	21.690	2.208	3.5183	0.2378	2.8254	0.08759	3.4923	0.096
FREON-12	0.47968	143.0	1.1200E+00	21.121	1.974	4.8251	0.3035	3.2659	0.07978	3.4626	0.025
FREON-12B2	0.44801	284.9	1.8000E+00	25.877	2.195	5.7976	0.3406	3.7956	0.05144	3.5565	0.021
FREON-13	0.47866	126.6	9.5000E-01	19.432	2.116	4.7483	0.3659	3.2337	0.07238	3.5551	0.050
FREON-13B1	0.45665	210.5	1.5000E+00	23.849	2.233	5.3555	0.3522	3.7554	0.03925	3.7194	0.036
FREON-13I1	0.43897	293.5	1.8000E+00	25.615	1.924	5.8774	0.2847	3.7280	0.09112	3.1658	0.025
GADOLINIUM OXYSULFIDE	0.42266	493.3	7.4400E+00	51.099	2.179	5.5347	-0.1774	3.4045	0.22161	2.6300	0.056
GALLIUM ARSENIDE	0.44247	384.9	5.3100E+00	44.170	2.652	5.3299	0.1764	3.6420	0.07152	3.3356	0.027
GEL IN PHOTOGRAPHIC EMULSION	0.53973	74.8	1.2914E+00	24.058	2.156	3.2687	0.1709	2.7058	0.10102	3.4418	0.060
GLASS, BOROSILICATE (PYREX)	0.49707	134.0	2.2300E+00	30.339	2.369	3.9708	0.1479	2.9933	0.08270	3.5224	0.022
GLASS, LEAD	0.42101	526.4	6.2200E+00	46.631	2.085	5.8476	0.0614	3.8146	0.09544	3.0740	0.025
GLASS, PLATE	0.49731	145.4	2.4000E+00	31.481	2.329	4.0602	0.1237	3.0649	0.07678	3.5381	0.025
GLUCOSE	0.53489	77.2	1.5400E+00	26.153	2.174	3.1649	0.1411	2.6700	0.10783	3.3946	0.061
GLUTAMINE	0.53371	73.3	1.4600E+00	25.437	2.077	3.1167	0.1347	2.6301	0.11931	3.3254	0.055
GLYCEROL	0.54292	72.6	1.2613E+00	23.846	2.120	3.2267	0.1653	2.6862	0.10168	3.4481	0.067
GUANINE	0.51612	75.0	1.5800E+00	26.022	1.970	3.1171	0.1163	2.4296	0.20530	3.0186	0.049
GYPSUM, PLASTER OF PARIS	0.51113	129.7	2.3200E+00	31.379	2.187	3.8382	0.0995	3.1206	0.06949	3.5134	0.038
N-HEPTANE	0.57882	54.4	6.8376E-01	18.128	1.848	3.1978	0.1928	2.5706	0.11255	3.4885	0.059
N-HEXANE	0.58020	54.0	6.6030E-01	17.836	1.843	3.2156	0.1984	2.5757	0.11085	3.5027	0.061
"KAPTON" POLYIMIDE FILM	0.51264	79.6	1.4200E+00	24.586	2.109	3.3497	0.1509	2.5631	0.15972	3.1921	0.050
LANTHANUM OXYBROMIDE	0.42588	439.7	6.2800E+00	47.125	1.831	5.4666	-0.0350	3.3288	0.17830	2.8457	0.040
LANTHANUM OXYSULFIDE	0.42348	456.2	5.8600E+00	45.394	1.681	5.6151	-0.0934	3.2741	0.22579	2.7075	0.065
LEAD OXIDE	0.40323	766.7	9.5300E+00	56.488	2.012	6.2162	0.0356	3.5456	0.19645	2.7299	0.039
LITHIUM AMIDE	0.52257	55.5	1.1780E+00	22.609	1.740	2.7961	0.0198	2.5152	0.08740	3.7534	0.050
LITHIUM CARBONATE	0.48720	87.9	2.1100E+00	29.217	2.246	3.2029	0.0551	2.6598	0.09936	3.5417	0.062
LITHIUM FLUORIDE	0.46262	94.0	2.6350E+00	31.815	2.197	3.1667	0.0171	2.7049	0.07593	3.7478	0.084
LITHIUM HYDRIDE	0.50321	36.5	8.2000E-01	18.510	1.482	2.3580	-0.0988	1.4515	0.90567	2.5849	0.035
LITHIUM IODIDE	0.41839	485.1	3.4940E+00	34.841	1.706	6.2671	0.0892	3.3702	0.23274	2.7146	0.043
LITHIUM OXIDE	0.46852	73.6	2.0130E+00	27.984	2.039	2.9340	-0.0511	2.5874	0.08035	3.7878	0.043

Table II. (Continued)

Material	Z/A	I (ev)	Density, ρ_o (g/cm^3)	$h\nu_p$ (eV)	ρ	-C	X_0	X_1	a	m	Δ_{max}
LITHIUM TETRABORATE	0.48487	94.6	2.4400E+00	31.343	2.360	3.2093	0.0737	2.6502	0.11075	3.4389	0.048
LUNG (ICRP)	0.54965	75.3	1.0500E+00	21.891	2.184	3.4708	0.2261	2.8001	0.08588	3.5353	0.089
M3 WAX	0.55512	67.9	1.0500E+00	22.000	1.975	3.2540	0.1523	2.7529	0.07864	3.6412	0.044
MAGNESIUM CARBONATE	0.49814	118.0	2.9580E+00	34.979	2.388	3.4319	0.0860	2.7997	0.09219	3.5003	0.045
MAGNESIUM FLUORIDE	0.48153	134.3	3.0000E+00	34.634	2.330	3.7105	0.1369	2.8630	0.07934	3.6485	0.085
MAGNESIUM OXIDE	0.49622	143.8	3.5800E+00	38.407	2.412	3.6404	0.0575	2.8580	0.08313	3.5968	0.055
MAGNESIUM TETRABORATE	0.49014	108.3	2.5300E+00	32.089	2.430	3.4328	0.1147	2.7635	0.09703	3.4893	0.044
MERCURIC IODIDE	0.40933	684.5	6.3600E+00	46.494	1.892	6.3787	0.1040	3.4728	0.21513	2.7264	0.047
METHANE	0.62334	41.7	6.6715E-04	0.588	1.662	9.5243	1.6263	3.9716	0.09253	3.6257	0.112
METHANOL	0.56176	67.6	7.9140E-01	19.214	2.125	3.5160	0.2529	2.7639	0.08970	3.5477	0.080
MIX D WAX	0.56479	60.9	9.9000E-01	21.547	1.905	3.0780	0.1371	2.7145	0.07490	3.6823	0.047
MS20 TISSUE SUBSTITUTE	0.53886	75.1	1.0000E+00	21.153	2.070	3.5341	0.1997	2.8033	0.08294	3.6061	0.053
MUSCLE, SKELETAL (ICRP)	0.54938	75.3	1.0400E+00	21.781	2.185	3.4809	0.2282	2.7999	0.08636	3.5330	0.089
MUSCLE, STRIATED (ICRU)	0.55005	74.7	1.0400E+00	21.795	2.174	3.4636	0.2249	2.8032	0.08507	3.5383	0.086
MUSCLE-EQUIV. LIQ., WITH SUCROSE	0.54828	74.3	1.1100E+00	22.480	2.169	3.3910	0.2098	2.7550	0.09481	3.4699	0.080
MUSCLE-EQUIV. LIQ., W/O SUCROSE	0.55014	74.2	1.0700E+00	22.109	2.173	3.4216	0.2187	2.7680	0.09143	3.4982	0.086
NAPTHALENE	0.53053	68.4	1.1450E+00	22.459	1.956	3.2274	0.1374	2.5429	0.14766	3.2654	0.051
NITROBENZENE	0.51986	75.8	1.1987E+00	22.747	2.065	3.4073	0.1777	2.6630	0.12727	3.3091	0.051
NITROUS OXIDE	0.49985	84.9	1.8309E-03	0.872	2.059	10.1575	1.6477	4.1565	0.11992	3.3318	0.086
NYLON, DU PONT ELVAMIDE 8062	0.55063	64.3	1.0800E+00	22.221	1.967	3.1250	0.1503	2.6004	0.11513	3.4044	0.054
NYLON, TYPE 6 AND TYPE 6/6	0.54790	63.9	1.1400E+00	22.774	1.931	3.0634	0.1336	2.5834	0.11818	3.3826	0.051
NYLON, TYPE 6/10	0.55236	63.2	1.1400E+00	22.866	1.942	3.0333	0.1304	2.5681	0.11852	3.3912	0.050
NYLON, TYPE 11 ("RILSAN")	0.55649	61.6	1.4250E+00	25.661	1.902	2.7514	0.0678	2.4281	0.14868	3.2576	0.044
OCTANE, LIQUID	0.57778	54.7	7.0260E-01	18.360	1.851	3.1834	0.1882	2.5664	0.11387	3.4776	0.057
PARAFFIN WAX	0.57275	55.9	9.3000E-01	21.031	1.844	2.9551	0.1289	2.5084	0.12087	3.4288	0.052
N-PENTANE	0.58212	53.6	6.2620E-01	17.398	1.842	3.2504	0.2086	2.5855	0.10809	3.5265	0.064
PHOTOGRAPHIC EMULSION	0.45453	331.0	3.8150E+00	37.946	2.264	5.3319	0.1009	3.4866	0.12399	3.0094	0.028
PLASTIC SCINT. (VINYLTOLUENE)	0.54141	64.7	1.0320E+00	21.540	1.929	3.1997	0.1464	2.4855	0.16101	3.2393	0.050
PLUTONIUM DIOXIDE	0.40583	746.5	1.1460E+01	62.143	1.846	5.9719	-0.2311	3.5554	0.20594	2.6522	0.111
POLYACRYLONITRILE	0.52767	69.6	1.1700E+00	22.642	1.955	3.2459	0.1504	2.5159	0.16275	3.1975	0.050
POLYCARBONATE (MAKROLON, LEXAN)	0.52697	73.1	1.2000E+00	22.915	2.060	3.3201	0.1606	2.6225	0.12860	3.3288	0.049
POLYCHLOROSTYRENE	0.52518	81.7	1.3000E+00	23.810	1.902	3.4659	0.1238	2.9241	0.07530	3.5441	0.029
POLYETHYLENE	0.57034	57.4	9.4000E-01	21.099	1.882	3.0016	0.1370	2.5177	0.12108	3.4292	0.051
POLYETHYLENE TEREPHTHALATE,MYLAR	0.52037	78.7	1.4000E+00	24.595	2.144	3.3262	0.1562	2.6507	0.12679	3.3076	0.052
POLYMETHYL METHACRYLATE (LUCITE)	0.53937	74.0	1.1900E+00	23.086	2.173	3.3297	0.1824	2.6681	0.11433	3.3836	0.056
POLYOXYMETHYLENE	0.53287	77.4	1.4250E+00	25.110	2.175	3.2514	0.1584	2.6838	0.10808	3.4002	0.063
POLYPROPYLENE	0.55998	59.2	9.0000E-01	20.457	1.884	3.1252	0.1534	2.4822	0.15045	3.2855	0.055
POLYSTYRENE	0.53768	68.7	1.0600E+00	21.754	2.027	3.2999	0.1647	2.5031	0.16454	3.2224	0.051
POLYTETRAFLUOROETHYLENE (TEFLON)	0.47992	99.1	2.2000E+00	29.609	2.142	3.4161	0.1648	2.7404	0.10606	3.4046	0.073
POLYTRIFLUOROCHLOROETHYLENE	0.48081	120.7	2.1000E+00	28.955	2.094	3.8551	0.1714	3.0265	0.07727	3.5085	0.035
POLYVINYL ACETATE	0.53432	73.7	1.1900E+00	22.978	2.116	3.3309	0.1769	2.6747	0.11442	3.3762	0.055
POLYVINYL ALCOHOL	0.54480	69.7	1.3000E+00	24.251	2.071	3.1115	0.1401	2.6315	0.11178	3.3893	0.056
POLYVINYL BUTYRAL	0.54537	67.2	1.1200E+00	22.521	2.021	3.1865	0.1555	2.6186	0.11544	3.3983	0.054
POLYVINYL CHLORIDE	0.51201	108.2	1.3000E+00	23.510	1.840	4.0532	0.1559	2.9415	0.12438	3.2104	0.027
POLYVINYLIDENE CHLORIDE, SARAN	0.49513	134.3	1.7000E+00	26.437	1.814	4.2506	0.1314	2.9009	0.15466	3.1020	0.034

Table II. (Continued)

Material	Z/A	I (ev)	Density, ρ_0 (g/cm^3)	$h\nu_p$ (eV)	ρ	-C	X_0	X_1	a	m	Δ_{max}
POLYVINYLIDENE FLUORIDE	0.49973	88.8	1.7600E+00	27.024	2.160	3.3793	0.1717	2.7375	0.10316	3.4200	0.067
POLYVINYL PYRROLIDONE	0.53984	67.7	1.2500E+00	23.671	1.989	3.1017	0.1324	2.5867	0.12504	3.3326	0.051
POTASSIUM IODIDE	0.43373	431.9	3.1300E+00	33.575	1.784	6.1088	0.1044	3.3442	0.22053	2.7558	0.042
POTASSIUM OXIDE	0.48834	189.9	2.3200E+00	30.672	2.065	4.6463	0.0480	3.0110	0.16789	3.0121	0.027
PROPANE	0.58962	47.1	1.8794E-03	0.959	1.708	8.7878	1.4326	3.7998	0.09916	3.5920	0.093
PROPANE, LIQUID	0.58962	52.0	4.3000E-01	14.509	1.844	3.5529	0.2861	2.6568	0.10329	3.5620	0.068
N-PROPYL ALCOHOL	0.56577	61.1	8.0350E-01	19.429	1.972	3.2915	0.2046	2.6681	0.09644	3.5415	0.070
PYRIDINE	0.53096	66.2	9.8190E-01	20.807	1.895	3.3148	0.1670	2.5245	0.16399	3.1977	0.051
RUBBER, BUTYL	0.57034	56.5	9.2000E-01	20.873	1.852	2.9915	0.1347	2.5154	0.12108	3.4296	0.051
RUBBER, NATURAL	0.55785	59.8	9.2000E-01	20.644	1.889	3.1272	0.1512	2.4815	0.15058	3.2879	0.053
RUBBER, NEOPRENE	0.51956	93.0	1.2300E+00	23.036	1.874	3.7911	0.1501	2.9461	0.09763	3.3632	0.026
SILICON DIOXIDE	0.49930	139.2	2.3200E+00	31.014	2.335	4.0029	0.1385	3.0025	0.08408	3.5064	0.018
SILVER BROMIDE	0.43670	486.6	6.4730E+00	48.448	2.271	5.6139	0.0352	3.2109	0.24582	2.6820	0.043
SILVER CHLORIDE	0.44655	398.4	5.5600E+00	45.405	2.096	5.3437	-0.0139	3.2022	0.22968	2.7041	0.062
SILVER HALIDES IN PHOTO EMULSION	0.43663	487.1	6.4700E+00	48.433	2.270	5.6166	0.0353	3.2117	0.24593	2.6814	0.043
SILVER IODIDE	0.42594	543.5	6.0100E+00	46.105	1.945	5.9342	0.0148	3.2908	0.25059	2.6572	0.071
SKIN (ICRP)	0.54932	72.7	1.1000E+00	22.400	2.140	3.3546	0.2019	2.7526	0.09459	3.4643	0.076
SODIUM CARBONATE	0.49062	125.0	2.5320E+00	32.117	2.557	3.7178	0.1287	2.8591	0.08715	3.5638	0.074
SODIUM IODIDE	0.42697	452.0	3.6670E+00	36.057	1.857	6.0572	0.1203	3.5920	0.12516	3.0398	0.031
SODIUM MONOXIDE	0.48404	148.8	2.2700E+00	30.205	2.689	4.1892	0.1652	2.9793	0.07501	3.6943	0.097
SODIUM NITRATE	0.49415	114.6	2.2610E+00	30.459	2.456	3.6502	0.1534	2.8221	0.09391	3.5097	0.081
STILBENE	0.53260	67.7	9.7070E-01	20.719	1.963	3.3680	0.1734	2.5142	0.16659	3.2168	0.052
SUCROSE	0.53170	77.5	1.5805E+00	26.416	2.167	3.1526	0.1341	2.6558	0.11301	3.3630	0.057
TERPHENYL	0.52148	71.7	1.2340E+00	23.116	1.976	3.2639	0.1322	2.5429	0.14964	3.2685	0.043
TESTES (ICRP)	0.55108	75.0	1.0400E+00	21.815	2.185	3.4698	0.2274	2.7988	0.08533	3.5428	0.091
TETRACHLOROETHYLENE	0.48241	159.2	1.6250E+00	25.513	1.790	4.6619	0.1713	2.9083	0.18595	3.0156	0.038
THALLIUM CHLORIDE	0.40861	690.3	7.0040E+00	48.749	1.997	6.3009	0.0705	3.5716	0.18599	2.7690	0.040
TISSUE, SOFT (ICRP)	0.55121	72.3	1.0000E+00	21.394	2.144	3.4354	0.2211	2.7799	0.08926	3.5110	0.077
TISSUE, SOFT (ICRU FOUR-COMP.)	0.54975	74.9	1.0000E+00	21.366	2.192	3.5087	0.2377	2.7908	0.09629	3.4371	0.092
TISSUE-EQUIV. GAS (METHANE BASE)	0.54993	61.2	1.0641E-03	0.697	1.890	9.9500	1.6442	4.1399	0.09946	3.4708	0.098
TISSUE-EQUIV. GAS (PROPANE BASE)	0.55027	59.5	1.8263E-03	0.913	1.856	9.3529	1.5139	3.9916	0.09802	3.5159	0.092
TITANIUM DIOXIDE	0.47572	179.5	4.2600E+00	41.022	2.307	3.9522	-0.0119	3.1647	0.08569	3.3267	0.027
TOLUENE	0.54265	62.5	8.6690E-01	19.764	1.880	3.3026	0.1722	2.5728	0.13284	3.3558	0.052
TRICHLOROETHYLENE	0.48710	148.1	1.4600E+00	24.301	1.789	4.6148	0.1803	2.9140	0.18272	3.0137	0.036
TRIETHYL PHOSPHATE	0.53800	81.2	1.0700E+00	21.863	2.100	3.6242	0.2054	2.9428	0.06922	3.6302	0.049
TUNGSTEN HEXAFLUORIDE	0.42976	354.4	2.4000E+00	29.265	2.325	5.9881	0.3020	4.2602	0.03658	3.5134	0.055
URANIUM DICARBIDE	0.39687	752.0	1.1280E+01	60.969	1.703	6.0247	-0.2191	3.5208	0.21120	2.6577	0.120
URANIUM MONOCARBIDE	0.39194	862.0	1.3630E+01	66.602	1.680	6.1210	-0.2524	3.4941	0.22972	2.6169	0.132
URANIUM OXIDE	0.39996	720.6	1.0960E+01	60.332	1.760	5.9605	-0.1938	3.5292	0.20463	2.6711	0.098
UREA	0.53284	72.8	1.3230E+00	24.194	2.022	3.2032	0.1603	2.6525	0.11609	3.3461	0.060
VALINE	0.54632	67.7	1.2300E+00	23.622	2.024	3.1059	0.1441	2.6227	0.11386	3.3774	0.056
"VITON" FLUOROELASTOMER	0.48585	98.6	1.8000E+00	26.948	2.227	3.5943	0.2106	2.7874	0.09965	3.4556	0.070
WATER, LIQUID	0.55509	75.0	1.0000E+00	21.469	2.203	3.5017	0.2400	2.8004	0.09116	3.4773	0.097
WATER VAPOR	0.55509	71.6	7.5618E-04	0.590	2.175	10.5962	1.7952	4.3437	0.08101	3.5901	0.121
XYLENE	0.54631	61.8	8.7000E-01	19.866	1.882	3.2698	0.1695	2.5675	0.13216	3.3564	0.051

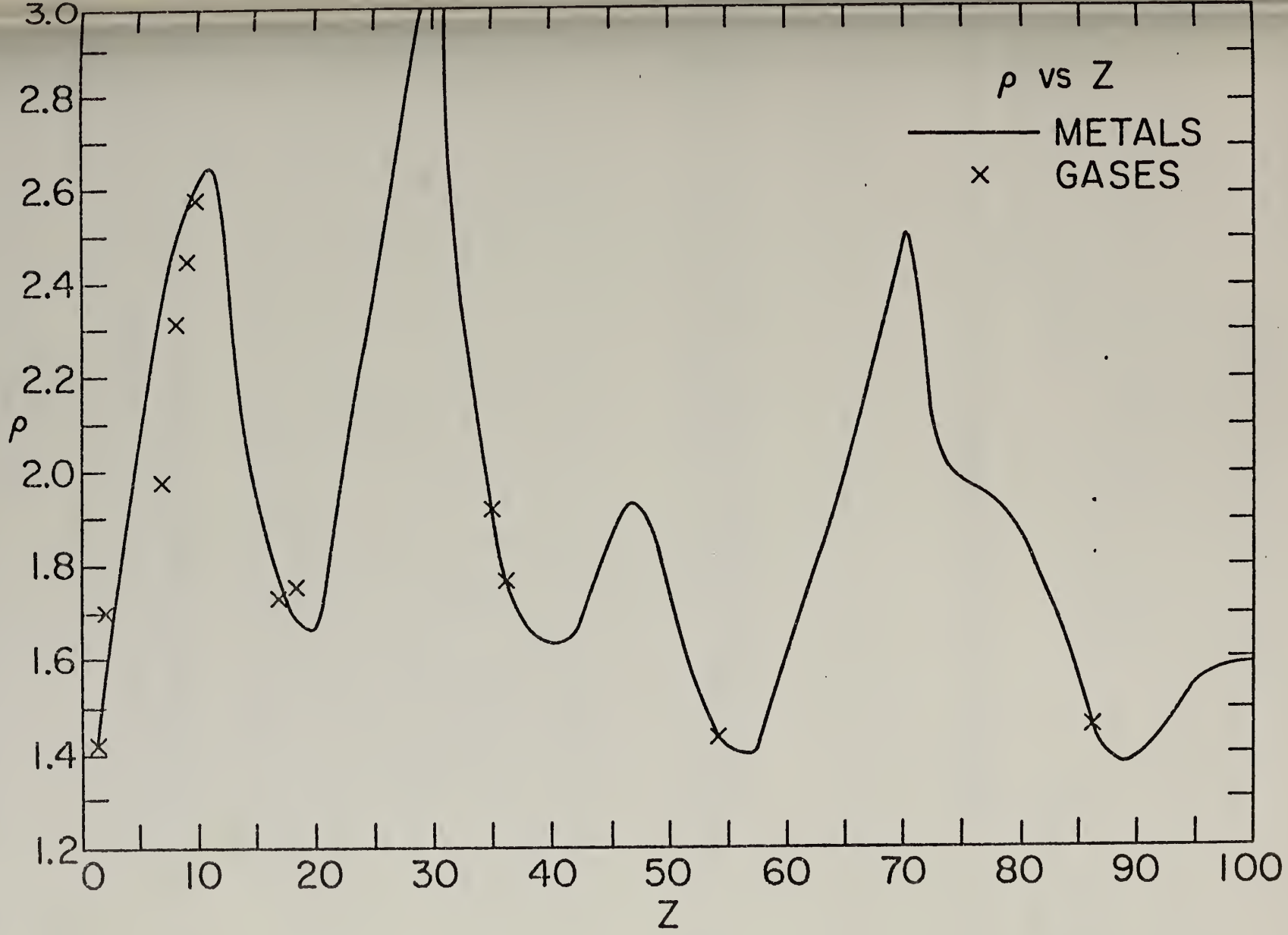

Fig. 1. Values of the Sternheimer adjustment factor ρ [see Eqs. (3) and (8)] as a function of the atomic number Z. The smooth curve is drawn through the values of ρ for the case of metals. The crosses pertain to the values of ρ for the 12 gases. The successive maxima and minima of ρ are correlated with the atomic shell structure [see the discussion in the text following Eq. (8)].

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The density-effect correction $\delta(\beta)$ for the ionization energy loss of charged particles has been evaluated for a total of 278 substances including 98 cases of elements of the Periodic Table (12 gases and 86 condensed materials, including liquid hydrogen and graphite of three different densities) and including also 180 chemical compounds and substances of biological interest (13 gases and 167 liquid or solid substances). In the calculations, up-to-date values of the mean excitation potential I and of the atomic absorption edges $h\nu_i$ were employed as input data for the general equations for $\delta(\beta)$ previously derived by Sternheimer.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

charged particles; compounds; density effect; elements; mean excitation energies; stopping power.

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