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Continuous Slowing Down Approximation (CSDA) ranges of electrons for biomedical materials

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ABSTRACT

In this paper we present a relation for continuous slowing down approximation (CSDA) ranges for electrons of biomedical materials such as bones, muscles, fat, water and air in terms of energy from 20 keV to 50000 keV and have been fitted by least square approximation with two parameters. These parameters depend upon the total energy and atomic number of the absorber. It has been found that this method gives better agreement with the available experimental data.

Introduction

Stopping media are characterized by their stopping power (SP), the inelastic mean free path (IMFP), the continuous slowing down approximation-range (CSDA-range) (R) and the energy straggling parameter. These physical quantities are important for application such as radiation biology, electron beam lithography, and chemical analyses of surface regions of a solid and in calculation of radiation dose in radiotherapy. The principal characteristic of ionizing radiation is that it has sufficient energy to break any chemical bond and to cause ionization in all materials.

Whenever the energy of a particle exceeds the ionization potential of a molecule, a collision with the molecule might lead to ionization.

The knowledge of the mean free path and CSDA-range of electrons is important, especially at low energies; in line with this, number of authors has made associated studies of biological compounds [1-5].

For electrons of low energies, the inelastic interaction characteristics, the stopping power, the mean free path and the CSDA-range cannot be obtained directly from experiments or from Bethe's SP theory, the latter giving accurate SPs at energies larger than 10 keV.

At lower energies, the theory is, in general, invalid. For low-energy electrons, a method has been used to estimate the mentioned characteristics, based on the use of the complex dielectric function ε□□q, ω□□□ħq□and ħω being the momentum and energy transfer, respectively. As mentioned by Akkerman and Akkerman [3] restrictions in these theories prevent their use for a wide range of non-organic and organic materials [3].

To calculate the mean free path and the CSDA-range, another method is to make use of the inelastic differential cross section (IDCS) suggested by [6] with the generalized oscillator strength (GOS). For this, the GOS has to be calculated from matrix elements that involve numerical integration of atomic wave functions. This calculation is too complicated.

During the last few years, a number of optical data models have been proposed to compute the inelastic scattering of electrons, avoiding the calculation of the GOS from matrix elements.

In recent years, [5] have calculated the IMFP and the CSDA-range in DNA (thymine–adenine or cytosine–guanine) for low and intermediate energy ranges.

These calculations were also studied for liquid water, guanine and organic molecules in the energy range 20 eV–10 keV [1,5].

In this paper, we propose a method to obtain the CSDA ranges for electrons at intermediate energy (20–50000 keV) in terms of least square method. Results obtained by this procedure are compared with the available data, above 20 keV, derived from the Born–Bethe approximation.

Previous empirical relations for CSDA Ranges

The exact knowledge of range of electrons and positrons in several media is of practical interest for many applications in nuclear physics, radiation protection and semiconductor detector fabrication. The main effects produced by the passage of electrons through matter are:

1. Non radiative collision process and
2. Radiative collision process.

Therefore the total energy loss during the passage of electron will be the sum of these two losses. In determining CSDA ranges fluctuations in energy losses are neglected and electrons are assumed to loss energy continuously along their track with a mean energy loss per unit path length given by the stopping power.

Nelms [7] has calculated CSDA ranges using collisions loss expressions. Using collision loss expressions the following equation was solved numerically by Simpson's 1/3rd rule.

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$$R_{csda} = \int_0^E \left[\left| -\left(\frac{1}{\gamma}\right)\frac{dE}{dx} \right|^{\pm} \right]^{-1} dE \qquad (1)$$

Rohrlich et al [8] have tabulated CSDA ranges of electrons and positrons for several media at different energies. Tung et al [9] calculated electron ranges using electron gas model. Berger and Seltzer [10] published extensive tables containing CSDA ranges from 10 KeV to1000MeV. Gupta et al [11] also presented an empirical formula for CSDA range but it is not applicable in low energy region. According to him an empirical equation has been derived for the csda ranges of monoenergetic electrons in the energy region 0.2-10 MeV by using the empirical relation for total stopping power. The corresponding equation for csda ranges is

$$R(T_O) = \frac{mc^2}{sz + 1.3230}\left[\frac{\gamma^{az+b-1}}{az+b-1} + \frac{1}{\gamma}\right]_{1.1957}^{\gamma} \qquad (2)$$

Tan et al [12] have proposed a simple empirical relation for CSDA ranges for electrons with energies between 25 to 200 keV by the following relation,

$$R_{csda}^{-} = 190 \times 10^{-6}\left(\frac{A}{Z}\right)^{2.5} E^{1.6} \quad g/cm^2 \qquad (3)$$

where A, Z and E are atomic weight, atomic number and energy respectively. This relation is valid for atomic numbers 30 to 92 with error comprising 2 to 10 %. The drawback of the relation is that it is valid for very small energy range and does not give any information for lower atomic number.

Proposed relation for CSDA ranges

The abbreviation CSDA stands for continuous slowing down approximation. Under this approximation an electron which penetrates into the absorbers, looses energy continuously by inelastic collision, and the total path length which the particle would travel in the absorbers during slowing down process in an unbounded homogeneous medium from initial energy to the final kinetic energy zero is called CSDA range of the particle. It can be expressed by the relation

$$R_{CSDA}^{\pm}(E_0) = \left(-\frac{1}{\rho}\left(\frac{dE}{dS}\right)_{Tot}^{\pm}\right)dE + R^{\pm}(E_0)$$

$$-\frac{1}{\rho}\left(\frac{dE}{dS}\right)_{Tot}^{\pm} = (MZ + C)\left(\frac{\gamma^{A^{\pm}Z+B^{\pm}}}{\gamma^{k^{\pm}-1}}\right)$$

The equation for stopping power in the energy region 20 KeV to 50000 KeV for the absorbers of atomic number 1 to 92 is [13]

$$-\frac{1}{\rho}\left(\frac{dE}{dS}\right)_{Tot}^{\pm} = (MZ + C)\left(\frac{\gamma^{A^{\pm}Z+B^{\pm}}}{\gamma^{k^{\pm}-1}}\right) \qquad (4)$$

By using eqn.(4) the CSDA ranges of electron are given as:-

$$R(T_0) = \frac{m_e c^2}{(M \times Z + C)}\left[\frac{\gamma^{K-(A^{\pm}Z+B^{\pm})+1}}{K-(A^{\pm}Z+B^{\pm})+1} + \frac{\gamma^{-(A^{\pm}Z+B^{\pm}-1)}}{-(A^{\pm}Z+B^{\pm}-1)}\right]_{1.02}^{\gamma_0} \qquad (5)$$

Where γ is the total energy of electron or positron in electron mass unit, Z is the atomic number of the material and M, C and k are constants. The values of constants are presented in tables 1 and 2.

Comparison between proposed and reported values

The equation (5) has been used to calculate CSDA ranges of electrons and positrons in different elements for various energies in their prescribed energy regions [10]. The calculated values for electrons thus obtained were compared with the standard values due to Berger and Seltzer [10]. In order to compare evaluated values of CSDA ranges of positrons, following method has been adopted. The evaluated values of CSDA ranges have been presented in the tables 3 and 4. This relation is valid for lower atomic numbers. We note that the values of CSDA ranges evaluated by proposed relation are in close agreement with the reported data as compared to the values reported by previous researchers so far.

Summary and Conclusions

From the above results obtained using the proposed empirical relation (5), it is quite obvious that the CSDA ranges of materials can be expressed in terms of energy and atomic number of the material. We come to the conclusion that energy of the material is key parameter for the calculation of CSDA ranges. It is also noteworthy that proposed empirical relation is simpler, widely applicable and values obtained are in better agreement with the theoretical data as compared to the empirical relations proposed by previous researchers [11,12].

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Table 1(a). Values of constants

Range (Atomic Number)	M	C
1≤Z≤10	-0.3215	3.675
10≤Z≤36	-0.0132	1.677
Z>36	-0.00655	1.4177

Table1 (b). values of constants.

Energy	K
20KeV<E≤1500KeV	2.8
1500KeV<E≤50000KeV	3.8

Table 2. Values of CSDA ranges for electrons of Fat, Muscle and Bone.

	fat		muscle		Bone	
E (keV)	Cal	Sta [10]	cal	Sta [10]	cal	Sta [10]
20	0.00064	0.00082	0.00082	0.00087	0.00067	0.00098
30	0.00138	0.00169	0.00178	0.00178	0.00145	0.00200
40	0.00237	0.00282	0.00305	0.00295	0.00248	0.00331
50	0.00357	0.00418	0.00460	0.00437	0.00373	0.00488
60	0.00497	0.00575	0.00639	0.00601	0.00519	0.00670
70	0.00653	0.00751	0.00840	0.00785	0.00682	0.00875
80	0.00824	0.00946	0.01061	0.00988	0.00861	0.01100
90	0.01009	0.01159	0.01298	0.01209	0.01053	0.01345
100	0.01205	0.01387	0.01551	0.01447	0.01258	0.01607
150	0.02321	0.02734	0.02985	0.02848	0.02419	0.03155
200	0.03576	0.04359	0.04599	0.04537	0.03723	0.05015
250	0.04896	0.06194	0.06294	0.06442	0.05092	0.07111
300	0.06235	0.08190	0.08014	0.08513	0.06478	0.09386
350	0.07567	0.10310	0.09724	0.10710	0.07854	0.11800
400	0.08875	0.12530	0.11403	0.13020	0.09204	0.14330
450	0.10150	0.14830	0.13039	0.15400	0.10518	0.16950
500	0.11387	0.17200	0.14626	0.17850	0.11791	0.19640
1000	0.21620	0.42750	0.27742	0.44180	0.22264	0.48570
1500	0.72153	0.69440	0.92473	0.71580	0.73832	0.78570
2000	0.96896	0.96210	1.24094	0.99030	0.98766	1.08500
2500	1.20901	1.22800	1.54740	1.26300	1.22833	1.38000
3000	1.44288	1.49100	1.84574	1.53200	1.46180	1.67100
3500	1.67151	1.75200	2.13720	1.79800	1.68921	1.95800
4000	1.89563	2.01000	2.42273	2.06200	1.91143	2.24100
4500	2.11581	2.26500	2.70308	2.32300	2.12911	2.52000
5000	2.33248	2.51800	2.97884	2.58000	2.34278	2.79500
10000	4.36380	4.93300	5.55913	5.03300	4.32568	5.37400
15000	6.23891	7.18300	7.93525	7.30300	6.13288	7.70700
20000	8.01739	9.30500	10.18533	9.42800	7.83258	9.85000
25000	9.72668	11.32000	12.34530	11.43000	9.45589	11.84000
30000	11.38252	13.24000	14.43571	13.33000	11.02051	13.69000
35000	12.99502	14.96000	16.46980	15.13000	12.53779	15.43000
40000	14.57126	16.83000	18.45678	16.85000	14.01559	17.07000
45000	16.11640	18.51000	20.40339	18.49000	15.45966	18.61000
50000	17.63439	20.13000	22.31478	20.06000	16.87436	20.08000

Table 3. Values of CSDA ranges for electrons of Water and air

	water		Air	
E (keV)	Cal	Sta [10]	cal	Sta [10]
20	0.00078	0.00086	0.00087	0.00098
30	0.00170	0.00176	0.00188	0.00200
40	0.00291	0.00292	0.00322	0.00332
50	0.00439	0.00432	0.00485	0.00491
60	0.00611	0.00594	0.00674	0.00675
70	0.00803	0.00776	0.00886	0.00882
80	0.01013	0.00977	0.01119	0.01110
90	0.01240	0.01196	0.01369	0.01357
100	0.01481	0.01431	0.01636	0.01623
150	0.02851	0.02817	0.03149	0.03193
200	0.04393	0.04487	0.04851	0.05082
250	0.06013	0.06372	0.06639	0.07212
300	0.07656	0.08421	0.08454	0.09527
350	0.09290	0.10600	0.10257	0.11990
400	0.10894	0.12880	0.12027	0.14560
450	0.12458	0.15230	0.13753	0.17220
500	0.13975	0.17660	0.15426	0.19950
1000	0.26511	0.43670	0.29254	0.49120
1500	0.88385	0.70750	0.97491	0.79000
2000	1.18622	0.97850	1.30810	1.08500
2500	1.47932	1.24700	1.63097	1.37400
3000	1.76469	1.51400	1.94522	1.65800
3500	2.04351	1.77700	2.25220	1.93500
4000	2.31668	2.03700	2.55289	2.20800
4500	2.58493	2.29500	2.84811	2.47600
5000	2.84880	2.55000	3.13846	2.74000
10000	5.31862	4.97500	5.85436	5.19200
15000	7.59392	7.21900	8.35425	7.40500
20000	9.74908	9.32000	10.72085	9.44600
25000	11.81833	11.30000	12.99218	11.35000
30000	13.82127	13.17000	15.18998	13.15000
35000	15.77049	14.96000	17.32827	14.85000
40000	17.67479	16.65000	19.41676	16.46000
45000	19.54057	18.28000	21.46261	18.01000
50000	21.37276	19.83000	23.47124	19.48000