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Estimation of the total energy loss and continuous slowing down range (CSDA) of positrons in carbon and silver

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Abstract

In this paper we calculate the total stopping power (collision and radiative) for positrons within the range of energies (0.02 – 50) MeV for two elements (carbon and silver), also we calculate continuous slowing down range (CSDA) for the same elements by using P. Bal etal. formula in the energy range (5-1000) MeV. The results were compared with the data of ICRU which shows a good agreement.

Keywords: total stopping power, radiative, collision, mean excitation energy, Carbon, Silver, Range (CSDA), ICRU .

1.Introduction

When a fast charged particles passing through matter, it will ionize the atoms or molecules, and gradually loses energy while interactions with targets. Stopping power is defined as the average energy loss of the particle per unit path length, measured in MeV/cm, it is a necessary ingredient for many parts of basic science i.e. medical and technological applications. Information about stopping power (s.p.) is essential in many fields involving radiation. Research concerning the stopping power has taken the position of the basic theme in the fields of ion-matter interactions for a long time, despite the long history of stopping power research, the current knowledge, both experimental and theoretical, is far from being complete, and is often inadequate for the determination its values for a variety of materials and a wide range of particle energies[1]. The study of s.p. for positron and electron through matter is an effective tool for exploring the structure of matter and of interest in many research fields, such as nuclear physics, atomic physics, solid-state physics, radiation dosimetry and nuclear technique applications. During the last two decades, it has attracted a great deal of attention. The s.p. calculations for β+ are studied in two different ways: the first is to consider the interactions of incoming positron with target electron, which is called collisional s.p. that may end with annihilation of radiation if the conditions are met, while the second is to consider the fact that accelerated charged particles is radiated, which is called radiative stopping power or Bremsstrahlung [2]. In (1982), Stephen M. Seletzer and Martin J. Berger [3] studied radiative stopping power for elements with atomic numbers Z of 1-100 and within range of energy (1keV-10GeV) and then in (1984), studied collection of stopping power for electrons and positrons, taking into account that the correct density obtained identical results with the practical consequences as the delinquency rate was up to 2-1%.[4], also Hasan. G et al. in(2006)[5] calculated the results of the stopping power for positrons in some materials, such as aluminum, silicon, copper, and liquid water. In (2009), Ashok. K et al.[6] studied approximate continuing slowdown (RSCDA) within the range of energy (0.01 - 100MeV) and in (2011) Priyanka. A et al. [7] calculated stopping power for electrons and positrons for the elements (C, Al, Si) within the range of energy (30 keV - 3 MeV) where they found the stopping power as a function of the atomic number Z and atomic weight A, and the results were match able with practical results.

2.Theoretical part:

2.1 Collision stopping power:

The theory of the mass collision stopping power for heavy charged particles, electrons and positrons as a result of soft and hard collisions combines the Bethe theory[8], for a light charged particle with mass m and velocity v, the collision stopping power is given by :- [9].

$$S_{coll} = k\left[\ln\left(\frac{\tau^2(\tau+2)}{2(I/m_o c^2)^2}\right) + F^+(\tau) - \delta - \frac{2c}{z}\right] \quad (1)$$

Where

F^+ is a dimensionless function for e^+ defined as:

$F^+(\tau) = 2\ln 2 - (\beta^2/12)[23 + 14/(\tau + 2) + 10/(\tau + 2)^2 + 4/(\tau + 2)^3$ (2)

and

r_o: is the classical electron radius ($r_o = \frac{e^2}{m_o c^2}$ =2.82×10^{-15} m).

z :is the projectile charge in units of electron charge;

I: is the mean excitation

C/Z :is the shell correction.

Electron rest mass energy = 0.511MeV

$$\tau = \frac{T}{m_0 c^2}$$

τ: kinetic energy in terms of rest mass

The mean excitation potential I is a geometric mean value of all ionization and excitation potentials of an atom of the absorbing material. Since binding effects influence the exact value of I, calculation models are often inadequate to estimate its value accurately. Hence, I values are usually derived from measurements of stopping powers in heavy charged particle beams, for which the effects of scattering in these measurements are kept minimal.

2.2 Radiative stopping power (bremsstrahlung):

The mass radiative stopping power is the rate of energy loss by electrons or positrons that results in

the production of bremsstrahlung only. Electrons and positrons are light enough to generate significant bremsstrahlung, which depends on the inverse square of the particle mass for equal velocities. The Bethe – Heitler [10] and Berger and Seltzer (1983)[11], theories lead to the following formula for the mass radiative
stopping Power (ICRU 37)[12]:

$$S_{rad} = \sigma_{\circ} \frac{N_A Z^2}{A} (E + m_0 c^2)\ B \quad (3)$$

where the constant $\sigma_{\circ} = \frac{1}{137}(e^2/m_0 c^2) = 5.80\times10^{-28}$ cm^2 /atom, T is the particle kinetic energy in MeV, and B, is a slowly varying function of Z and T having a value of $\frac{16}{3}$ for T << 0.5 MeV, and roughly 6 for T = 1 MeV, 12 for 10 MeV, and 15 for 100 MeV.

2.3 Semi empirical stopping power equations of positrons:

A semi empirical equation for the total stopping power for positrons in elements, compounds, and alloys has been used which is valid in the energy region from (0.02 to 1000) MeV. The probability of annihilation falls off rapidly with an increase of positron velocity. It has been shown that the positron behavior during penetration through matter is same as electron behavior in regard to loss of energy, but the absorption of positrons in a medium is important for checking the phenomenon of annihilation which causes the difference between the stopping powers for electrons and positrons. In the energy region from 0.01 to 1000 MeV which is of interest here, positrons lose energy mainly in two ways: (i) collision loss which is effective at low energies (*E* < 1 MeV), and (ii) radiation loss or bremsstrahlung loss which is important at high energies (*E* > 1 Me V) and high Z values. In spite of these two types of losses there occurs the annihilation of positrons with atomic electrons of the absorber. The loss of energy by the annihilation process of positrons differs from that of energy loss by electrons, and it should cause an increase in stopping power for positrons in matter. Analytical data shows that the stopping power for positrons in matter is less than that for electrons. It is due to less energy loss by positrons in the collision process than by electrons.[12-15]. The total stopping power S^+_{total} of any stopping medium for positrons is the sum of the collision stopping power S^+_{coll} and the radiative stopping power S^+_{rad} written as [16,17].

$$S^+_{total} = S^+_{coll} + S^+_{rad} \quad , \quad (4)$$

where superscripts (+) stand for positrons. Bethe and Heitler have obtained an approximate relation between collision stopping power and radiative stopping power as

$$S^+_{rad} / S^+_{coll} = ZE / 800 \ , \quad (5)$$

where Z is the atomic number of the target atom, *T* is the energy of incident positrons or electrons in MeV. Combining Eqs. (4) and (5) one can get

$$S^+_{total} = S^+_{coll}\ (1 + ZE / 800)\ . \quad (6)$$

With the help of a relativistic cross section for positron scattering given by Bhabha, Rohrlich and Carlson have shown that mass collision stopping power for positrons is given by[18,19].

$$S^+_{coll} = 2\pi\ N_A r_o^2 m_o c^2\ (Z/A)(1/\beta^2)\ x\ [\ \ln (E/I)^2 + \ln(1+\tau/2) + f^+(\tau)\ ] \quad (7)$$

Where

$$f^+(\tau) = 2\ln 2 - \beta^2 / 12\ [23 + 14/(\tau+2) + 10/(\tau+2)^2 + 4/(\tau+2)^3\ ]$$

and

$\tau = E / m_o c^2 = (E - m_o c^2) / m_o c^2 = \gamma - 1$.

τ is the kinetic energy of incident positrons in units of electron rest energy, N_A is Avogadro's number, *A* is the atomic weight in gram per mol, Z is the atomic number, *I* is the mean excitation energy of the target atom, $r_o = e^2/m_o C^2$ is the classical electron radius. Berger and Seltzer have shown that the corrected formula for collision stopping power for positrons is[15]

$$S^+_{coll} = 2\pi N_a r_o^2 m_o c^2 (Z/A)(1/\beta^2)\ x\ [\ln (E/I)^2 + \ln(1+\tau/2) + f^+(\tau) - \delta\ ] \quad (8)$$

where δ is the density effect correction.

We have expressed Eq. (8) as

$$S^+_{coll} = (\ 4\pi N_a r_o^2 m_o c^2\ )(Z/A)\ F^+(E/E_o\ , Z\ ) \quad (9)$$

Where

$$F^+(E/E_o\ , Z\ ) = 1/2\ \beta^2\ [\ln(E/I)^2 + \ln(1+\tau/2)\ f^+(\tau) - \delta\ ] \quad (10)$$

A dimensionless function depending on kinetic energy *E in* MeV of the incident positrons and atomic number Z of the stopping medium, E_O is taken 1 Me V in order to make the function F^+ dimensionless. Equations (7) and (10) represent the total stopping power semi empirical equation for positrons and can be written as

$$S^+_{total} = 4\pi N_a r_o^2 m_o c^2\ (Z/A)(\ 1 + ZE/800\ ) F^+\ (E/E_o\ , Z)\ , \quad (11)$$

where the function F^+ is given by

$$F^+ = P^+_0 + P^+_1(\ln E/E_o) + P^+_2(\ln E/E_o)^2 \quad (12)$$

and P_o^+ , P^+_1, and P_2^+ are the parameters depending on
atomic number Z as

$$P^+_n = a^+_n + b^+_n\ (\ln Z) + c^+_n\ (\ln Z)^2\ , \quad (13)$$

Where a_n^+ , b^+_n, and c^+_n are the coefficients and *n* = 0, I, and 2 The best-fit values of the coefficients have been given as shown in table(1)

Table (1): Values of the coefficients a_n^+ , b^+_n, and c^+_n.[18,19]

Coefficient	N	0.01<(E/E$_o$)<0.1	0.1<(E/E$_o$)<1	1<(E/E$_o$)<1000
a^+_n	0	+171.26	+11.717	+13.594
	1	+123.79	-0.6333	-3.6253
	2	27.550+	+2.6607	+0.7448
b^+_n	0	-27.398	-0.6784	-2.7184
	1	-20.171	+0.4034	+3.0727
	2	-4.2187	-0.1826	-0.4487
c^+_n	0	+0.2366	-0.0537	+0.2594
	1	+0.1906	-0.0547	-0.4574
	2	+0.0377	-0.0153	+0.0624

2.4 Approximate expressions for R^+_{CSDA}

The CSDA range of electrons or positrons in any absorber is defined as:

$$R^{+}_{CSDA} = \int_0^{E_0} \left[-\frac{1}{\rho}\left(\frac{dE}{dx}\right)\right]^{-1} dE \,, \quad (14)$$

Where $-1/\rho\,(dE/dx)$: is the mass stopping power of the absorber, ρ is the density of the absorber, superscript (+) stand for positron, E_o is the kinetic energy of the incident electrons or positrons. The total stopping theory is poor at the lowermost energies. Batra and Sehgal[16] have given expressions for the total stopping power for electrons and positrons in matter in the energy region 0.3-5.0 MeV. Gupt a and G u p t a [17] have checked the validity of Batra's expressions, and modified the expressions to make them valid in the wider energy region 0.2 - 10 MeV. They have also calculated the CSDA ranges of electrons and positrons making use of their proposed expressions in the same energy region. At energies above 10 MeV their proposed expressions are not valid. In spite of this the analytical expressions for the total stopping power and evaluation of CSDA ranges of electrons and positrons from them involve the use of a computer and much labor. Therefore to avoid this difficulty, the authors [20] have proposed simple expressions for the total stopping power for electrons and positrons of energies 5-1000 MeV in any absorber to be

$$\frac{1}{\rho}\left(\frac{dE}{dx}\right)^{+} = (MZ + N)\,(P^{+}_{0} + P^{+}_{1}\,\gamma)\,, \quad (15)$$

Where M, N, P^{+}_{0} and $P^{+}_{1}\gamma$ are parameters. The numerical values of the parameters M and N are the same as listed by Batra and Sehgal [11] for m and c respectively, and are listed in table(2)

Table (2): Numerical values of the parameters M and N [16]

Z	M (MeV cm^2/g)	N (MeV cm^2/g)
$1\leq Z \leq 10$	-0.330	1.3230
$10\leq Z \leq 36$	-0.0097	1.0911
$36\leq Z \leq 92$	- 0.0048	0.9156

The parameters P^{+}_{0} and P^{+}_{1} are given as:

$$P^{+}_{0} = A^{+}_{0} + B^{+}_{0} Z + C^{+}_{0} Z^2 \,, \quad (16)$$

$$P^{+}_{1} = A^{+}_{1} + B^{+}_{1} Z + C^{+}_{1} Z^2 \,, \quad (17)$$

Where A^{+}_{n}, B^{+}_{n} and C^{+}_{n} (n = 0, 1) are the coefficients, γ is the total energy of electrons or positrons in units of m_oc^2 (511 keV). One can get expressions for the CSDA ranges of electrons and positrons from eqs. (14) and (15):

$$R^{+}_{CSDA} = \frac{m_0c^2}{(MZ+N)P^{+}_{1}} \ln\left[\frac{P^{+}_{0}+P^{+}_{1}\,\gamma_0}{P^{+}_{0}+P^{+}_{1}\,1.1957}\right] + (R^{+}_{CSDA})_{100\,keV} \quad (18)$$

Where the values of $(R^{+}_{CSDA})_{100\,keV}$ are obtained using the stopping power expressions given by Batra and Sehgal [16]. Thus the CSDA range of positrons in the energy region 5-1000 MeV in any absorber are expressed as.

$$R^{+}_{CSDA} = \frac{m_0c^2}{(MZ+N)}\,\frac{1}{P^{+}_{1}}\left[\left(\frac{P^{+}_{0}+P^{+}_{1}\,\gamma_0}{P^{+}_{0}+P^{+}_{1}\,1.1957\,P^{+}_{1}}\right) + K^{+}\right] \quad (19)$$

Where $K^{+} = 0.0288$

Where A^{+}_{n}, B^{+}_{n} and C^{+}_{n} are parameters. The numerical values are listed in table(3)

Table (3): Numerical values of the coefficients A^{+}_{n} , B^{+}_{n} and C^{+}_{n}.[16]

Kinetic energy(T) (MeV)	Atomic number Z	n	A^{+}_{n}	B^{+}_{n}	C^{+}_{n}
$5\leq E \leq 10$	$1\leq Z \leq 92$	0 1	1.3580481 4.55151X10^{-3}	3.16801X10^{-3} 1.38636X10^{-3}	- -
$5\leq E \leq 10^3$	$1 \leq Z \leq 92$	0 1	1.4214145 1.02208X10^{-3}	1.22493X10^{-3} 1.52484X10^{-3}	-8.7690X10^{-5} +3.81085X10^{-6}

3.Results and Discussion

3.1 Discussion of S_{Coll} , S_{rad} and S_{tot}

The total stopping power S_{tot} was calculated by using equations (11, 12, 13) Via Matlab R2008 b for the elements C and Ag in the energy range (0.02 - 50) MeV. Tables (4 and 5) and figures (1, 2, 3, 4) represent the values of S_{call} .S_{rad} and S_{tot} for elements C and Ag. From these tables and figures, we found , that the results of S_{coll} is dominate S_{rad}, due to the smallness of energy range and the large electron density for the elements under study. Hence the probability of energy loss in electron field is greater than that of nuclear field. The mechanism of energy loss of emission of electromagnetic rediation arising due to the smallness of positron mass which scattered by the electric field of nucleus, that the result is the positron deviation from its straight line caused by electrical attraction of the nucleus. At energies of (0.02 – 2.5) MeV this process is still relatively small. However as the positron energy increases, the probability of Bremsstrahlung quickly shoots up so that at energy of few tens of MeV loss of energy S_{Red} will become more than S_{Call} results. At positrons energies above the critical energy which is defined by [21].

$$E_c = \frac{1600 m_e c^2}{Z} \quad (20)$$

the S_{Rad} dominates completely. Since the values depend on the strength of the electric field felt by the positrons, the amount of screening from atomic electrons surrounding the nucleus, play an important role. Thus the cross section is dependent not only on the incident positron energy, but as well as on its impact parameter and the atomic number Z of the target material. The effect of screening can be parameterized by the quantity[22].

$$\mathcal{E} = \frac{100 m_e\, C^2\, hf}{E_o E\, Z^{0.34}} \quad (21)$$

Where E_o: initail total energy of positron, E: final total energy of positron, hf: energy of emitted photon(E-E_o).

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Table(4) :The values of radiative, collision and total stopping power of Carbon of present study and comparison of the values of Total stopping power and ICRU [12]. $(MeV.cm^2)/g$

E(MeV)	(S_{Rad})Present Study/C	(S_{Coll})Present Study/C	(S_{total})Present Study/C	ICRU (S_{total})	Error %
0.02	0.0019707	13.137809	13.14	12.76	2.89
0.03	0.0021012	9.3385053	9.34	9.26	0.86
0.04	0.0021778	7.2594823	7.26	7.41	2.04
0.05	0.0022498	5.9993518	6.00	6.25	4.14
0.06	0.0023393	5.1983496	5.20	5.46	4.99
0.07	0.0024578	4.6815022	4.68	4.89	4.40
0.08	0.0026115	4.3525786	4.36	4.45	2.18
0.09	0.0028039	4.1539817	4.16	4.1	1.37
0.1	0.0026707	3.5609169	4.05	3.82	5.73
0.3	0.004804	2.1351016	2.14	2.09	2.33
0.35	0.0052652	2.0057852	2.01	1.97	2.04
0.4	0.0057235	1.9078391	1.91	1.89	1.23
0.45	0.006184	1.8322884	1.84	1.82	1.00
0.5	0.0066499	1.7733188	1.78	1.77	0.56
0.6	0.0076072	1.6904895	1.70	1.7	0.11
0.7	0.0086072	1.6394594	1.65	1.65	0.12
0.9	0.0107568	1.5935939	1.60	1.6	0.27
1	0.0110196	1.4692787	1.60	1.58	1.25
2	0.0228539	1.5235942	1.55	1.57	1.52
2.5	0.0289785	1.5455177	1.57	1.58	0.35
3	0.0352133	1.5650351	1.60	1.6	0.02
3.5	0.0415449	1.5826626	1.62	1.62	0.26
4	0.047963	1.598766	1.65	1.64	0.41
4.5	0.0544594	1.6136127	1.67	1.66	0.48
5	0.0610276	1.6274038	1.69	1.68	0.50
10	0.129761	1.7301462	1.86	1.83	1.61
15	0.2024904	1.799915	2.00	1.97	1.62
20	0.2780617	1.8537449	2.13	2.09	1.96
25	0.3558699	1.8979727	2.25	2.21	1.95
30	0.4355356	1.935714	2.37	2.33	1.74
40	0.59946	1.9982	2.60	2.56	1.45
45	0.6833766	2.0248197	2.71	2.67	1.41
50	0.7684283	2.049142	2.82	2.79	0.98

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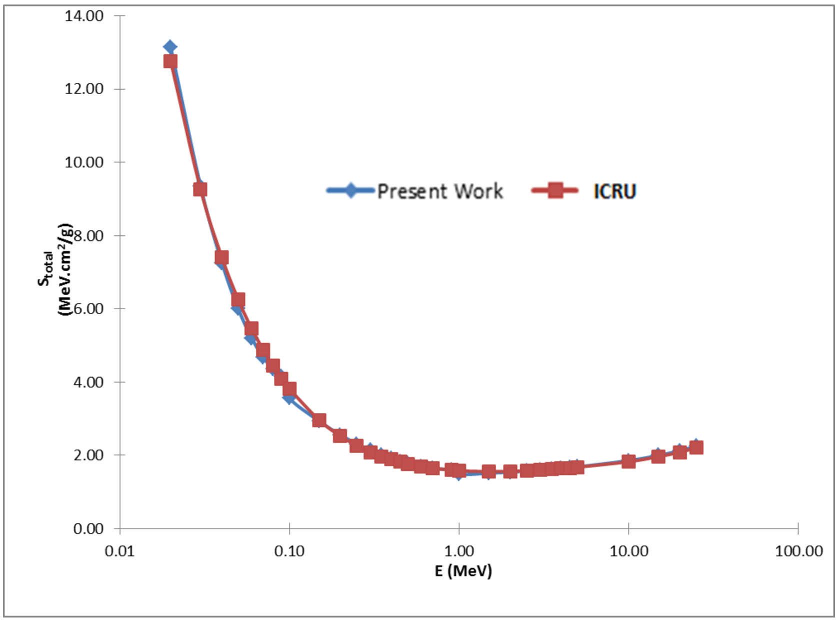
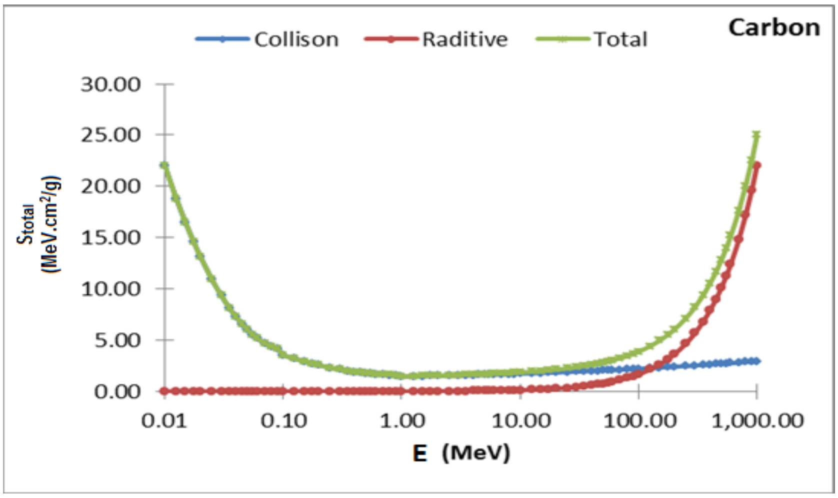
Table(5): The values of radiative, collision and total stopping power of Silver of present study and comparison of the values of Total stopping power and ICRU [12]. ($MeV.cm^2)/g$

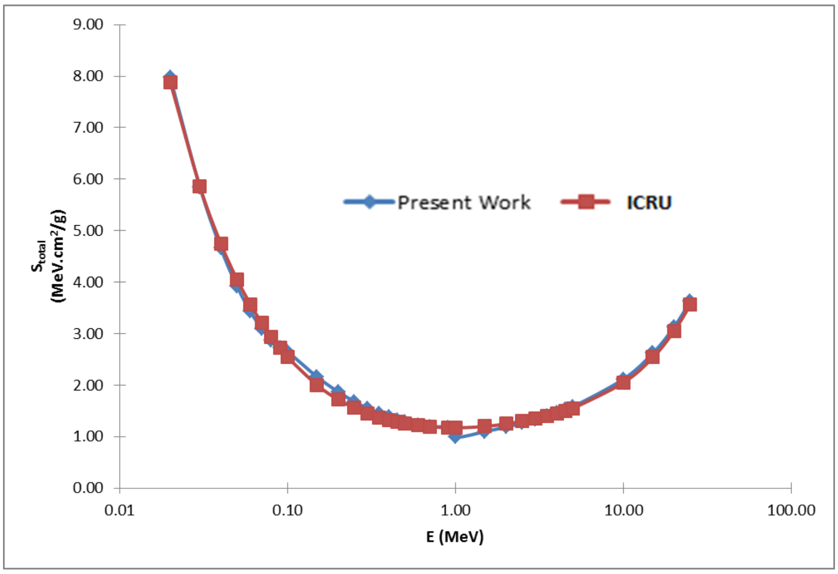
E(MeV)	(S_{Rad})Present Study/C	(S_{Coll})Present Study/C	(S_{total})Present Study/C	ICRU (S_{total})	Error %
0.02	0.0093555	7.9621104	7.97	7.88	1.15
0.03	0.0102882	5.8372999	5.85	5.86	0.21
0.04	0.0109206	4.6470459	4.66	4.75	1.98
0.05	0.0114715	3.9052061	3.92	4.05	3.40
0.06	0.0120439	3.4167188	3.43	3.57	4.12
0.07	0.0126922	3.0862474	3.10	3.21	3.58
0.08	0.0134472	2.8611108	2.87	2.94	2.28
0.09	0.0143272	2.7096309	2.72	2.72	0.15
0.1	0.0154738	2.6338374	2.63	2.54	3.31
0.3	0.0268137	1.5213457	1.55	1.45	6.34
0.35	0.0292362	1.4218206	1.45	1.37	5.59
0.4	0.0316512	1.3468617	1.38	1.32	4.24
0.45	0.0340889	1.2894147	1.32	1.28	3.29
0.5	0.0365694	1.2449141	1.28	1.25	2.46
0.6	0.0417104	1.1832733	1.22	1.22	0.41
0.7	0.0471437	1.1463514	1.19	1.19	0.29
0.9	0.059009	1.1160085	1.18	1.18	0.42
1	0.0549387	0.9351273	1.18	1.17	0.83
2	0.1250013	1.0638409	1.19	1.25	5.14
2.5	0.162105	1.1036934	1.27	1.3	2.70
3	0.2001641	1.1356826	1.34	1.35	1.06
3.5	0.2390036	1.1623273	1.40	1.4	0.09
4	0.278501	1.1851104	1.46	1.45	0.93
4.5	0.3185659	1.2049772	1.52	1.5	1.55
5	0.3591289	1.2225665	1.58	1.55	2.00
10	0.7837225	1.3339957	2.12	2.05	3.20
15	1.2299842	1.3957267	2.63	2.54	3.26
20	1.6896275	1.4379808	3.13	3.05	2.48
25	2.1588754	1.4698726	3.63	3.56	1.89
30	2.6355674	1.4953574	4.13	4.08	1.23
40	3.6061266	1.534522	5.14	5.13	0.21
45	4.0983063	1.5501868	5.65	5.66	0.20
50	4.5943009	1.5640173	6.16	6.19	0.51



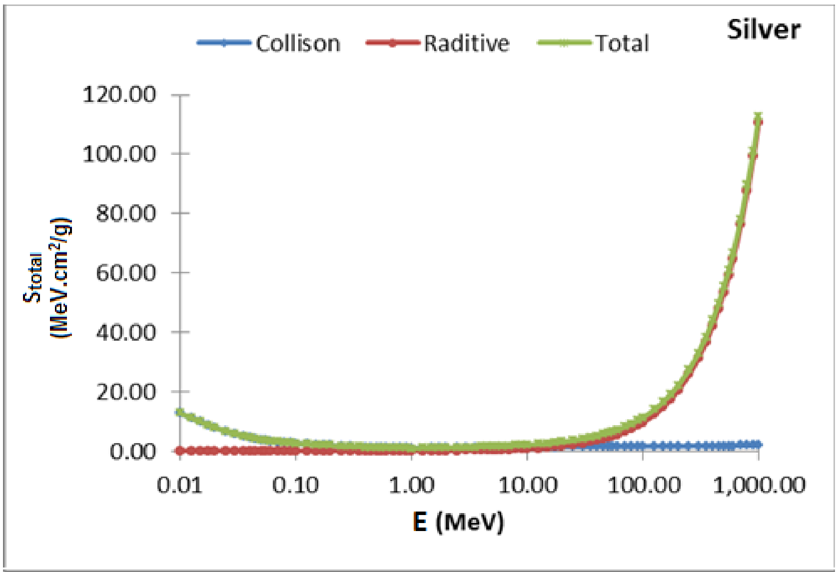
Fig(1) Comparison of the Total Stopping Power of Carbon of present work with ICRU



Fig(2) Collision, Radiative and total stopping power of Carbon



Fig(3) Comparison of the Total Stopping Power of Silver of present work with ICRU



Fig(4) Collision, Radiative and total stopping power of Silver

3.2 Discussion of R_{CSDA} ranges:

R_{CSDA} represents the total path length which the particle would travel into the absorber material during slow down process in homogenous medium from the initial to final zero kinetic energy.

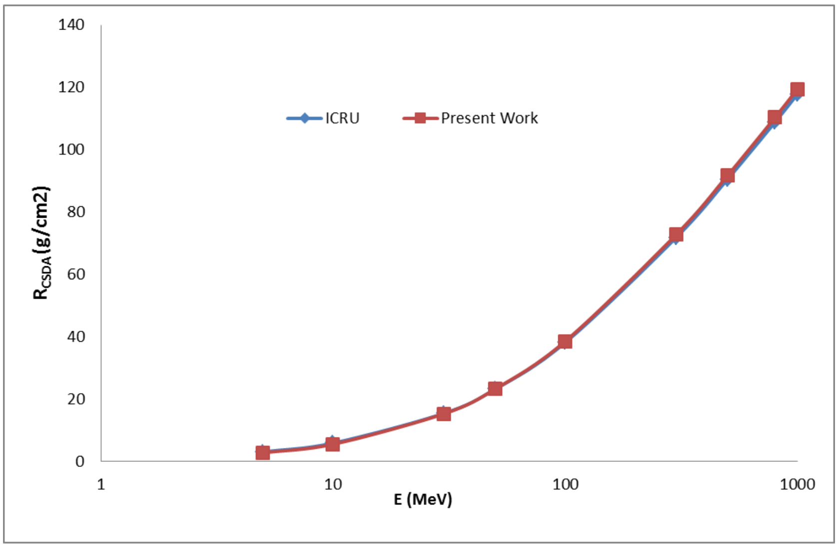
Tables (6 and 7) and figures (5 and 6) represent R_{CSDA} of C and Ag in the energy range (5-1000) MeV by employing equations (20, 21) respectively. These values are mean quantities resulting from large number of individual interactions which involve transfering a small energy at small angles. The tending to increase as Z increases due to effect of multiple scattering, is responsible for reducing the Colomb attraction and increasing R_{CSDA} .

Table(6): Comparison of the values of R_{CSDA} range of positron (g/cm^2) in Carbon

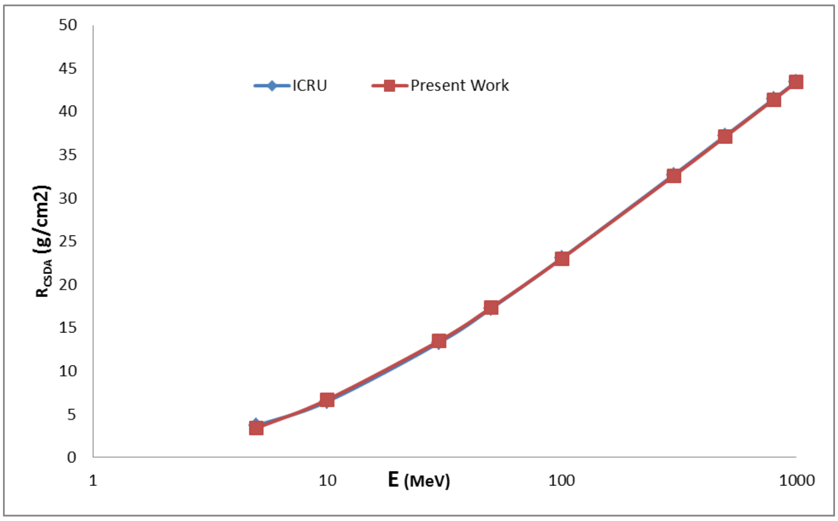
E(MeV)	R_{CSDA}	Present Work/ C	Error %
5	2.975	2.7092	9.81
10	5.8	5.4654	6.12
30	15.35	15.2247	0.82
50	23.13	23.2096	0.34
100	38.08	38.4853	1.05
300	71.75	72.6603	1.25
500	90.5	91.6737	1.28
800	108.8	110.2885	1.35
1000	117.8	119.3999	1.34

Table(7): Comparison of the values of R_{CSDA} range of positron (g/cm^2) in Silver

E(MeV)	R_{CSDA}	Present Work/ Ag	Error %
5	3.692	3.416	8.08
10	6.487	6.7002	3.18
30	13.3	13.497	1.46
50	17.25	17.3499	0.58
100	23.05	23.0193	0.13
300	32.69	32.5828	0.33
500	37.25	37.1505	0.27
800	41.46	41.3873	0.18
1000	43.46	43.4065	0.12



Fig(5) Comparsion of R_{CSDA} range of positron in Carbon



Fig(6) Comparsion of R_{CSDA} range of positron in Silver

Conclusions

1. Total stopping power is a function to the kinetic energy of the incident particle and atomic number Z of target material.
2. The range tends to increase as the incident energy are increasing. In other words, as Z increases, the multiple scattering of the positrons increases.
3. The behavior of the positron during penetration throughout matter is the same as electron behavior in regard to loss of energy.
4. When the positron energies exceed a few tens of MeV, the dominant mechanism of energy loss is by emitting photons, i,e., by *rediative energy loss*.
5. Total stopping power values for positrons decreases as atomic number Z of absorber element increases.

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تقدير خسارة الطاقة الكلية ومدى التباطؤ المستمر للبوزترونات في الكاربون والفضة

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الملخص

في الدراسة الحالية، تم حساب قدرة الايقاف الكلية (S_{rad} , S_{coll}) للبوزترونات في مدى الطاقة (0.02 – 50) ميكا الكترون فولت باستخدام المعادلات شبه التجريبية لموديل بي – بال و جماعته لعنصري الكاربون والفضة، كما وتم حساب المدى التقريبي للتباطؤ المستمر R_{CSDA} للبوزترونات بطاقة (5 – 1000) ميكا الكترون فولت باستخدام موديل اخر لـ بي– بال و جماعته، ولنفس العنصرين. القيم التي حصلنا عليها اثبت تطابقاً جيداً عند مقارنتها مع قيم ICRU .

الكلمات المفتاحية: قدرة الايقاف الكلية ، تصادمية ، اشعاعية ، متوسط جهد التأين ، الكاربون ، الفضة ، تقريب مدى التباطئ المستمر .