RESEARCH ARTICLE

A Theoretical Study of Stopping Power and Range For Low Energy (<3.0mev) Protons In Aluminium, Germanium, Lead, Gold and Copper Solid Materials

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Abstract

A new empirical relation was obtained by modifying an empirical relation deduced by Chaubey (1977) based on Bohr's classical mechanics by using least squared fitting method for stopping powers from 0.20MeV to 2.90MeV protons in Aluminium (Al), Germanium (Ge), Lead (Pb), Gold (Au) and Copper (Cu) solid target materials and the results compared with some available experimental values and earlier investigations as well as PSTAR and SRIM (2013) results. The proton range relation was obtained by directly integrating the stopping power formula and the values of the ranges for the elements are calculated and compared with PSTAR and Janni (1982) values. The calculated stopping powers and range values were in excellent agreement with the experimental values of Bichsel since the percentage uncertainty was within 10% and the theoretical values of Janni (1982) and, the PSTAR and SRIM-2013 codes generated values had the percentage difference approximately within 10%. The cross section was also calculated and the results discussed. The practical applications of the stopping power, range and cross section values of the selected materials are discussed.

Introduction

Interest in experimental and theoretical studies of stopping power and range of particles in different materials have increased tremendously in recent years. When charged particles interact with matter, as a result of continuous collision, the charged particles lost energy. The average of these energy loss per unit path length is known as stopping power, which plays an important role in many fields such as structure analysis of solid target by Rutherford backscattering spectroscopy (RBS), Proton induced X-ray emission (PIXE), Proton Induced Gamma emission (PIGE), plasma-first wall interactions in nuclear-fusion reactor and others.

The range is the mean path length a charged particle travels in target matter before coming to rest. When a proton enters into a medium it immediately interacts simultaneously with many electrons. In any one encounter the electron feels an impulse from the attractive coulomb forces as the particle passes its vicinity. This impulse may be sufficient either to raise the electron to a higher level shell within the target atom (excitation) or to remove completely the electron from the atom (ionization). The energy that is transferred to the electron come at the expense of the charged particle, and its velocity is therefore, decreased as a result of inelastic collision. The maximum energy that can be transferred from a charged particle of mass, m with kinetic energy, E to an electron of mass, m_e in a single collision is given by the expression;

$$\frac{4Em_e}{m}$$

Because, this is a small fraction of the total energy, the primary particle must lose its energy in many such interactions during its passage through matter. At any given time the particle is interacting with many electrons, so the net effect is to decrease its velocity continuously until the particle is completely stopped.

Stopping power of any particle is the mean average energy loss by the particle per unit path length and this is designated by the expression;

$$-\frac{dE}{dx}$$

It is measured for example in MeV/cm.

The stopping power depends on the properties of the material the particle is passing through, as well as the type and energy of the particle. Since the production of an ion pair requires specific fixed amount of energy, the density of ionization along the path is proportional to the stopping power of the material. Stopping power therefore refers to the property of the material while energy loss per unit path length describes what happens to the particle.

For the past few decades, there have been quite a number of reviews of stopping power theory and a few tabulations of numerical stopping powers. Bohr (1948) earliest reviews of the stopping power and later discussions and summaries

have been done by Rossi (1952), Bethe and Ashkin (1953). Two reviews by Fano (Fano, 1956 and Fano, 1964) and Northcliffe (1963) on light and heavy-ion stopping, respectively, summarize the state of the art at the time. This was followed by Ahlen (1980) and a summary by Evans (1955). Jackson (1975) includes a clear treatment of energy loss. Berger and Seltzer (1982) include both electron and heavy ion energy loss treatment. The general review by Ziegler et al. (1985) is widely referenced and contains an excellent historical summary, as do Ziegler (Ziegler, 1999] and the online SRIM site (SRIM, 2003). Special attention has been given to the lightest ions, with discussion or data presented by Andersen and Ziegler (1977), Ziegler (Ziegler, 1977, 1999a), Kaneko (Kaneko, 1993), International Commission on Radiation Units and Measurement ICRU (1993), etc. Widely cited, older compilations are by Barkas and Berger (Barkas, 1964), Bichsel and Tschalaer (Bichsel, 1967), Northcliffe and Schilling (Northcliffe, 1970), and Janni [Janni-1966, 1982a, 1982b). More recent ones are by Hubert et al. (Hubert, 1990) and by Paul and Schinner (Paul, 2003]. Scott (Scott, 1963) has reviewed the effects of multiple small angles scattering on the penetration of heavy ions. .

Experimental measurements of stopping power, current computer codes, and tabulated data compilations do not always agree. The theory of ion stopping power is still evolving, but it is generally thought that calculated stopping powers can be believed to be about 1% for energies above 1 MeV (Fano, 1963), and, for light ions, a few percent at the lower energies (Ziegler, 1999a). One may follow a discussion of differences concerning two main databases, NIST and SRIM, for example, (Ziegler, 1999b] and (Seltzer, 2001). Paul and Schinner (2003b) have presented a recent comparison of data with tables and codes, although it is not clear that the latest version of SRIM was used in their comparison. At low energies, some alpha particle stopping power calculations differed by several percent from SRIM 2000 to SRIM 2013. In spite of the enormous amount of work devoted to the subject, it is still not possible to accurately calculate ion stopping power truly from first principles. Phenomenological parameters are required to pin the calculations to data. For example, the mean ionization potential is often adjusted empirically.

Methods

Empirical relation for stopping power

The empirical relation which was deduced by Chaubey (1977) for stopping power (for the energy range of 0.7 to 12MeV/amu):

$$\left(-\frac{dE}{\rho dx}\right) = \frac{a}{A} E^{-b} Z^{c\log E + d} \qquad 1.0$$

Where the appropriate values of the constants **a, b, c,** and **d** were 915, 0.84, 0.145 and 0.635 respectively and ρ = density, Z = atomic number, A = mass number of the target material and E denote the kinetic energy of the projectile in MeV.

The equation (1) was modified by fitting the Northcliffe and Schilling (1970) data using least squares method and the constants **a, b** and **c** in the relation are replaced by new constants but **b** was kept constant.

$$\left(-\frac{dE}{\rho dx}\right) = \frac{1000}{A} E^{-0.84} Z^{0.233\log E + 0.54} \qquad 2.0$$

The new relation obtained was used to calculate the stopping power of protons of energy 0.20MeV to 2.99MeV. The range relation was derived by integrating numerically the reciprocal of the stopping power formula.

Range relation

The range of proton in matter is calculated simple numerical integration of the reciprocal of the stopping power. The range R_p is given as;

$$R_p = \int_{E_0}^{E_1} \left(-\frac{dE}{\rho dx}\right)^{-1} dE \qquad 3.0$$

The range R_p in the continuous slowing down approximation (csda) is give as

$$R_p = \int_{E_0}^{E_1} \left(-\frac{dE}{\rho dx}\right)^{-1} dE + R(E_0) \qquad 4.0$$

Where $R(E_0)$ is the measured range at the minimum proton energy E_0 which is added to the integral equation (3) and is treated as a constant for a particular particle and material.

In the calculation of ranges for protons in matter, we consider E_0 as 0.20MeV and equation (2) was substitute into equation (4) and by converting the energy units from MeV to MeV/amu we had:

$$R_p = \int_{E_0}^{E_1} m_p \left(\frac{1000}{A} E^{-0.84} Z^{0.233\log E + 0.54}\right)^{-1} dE + R(E_0) \qquad 5.0$$

Where m_p is the mass of the proton.

By integrating and replacing the values of the constants **a, b, c** and **d**, we obtained:

$$R = m_p \left[\frac{1}{1000 \times 1.84 \times Z^{0.54}\left(1 - \frac{0.233\log Z}{1.84}\right)}\right] \times \left[E^{1.84} \times Z^{-0.233\log E} - E_0^{1.84} \times Z^{-0.233\log E_0}\right]$$

$$+ R(E_0) \qquad 6.0$$

Results and discussions

Results

Using the new empirical relations given in the equations above, we have computed the stopping powers and ranges from 0.20MeV to 2.90MeV for Aluminium (Al), Copper (Cu), Germanium (Ge), Lead (Pb) and Gold (Au). The measured range $R(E_0)$ values were taken from the literature and are tabulated in table 1.0 with their references. Figures 1 to 5 shows the stopping powers and proton energies whilst figure 6 to 10 indicates the ranges and proton energies in Al, Cu, Ge, Pb and Au.

Table 1 : Showing the proton energy in MeV and the stopping power for values for Aluminium and Copper in MeV/g/cm²

E/MeV	Stopping power in MeV/g/cm² for Aluminium (Al)									Stopping power in MeV/g/cm² for Copper (Cu)								
	Bichsel	This Work	% T	Janni-1982	% J	SRIM-2013	% S	PSTAR	% P	Bichsel	This Work	% T	Janni-1982	% J	SRIM-2013	% S	PSTAR	% P
0.20	344.00	432.84	-25.83	359.36	-4.47	373.00	-8.43	371.00	-7.85	221.00	259.74	-17.53	213.74	3.29	211.80	4.16	205.10	7.19
0.30	310.00	342.07	-10.35	310.75	-0.24	317.80	-2.52	321.50	-3.71	201.00	212.14	-5.54	197.27	1.86	195.10	2.94	192.30	4.33
0.40	279.00	289.46	-3.75	276.94	0.74	279.20	-0.07	284.20	-1.86	183.00	183.76	-0.42	179.95	1.67	178.80	2.30	178.60	2.40
0.50	252.00	254.30	-0.91	251.35	0.26	250.80	0.48	254.80	-1.11	168.00	164.39	2.15	164.56	2.05	164.60	2.02	165.80	1.31
0.60	230.00	228.76	0.54	230.67	-0.29	228.90	0.48	231.40	-0.61	155.00	150.08	3.17	151.49	2.26	152.50	1.61	153.60	0.90
0.70	212.00	209.18	1.33	213.16	-0.55	211.50	0.24	212.40	-0.19	144.00	138.97	3.49	140.54	2.40	142.10	1.32	142.70	0.90
0.80	197.00	193.58	1.74	196.53	0.24	197.20	-0.10	196.60	0.20	135.00	130.00	3.70	131.71	2.44	133.30	1.26	133.30	1.26
0.90	185.00	180.79	2.28	182.94	1.11	185.20	-0.11	183.30	0.92	128.00	122.58	4.23	124.38	2.83	125.60	1.88	125.20	2.19
1.00	173.00	170.06	1.70	171.58	0.82	174.90	-1.10	171.90	0.64	121.00	116.30	3.88	118.18	2.33	118.90	1.74	118.30	2.23
1.10	163.00	160.91	1.28	-	-	165.40	-1.47	162.00	0.61	114.00	110.89	2.73	-	-	113.10	0.79	112.40	1.40
1.20	155.00	152.98	1.30	-	-	155.80	-0.52	153.30	1.10	109.00	106.18	2.59	-	-	107.30	1.56	107.20	1.65
1.30	147.00	146.04	0.65	-	-	147.80	-0.54	145.70	0.88	104.00	102.02	1.90	-	-	102.50	1.44	102.50	1.44
1.40	140.00	139.89	0.08	-	-	140.80	-0.57	138.80	0.86	99.00	98.32	0.69	-	-	98.29	0.72	98.22	0.79
1.50	134.30	134.40	-0.07	133.31	0.74	134.60	-0.22	132.70	1.19	95.00	94.99	0.01	95.52	-0.55	94.47	0.56	94.43	0.60
1.60	129.00	129.46	-0.36	-	-	128.90	0.08	127.20	1.40	92.00	91.97	0.03	-	-	91.01	1.08	91.02	1.07
1.70	-	124.98	-	-	-	123.80	-	122.10	-	-	89.23	-	-	-	87.84	-	87.91	-
1.80	119.00	120.90	-1.60	-	-	119.10	-0.08	117.50	1.26	80.00	86.72	-8.40	-	-	84.93	-6.16	85.05	-6.31
1.90	-	117.17	-	-	-	114.90	-	113.30	-	-	84.41	-	-	-	82.34	-	82.38	-
2.00	110.70	113.73	-2.74	110.27	0.39	110.80	-0.09	109.40	1.17	-	82.28	-	80.30	-	79.75	-	79.87	-
2.10	-	110.55	-	-	-	107.30	-	105.80	-	-	80.30	-	-	-	77.54	-	77.50	-
2.20	-	107.61	-	-	-	103.90	-	102.50	-	-	78.45	-	-	-	75.34	-	75.29	-
2.30	-	104.87	-	-	-	100.70	-	99.38	-	-	76.73	-	-	-	73.30	-	73.24	-
2.40	-	102.31	-	-	-	97.76	-	96.48	-	-	75.12	-	-	-	71.43	-	71.34	-
2.50	94.70	99.91	-5.50	94.61	0.10	94.86	-0.17	93.77	0.98	70.00	73.60	-5.14	69.92	0.11	69.56	0.63	69.55	0.64
2.60	-	97.66	-	-	-	92.39	-	91.23	-	-	72.18	-	-	-	67.94	-	67.87	-
2.70	-	95.55	-	-	-	89.92	-	88.84	-	-	70.83	-	-	-	66.32	-	66.28	-
2.80	-	93.55	-	-	-	87.62	-	86.58	-	-	69.55	-	-	-	64.81	-	64.77	-
2.90	-	91.67	-	-	-	85.49	-	84.46	-	-	68.35	-	-	-	63.40	-	63.32	-

Where % T, % J, % S and % P represents the percentage difference of This work, Janni-1982, SRIM-2013 and PSTAR values from Bichsel stopping power values respectively.

Table 2 : Showing the proton energy in MeV and the stopping power for values for Lead and Germanium in MeV/g/cm²

E/MeV	Stopping Power in MeV/g/cm² for Lead							Stopping Power in MeV/g/cm² for Germanium						
	This Work	Janni-1982	% J	SRIM-2013	% S	PSTAR	% P	This Work	Janni-1982	% J	SRIM-2013	% S	PSTAR	% P
0.20	124.71	121.79	2.34	122.10	2.09	126.30	-1.27	237.17	215.87	8.98	215.20	9.26	211.60	10.78
0.30	106.29	109.46	-2.98	110.50	-3.96	113.30	-6.60	194.49	191.75	1.41	190.90	1.85	189.00	2.82
0.40	94.90	98.30	-3.58	98.99	-4.31	99.98	-5.35	168.96	173.91	-2.93	172.30	-1.98	172.30	-1.98
0.50	86.91	89.34	-2.80	89.50	-2.98	89.50	-2.98	151.48	160.20	-5.76	157.60	-4.04	158.80	-4.83
0.60	80.88	82.20	-1.63	81.91	-1.27	81.37	-0.61	138.55	149.17	-7.67	145.60	-5.09	146.60	-5.81
0.70	76.12	76.45	-0.43	75.77	0.46	75.05	1.41	128.49	139.95	-8.92	135.60	-5.53	135.70	-5.61
0.80	72.21	71.50	0.98	70.70	2.09	70.08	2.95	120.36	132.04	-9.70	127.10	-5.60	126.30	-4.94
0.90	68.94	67.40	2.23	66.44	3.63	66.12	4.09	113.62	125.42	-10.39	119.80	-5.44	118.30	-4.12
1.00	66.14	63.94	3.33	62.79	5.07	62.92	4.87	107.91	119.79	-11.01	113.50	-5.18	111.30	-3.14
1.10	63.70	-	-	60.37	-	60.25	5.42	102.99	-	-	108.10	-	105.30	-2.24
1.20	61.55	-	-	58.04	-	57.94	5.87	98.70	-	-	102.70	-	100.10	-1.42
1.30	59.64	-	-	55.97	-	55.86	6.34	94.91	-	-	98.18	-	95.49	-0.61
1.40	57.92	-	-	54.11	-	53.96	6.84	91.53	-	-	94.15	-	91.41	0.13
1.50	56.37	51.78	8.14	52.39	7.06	52.22	7.36	88.49	98.02	-10.77	90.50	-2.27	87.77	0.81
1.60	54.95	-	-	50.80	-	50.62	7.88	85.74	-	-	87.18	-	84.50	1.45
1.70	53.66	-	-	49.33	-	49.15	-	83.23	-	-	84.14	-	81.55	-
1.80	52.46	-	-	47.97	-	47.79	8.90	80.94	-	-	81.34	-	78.88	2.55
1.90	51.36	-	-	46.74	-	46.52	-	78.83	-	-	78.86	-	76.43	-
2.00	50.33	45.43	9.74	45.50	9.60	45.34	9.91	76.87	81.87	-6.50	76.37	-	74.18	-
2.10	49.37	-	-	44.44	-	44.23	-	75.06	-	-	74.25	-	72.09	-
2.20	48.47	-	-	43.37	-	43.19	-	73.37	-	-	72.14	-	70.13	-
2.30	47.63	-	-	42.37	-	42.20	-	71.79	-	-	70.18	-	68.29	-
2.40	46.84	-	-	41.45	-	41.28	-	70.31	-	-	68.39	-	66.54	-
2.50	46.09	40.71	11.67	40.53	12.06	40.40	12.35	68.92	70.80	-2.73	66.59	3.38	64.89	5.85
2.60	45.38	-	-	39.72	-	39.57	-	67.61	-	-	65.04	-	63.32	-
2.70	44.71	-	-	38.91	-	38.78	-	66.37	-	-	63.50	-	61.83	-
2.80	44.08	-	-	38.15	-	38.03	-	65.20	-	-	62.05	-	60.42	-
2.90	43.47	-	-	37.44	-	37.31	-	64.09	-	-	60.70	-	59.09	-

Where % T, % J, % S and % P represents the percentage difference of This work, Janni-1982, SRIM-2013 and PSTAR values from Bichsel stopping power values respectively

Table 3: Showing the proton energy in MeV and the stopping power for values for Gold in MeV/g/cm²

|				Stopping Power in MeV/g/cm² for Gold					
E/MeV	Bichsel	Janni-1982	% J.	SRIM-2013	% S.	PSTAR	% P.	This Work	% T.
0.20	119.00	111.45	6.34	111.10	6.64	109.60	7.90	129.09	-8.48
0.30	110.00	103.97	5.48	101.90	7.36	101.00	8.18	109.85	0.13
0.40	98.80	94.84	4.01	93.24	5.63	91.80	7.09	97.97	0.84
0.50	88.00	86.58	1.61	86.07	2.19	84.05	4.49	89.65	-1.88
0.60	81.00	79.69	1.62	80.04	1.19	78.00	3.70	83.38	-2.94
0.70	75.00	74.14	1.15	74.84	0.21	73.18	2.43	78.42	-4.56
0.80	70.00	69.75	0.36	70.30	-0.43	69.21	1.13	74.36	-6.23
0.90	66.00	66.10	-0.15	66.28	-0.42	65.83	0.26	70.96	-7.51
1.00	63.00	62.99	0.02	62.70	0.48	62.91	0.14	68.04	-8.01
1.10	59.60	-	-	60.51	-1.53	60.34	-1.24	65.51	-9.92
1.20	57.00	-	-	58.42	-2.49	58.04	-1.82	63.28	-11.02
1.30	54.30	-	-	56.48	-4.01	55.98	-3.09	61.30	-12.89
1.40	52.50	-	-	54.67	-4.13	54.10	-3.05	59.52	-13.37
1.50	50.50	52.61	-4.18	52.98	-4.91	52.39	-3.74	57.91	-14.67
1.60	49.00	-	-	51.40	-4.90	50.82	-3.71	56.44	-15.18
1.70	-	-	-	49.93	-	49.36	-	55.09	-
1.80	-	-	-	48.56	-	48.02	-	53.86	-
1.90	-	-	-	47.32	-	46.76	-	52.71	-
2.00	44.00	46.24	-5.09	46.08	-4.73	45.58	-3.59	51.64	-17.37
2.10	-	-	-	45.00	-	44.48	-	50.65	-
2.20	-	-	-	43.92	-	43.44	-	49.72	-
2.30	-	-	-	42.91	-	42.47	-	48.85	-
2.40	-	-	-	41.98	-	41.55	-	48.03	-
2.50	39.80	41.47	-	41.04	-3.12	40.67	-2.19	47.26	-18.74
2.60	-	-	-	40.22	-	39.84	-	46.53	-
2.70	-	-	-	39.41	-	39.06	-	45.83	-
2.80	-	-	-	38.64	-	38.31	-	45.17	-
2.90	-	-	-	37.92	-	37.6	-	44.55	-
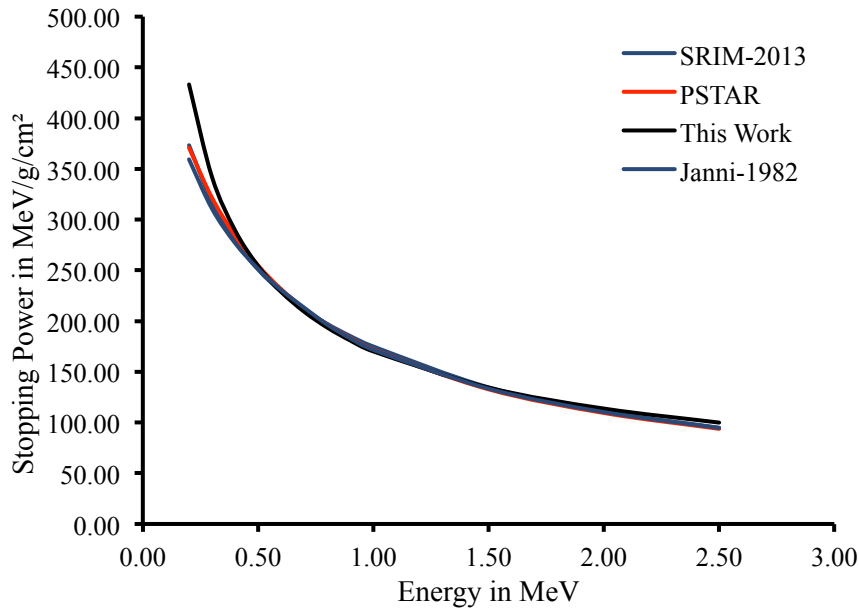
Figure 1: A graph of Stopping Power of protons versus energy in Aluminium for Janni-1982, SRIM-2013, PSTAR codes and New Empirical relation.
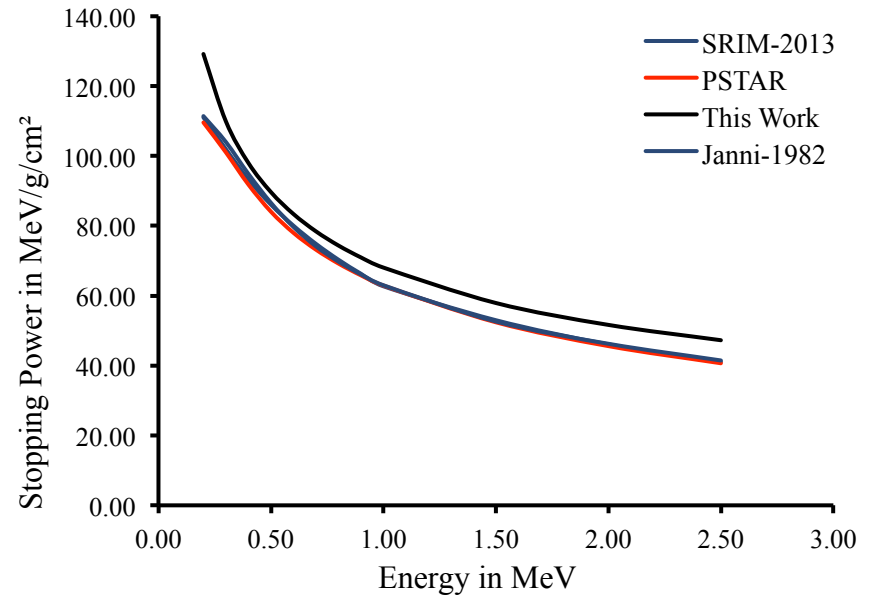

Figure 2: A graph of Stopping Power of protons versus energy in Copper for Janni-1982, SRIM-2013, PSTAR codes and Modified Empirical relation.
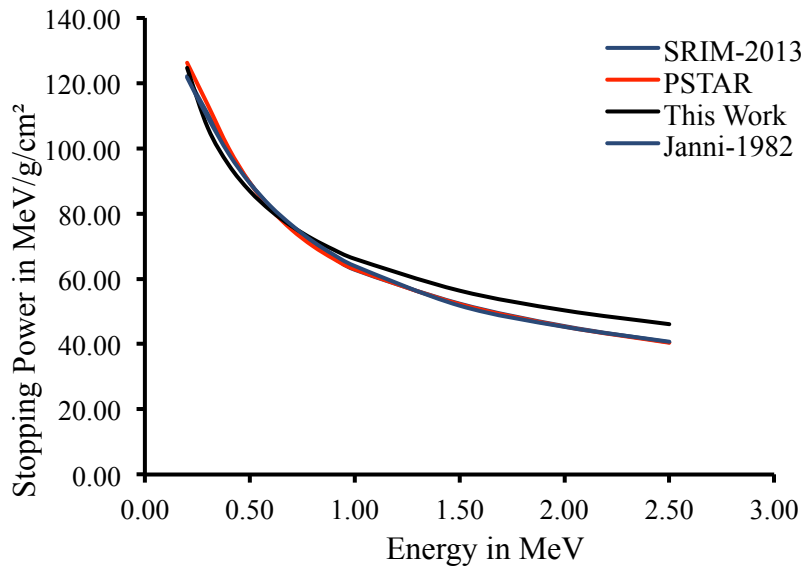

Figure 3: A graph of Stopping Power of protons versus energy in Lead for Janni-1982, SRIM-2013, PSTAR codes and New Empirical relation.
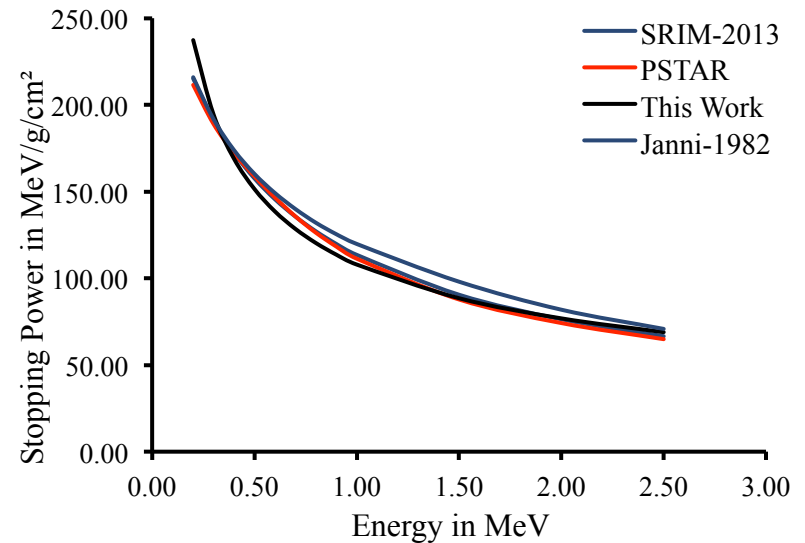

Figure 4: A graph of Stopping Power of protons versus energy in Germanium for Janni-1982, SRIM-2013, PSTAR codes and New Empirical relation.
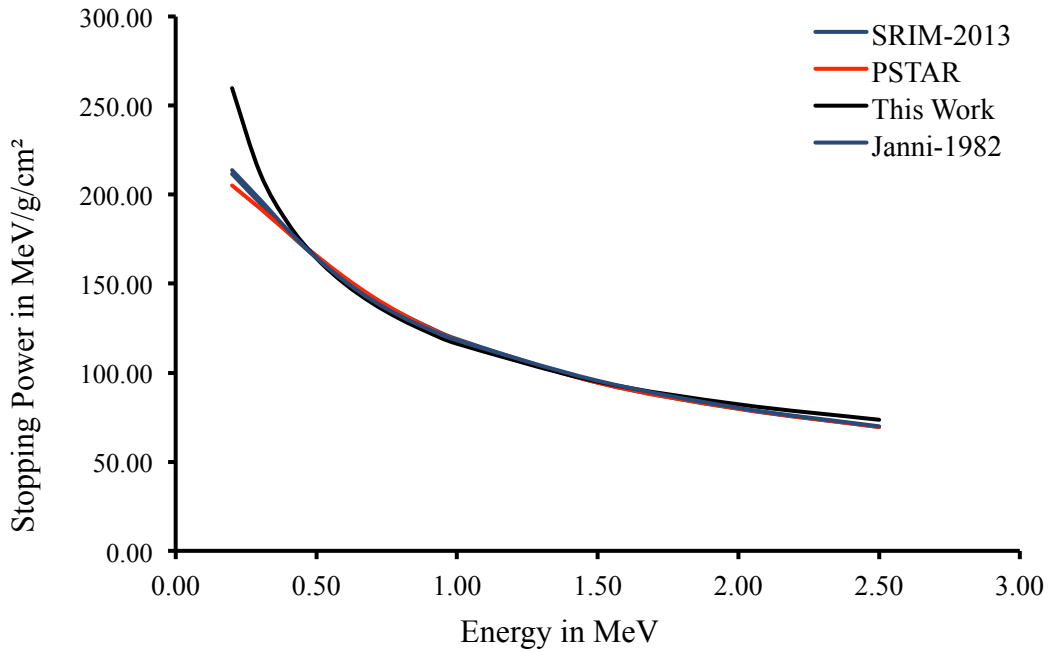
Figure 5: A graph of Stopping Power of protons versus energy in Copper
for Janni-1982, SRIM-2013, PSTAR codes and New Empirical

Comparison of the empirical stopping power values with previews researchers/Authors

The percentage difference between the stopping power values calculated using equation (2) and the other values obtained from SRIM-2013 and PSTAR codes, and also the Janni-1982 and Bichsel experimental values are shown in table 1 to 3 and also illustrated graphically in figure 1 to 5 for Aluminium, Copper, Germanium, Lead and Gold.

Table 1 and 3 shows Bichsel experimental stopping power values compared to the calculated values and to that of Janni-1982, SRIM-2013 and PSATR codes whilst table 2 indicates the comparison of the calculated stopping power values with Janni-1982, SRIM-2013 and PSTAR codes values. From table 1, the maximum percentage difference of the Janni-1982 stopping values, SRIM code, PSTAR code and this work values from Bichsel experimental values are approximately 4%, 8%, 8% and 26% both occurred at the 0.20MeV proton energy whilst the minimum percentage deviation is 0.1% observed at 2.50MeV, 0.07% at 0.40MeV, 0.20% at 0.80MeV and 0.07% at 1.50MeV respectively for aluminium target. For Copper target, the minimum percentage difference of the Janni-1982 stopping values, SRIM code, PSTAR code and this work values from Bichsel experimental values are approximately 0.11%, 0.56%, 0.60% and 0.01% both occurred at the 1.50MeV proton energy except Janni-1982 which occurred at 2.50MeV whilst the maximum percentage deviation is 3.29% observed at 0.20MeV, 6.16% at 1.80MeV, 7% at 0.20MeV and 17.53% at 0.20MeV respectively.

For table 2, because of lack of enough experimental data, we compared the calculated stopping power values with Janni-1982, SRIM-2013 code values and PSTAR code values for Lead and Germanium. From the table, The minimum percentage difference of the calculated stopping power values from Janni-1982, SRIM-2013 and PSTAR codes stopping power values are approximately 0.43%, 0.46% both occurred at 0.70MeV and 0.61% which occurred at the 0.60MeV proton energy whilst the maximum percentage deviation is 11.67%, 12.06% and 12.35% all observed at 2.50MeV respectively for lead target. For Germanium target, the minimum percentage difference of the Janni-1982 stopping values, SRIM-2013 and PSTAR codes values from this work values are approximately 1.41%, 1.85% both are observed at 0.30MeV and 0.13% at the 1.40MeV proton energy whilst the maximum percentage deviation is 11.01% observed at 1.00MeV, 5.60% at 0.80MeV and 10.78% at 0.20MeV respectively.

The table 3 indicates the Bichsel experimental stopping power values compared to the calculated values and to that of Janni-1982, SRIM-2013 and PSATR codes values for Gold. The minimum percentage difference of the Janni-1982 stopping values, SRIM code, PSTAR code and this work values from Bichsel experimental values are approximately 0.02% at 1.00MeV, 0.21% at 0.70MeV, 0.14% at 1.00MeV and 0.13% which occurred at the 0.30MeV proton energy whilst the maximum percentage deviation is 6.34% observed at 0.20MeV, 7.36% at 0.30MeV, 8.18% at 0.30MeV and 18.74% at 2.50MeV respectively.

The figures illustrate the graphical representation of the stopping power values and the proton energies. The figures indicate the same trend of decreasing proton leading to increasing stopping power values.

Table 4: Proton Range for AL, Au and Ge for proton energy 0.2MeV to 2.9MeV

	Aluminium					Germanium					Gold				
E/MeV	Janni-1982	% J.	PSTAR	% P.	This Work	Janni-1982	% J.	PSTAR	% P.	This Work	Janni-1982	%. J.	PSTAR	This Work	% P.
0.20	0.49	0.00	0.51	3.92	0.49	0.81	0.00	0.95	14.83	0.81	1.50	0.00	2.35	1.50	36.17
0.30	0.79	4.47	0.80	5.67	0.75	1.28	-0.25	1.45	11.62	1.28	2.31	-1.82	3.29	2.35	28.51
0.40	1.12	3.87	1.13	4.72	1.08	1.81	-1.75	2.01	8.19	1.84	3.22	-3.32	4.33	3.33	23.17
0.50	1.50	3.38	1.50	3.38	1.45	2.40	-3.05	2.61	5.27	2.47	4.23	-4.12	5.47	4.40	19.48
0.60	1.91	2.19	1.92	2.70	1.87	3.03	-4.63	3.27	2.93	3.17	5.34	-4.34	6.71	5.57	16.96
0.70	2.36	1.29	2.37	1.70	2.33	3.70	-6.13	3.98	1.22	3.93	6.54	-4.28	8.03	6.82	15.07
0.80	2.84	0.31	2.86	1.01	2.83	4.42	-7.19	4.74	0.00	4.74	7.84	-3.83	9.43	8.14	13.67
0.90	3.37	-0.01	3.38	0.28	3.37	5.18	-8.12	5.56	-0.80	5.60	9.22	-3.35	10.91	9.53	12.66
1.00	3.93	-0.40	3.95	0.11	3.95	5.98	-8.89	6.43	-1.30	6.51	10.67	-2.91	12.47	10.98	11.95
1.10	-	-	4.55	-0.12	4.56	-	-	7.35	-1.59	7.47	-	-	14.09	12.49	11.35
1.20	-	-	5.18	-0.35	5.20	-	-	8.32	-1.73	8.47	-	-	15.78	14.06	10.92
1.30	-	-	5.85	-0.39	5.87	-	-	9.35	-1.74	9.51	-	-	17.53	15.68	10.58
1.40	-	-	6.55	-0.43	6.58	-	-	10.42	-1.65	10.59	-	-	19.35	17.34	10.36
1.50	7.25	-0.88	7.29	-0.32	7.31	10.52	-11.33	11.53	-1.58	11.71	18.93	-0.70	21.22	19.06	10.17
1.60	-	-	8.06	-0.22	8.08	-	-	12.69	-1.41	12.87	-	-	23.16	20.83	10.08
1.70	-	-	8.86	-0.12	8.87	-	-	13.90	-1.17	14.06	-	-	25.16	22.63	10.04
1.80	-	-	9.69	-0.01	9.69	-	-	15.14	-1.00	15.29	-	-	27.21	24.48	10.02
1.90	-	-	10.56	0.21	10.54	-	-	16.43	-0.75	16.55	-	-	29.32	26.38	10.04
2.00	11.37	-0.36	11.46	0.43	11.41	16.04	-11.27	17.76	-0.50	17.85	28.59	0.98	31.48	28.31	10.07
2.10	-	-	12.39	0.64	12.31	-	-	19.13	-0.24	19.18	-	-	33.70	30.28	10.15
2.20	-	-	13.35	0.86	13.23	-	-	20.53	-0.02	20.53	-	-	35.98	32.29	10.26
2.30	-	-	14.34	1.09	14.18	-	-	21.97	0.21	21.92	-	-	38.30	34.33	10.36
2.40	-	-	15.36	1.32	15.16	-	-	23.46	0.50	23.34	-	-	40.68	36.41	10.48
2.50	16.25	0.59	16.41	1.56	16.15	22.55	-9.93	24.98	0.76	24.79	39.58	2.65	43.11	38.53	10.62
2.60	-	-	17.49	1.80	17.17	-	-	26.54	1.03	26.27	-	-	45.59	40.68	10.77
2.70	-	-	18.60	2.05	18.22	-	-	28.13	1.27	27.77	-	-	48.13	42.86	10.94
2.80	-	-	19.74	2.31	19.28	-	%.	29.77	1.56	29.30	-	%.	50.71	45.08	11.10
2.90	-	-	20.91	2.57	20.37	-	-	31.44	1.83	30.86	-	-	53.34	47.33	11.27

Table 5: Proton Range for Copper and Lead for proton energy 0.2MeV to 2.9MeV

| E/MeV	Copper					Lead				
	Janni-1982	% J.	PSTAR	% P.	This Work	Janni-1982	% J.	PSTAR	% P.	This Work
0.20	0.90	0.00	1.13	20.35	0.90	1.40	0.00	2.15	35.00	1.40
0.30	1.36	1.98	1.63	18.32	1.33	2.17	-5.12	2.99	23.58	2.28
0.40	1.87	1.29	2.17	14.98	1.85	3.04	-8.16	3.93	16.23	3.29
0.50	2.44	0.52	2.75	11.80	2.43	4.02	-9.46	4.98	11.70	4.40
0.60	3.06	-0.33	3.38	9.11	3.07	5.10	-9.88	6.16	8.95	5.60
0.70	3.73	-1.04	4.05	7.01	3.77	6.27	-9.89	7.44	7.33	6.89
0.80	4.45	-1.56	4.78	5.41	4.52	7.54	-9.42	8.81	6.39	8.25
0.90	5.21	-2.09	5.55	4.20	5.32	8.88	-9.01	10.28	5.84	9.68
1.00	6.02	-2.38	6.37	3.29	6.16	10.31	-8.37	11.83	5.55	11.17
1.10	-	-	7.24	2.61	7.05	-	-	13.46	5.45	12.73
1.20	-	-	8.15	2.09	7.98	-	-	15.15	5.37	14.34
1.30	-	-	9.11	1.71	8.95	-	-	16.90	5.32	16.00
1.40	-	-	10.10	1.42	9.96	-	-	18.73	5.41	17.72
1.50	10.67	-3.09	11.14	1.26	11.00	18.55	-5.02	20.61	5.48	19.48
1.60	-	-	12.22	1.16	12.08	-	-	22.55	5.58	21.29
1.70	-	-	13.33	1.04	13.19	-	-	24.56	5.74	23.15
1.80	-	-	14.49	1.05	14.34	-	-	26.62	5.90	25.05
1.90	-	-	15.68	1.05	15.52	-	-	28.74	6.08	26.99
2.00	16.32	-2.48	16.92	1.15	16.73	28.38	-2.09	30.91	6.26	28.97
2.10	-	-	18.19	1.23	17.97	-	-	33.14	6.47	31.00
2.20	-	-	19.50	1.36	19.24	-	-	35.43	6.70	33.06
2.30	-	-	20.84	1.46	20.53	-	-	37.77	6.92	35.16
2.40	-	-	22.22	1.61	21.86	-	-	40.17	7.17	37.29
2.50	22.92	-1.30	23.64	1.78	23.22	39.49	0.08	42.61	7.39	39.46
2.60	-	-	25.10	1.99	24.60	-	-	45.11	7.64	41.66
2.70	-	-	26.59	2.18	26.01	-	-	47.66	7.89	43.90
2.80	-	-	28.11	2.36	27.45	-	-	50.27	8.15	46.17
2.90	-	-	29.67	2.56	28.91	-	-	52.92	8.40	48.47
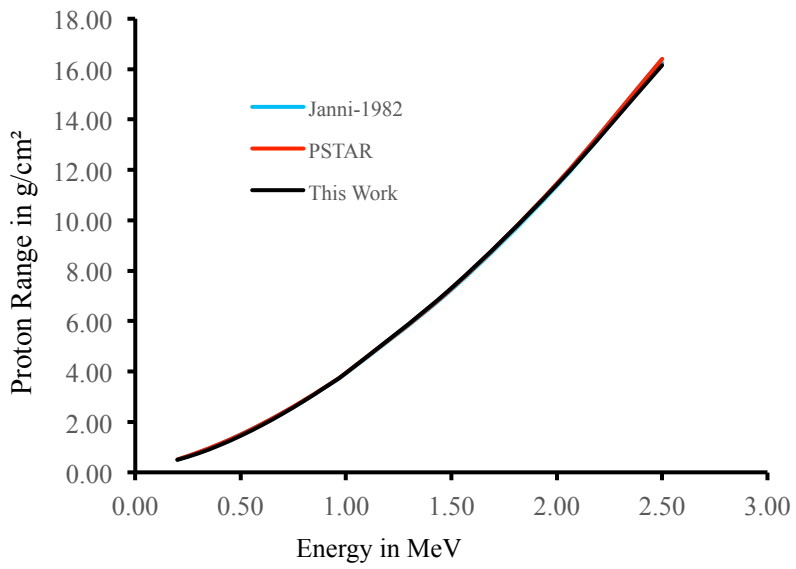
Figure 6: A graph of range values against proton energy in Aluminium with PSTAR values.
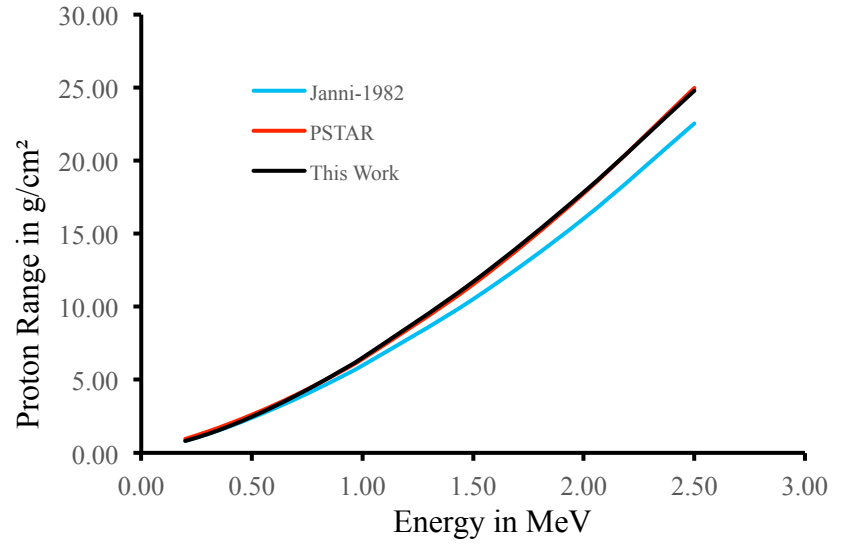

Figure 7: A graph of range values against proton energy in Germanium with PSTAR values.
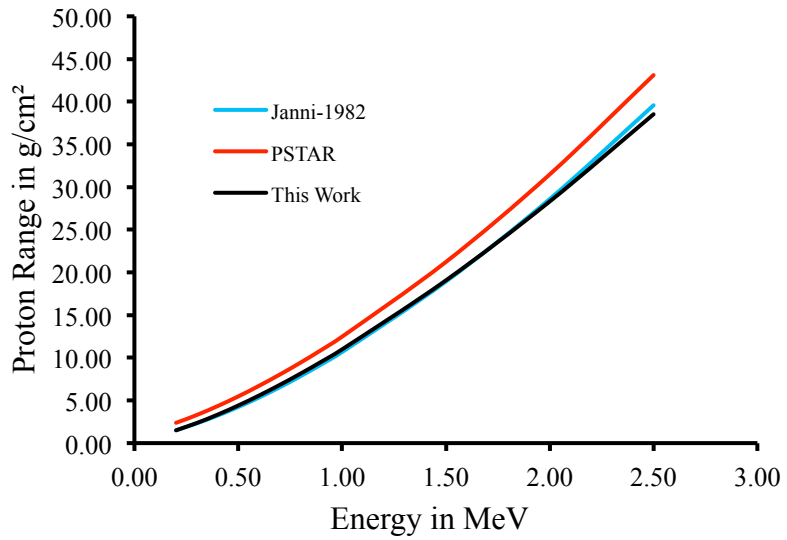

Figure 8: A graph of range values against proton energy in Gold with PSTAR values.
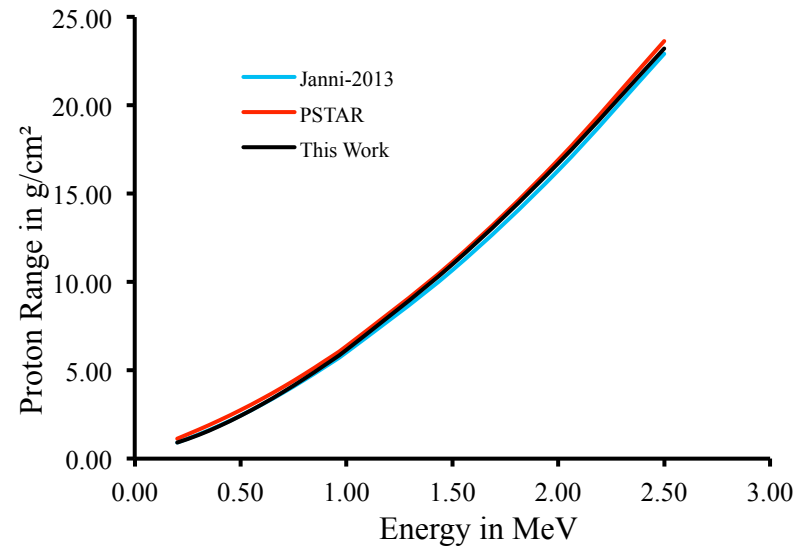

Figure 9: A graph of range values against proton energy in Gold with PSTAR values.
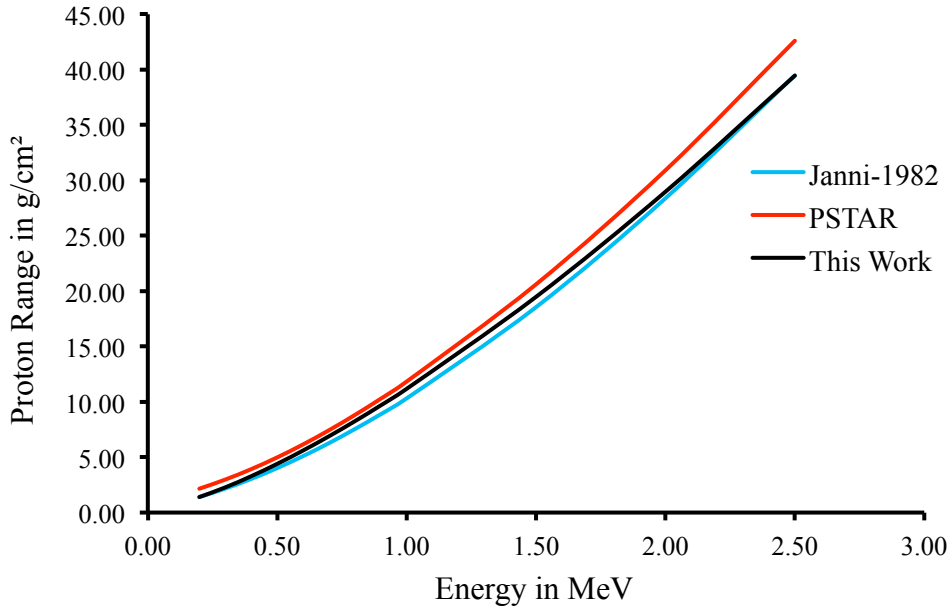
13

Figure 10: A graph of range values against proton energy in Lead with PSTAR values.

Comparison of Proton Range values Computed with that of PSTAR codes values and Janni-1982.

The proton range calculated for proton energy 0.20MeV to 2.90MeV using equation (3) are tabulated in table 4 and 5. The figure 6 to 10 shows the plots of proton range in g/cm2 against proton energy in MeV.

Table 4 gaves the proton energy and range values for Aluminium, Germanium and Gold and their percentage differences of the calculated values from the Janni-1982 and PSTAR values. The calculated values recorded minimum percentage difference of zero (0) from Janni-1982 both at 0.20MeV whiles from PSTAR code values for Al, Cu and Au are approximately 0.01% at 1.80MeV, 0.02% at 2.20MeV and 0% at 0.80MeV respectively. The maximum percentage difference of the calculated values from Janni-1982 values are about 4% at 0.30MeV, 11% at 1.50MeV and 4% at 0.60MeV whilst from PSTAR code values are 6% at 0.30MeV, 15% at 0.20MeV and 15% at 0.20MeV respectively.

From table 5, the minimum percentage difference for Janni was approximately 0% at 0.20MeV for both Copper and Lead whilst the maximum percentage difference are about 3% at 1.50MeV and 10% at 0.70MeV respectively. For PSTAR, the minimum percentage difference are 1% at 1.70MeV and 5% at 1.30MeV whilst the maximum percentage difference are approximately 20% at 0.20MeV and 35% at 0.20MeV respectively.

Conclusion

This work presents the results of the stopping power and range calculations from 0.20MeV to 2.90MeV protons in Al, Cu, Ge, Au and Pb. We have used the empirical relation, equation (3.0) and equation (4) to compute the stopping power and range values for the selected target materials. The results of the modified empirical relation are compared with the generated values of SRIM and PSTAR codes, Janni (1982a and 1982b) and only Bichsel experimental stopping power and range values due to scarcity of experimental data in the literature.

From this comparative analysis, it is inferred that the stopping power values predicted by various formulations for the selected target element and compound materials provide valuable information which can play an important role in material analyses and different applications. These types of analyses are very helpful for scientific community.

The formulations like SRIM-2013 and PSTAR codes provide reliable and accurate results of stopping power for various elemental target materials as compared to other codes. The SRIM-2013 have undergone several updates that ensures that the stopping power and range values are accurate and with less error.

We have also obtained an excellent agreement between our calculated stopping power values for Aluminium, Germanium and Copper, the Janni-1982 values and the values generated using the SRIM-2013 and PSTAR codes. Minor differences are observed in the vicinity of the stopping power values for copper at 0.30MeV and below. The calculated stopping power values are in good agreement with that of the Janni-1982 values and SRIM-2013 and PSTAR codes at 1.00MeV and below but deviated from 1.10MeV and above. From the results, as the atomic number increases, the percentage difference or the deviation of our calculated stopping power values with respect to that obtained from SRIM-2013 and PSTAR codes and the values of Janni-1982 increase.

The deviations of our data from the Janni-1982 values, SRIM-2013 and PSTAR codes values was random and energy independent (e.g. the deviations did not increase or decrease with increasing or decreasing proton energies).

Therefore, we think that the main reason for the deviations from the Janni-1982 values, SRIM-2013 and PSTAR codes values is inadequate treatment of the energy loss. In general, the average percentage difference of the calculated stopping power values from Janni-1982 values, SRIM-2013 and PSTAR codes values is 4%, 3% and 4% for aluminium and germanium respectively. For copper, it was 4% average percentage difference for Janni-1982 values, SRIM and PSTAR codes values. For gold, it was 11% for Janni-1982 values, 12% for SRIM code values and 7% for PSTAR code values. For lead and carbon dioxide, it was 7% and 4% for Janni-1982 values, 8% and 6% for SRIM code values and, 9% and 3% for PSTAR code values respectively. The average percentage difference indicates that the modified empirical relation can best be used for elements of low atomic numbers.

From the above results obtained using the modified empirical relation, it is quite obvious that the stopping power of materials can be expressed in terms of energy and atomic number of the material. It is also worth mentioning that modified empirical relation is simpler, widely applicable and values obtained are

in better agreement with the experimental and theoretical data of Janni-1982, PSTAR and SRIM codes.

It is concluded that the new formulation is able to predict the stopping power values once the input parameters are provided. In addition in the absence of sophisticated codes, the new predictor equation can be used as a good first step to obtaining stopping cross sections of target element and compound materials.

Recommendations

The main challenge of this work has being lack of sufficient experimental data for the selected target materials within the proton energy range used. The recommendations are therefore being made to improve upon the computation of stopping powers and range values and the estimation of uncertainty:

More experimental research should be conducted for projectiles of low energies to enhance the accuracy and estimation of uncertainty in the stopping powers and range values.

Further work should be conducted to formulate a unified empirical relation for the determination of stopping powers and range values in the low energy regions.

Below these energies and for higher atomic numbers, the values of the constant a, b, c and d should be changed or another parameter is required to minimize the error.

Further investigation is needed for empirical formula for stopping power and range of proton for low energy and elements having large atomic number.

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