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Article

Comparison of The Stopping Power of the Proton and Alpha Particle in Some Elements

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Abstract: This paper presents the results of stopping power for protons and alpha particles incident with range of kinetic energies (5-50) MeV on the elements: Beryllium, Aluminum, Titanium, and Copper. We used the relatively corrected Bethe-Bloch formula to calculate stopping power values for the selected target materials. The results of the modified or corrected Bethe-Bloch formula were compared with the values established in the (PSTAR and ASTAR) databases.It is clear that the stopping power of the proton and the alpha particle depends on the two relativistic variables, the Lorentz factor (γ) and beta (β). Slight differences were observed in the stopping power values for the elements as a whole at the lowest energy of (5 MeV), due to the decrease in the effect of the relativistic factor (β). The calculated stopping power values agree well with the values fixed in the (PSTAR & ASTAR) codes when the energy values gradually increase until they reach their highest value of (50 MeV). From the above, it is clear to us that the Bethe-Bloch formula for stopping power decreases with increasing kinetic energy of the incoming particle, and it is increases with increasing square of charge of the incoming particle. For example, from Tables (2,3) at the energy of (50 MeV) for the Aluminum element, we note that the stopping power for a proton is (9.68372 (MeV.cm^2)/g) and for an alpha particle is (115.6153 (MeV.cm^2)/g). It is clear that the largest percentage error when a proton falls with an energy of (5 MeV) on Copper is equal to (5.38%), while the lowest percentage error was for the element Titanium is equal to (0.07%) and at an energy of (10 MeV). The highest percentage error was when an alpha particle falls on the element Beryllium which is equal to (7.45%) at an energy of (5 MeV). While the lowest percentage error was for the element Titanium is equal to (0.02%) at an energy of (45 MeV).

Keywords: Alpha Particle, ASTAR, Bethe-Bloch Formula, Proton, PSTAR, Stopping Power

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1. Introduction

The importance of studying the stopping power for charged particles lies in the fact that it is the primary factor determining energy loss as protons and other charged particles traverse various materials. This study is essential for applications such as radiation dosimetry, detector design, proton therapy planning, and ion-beam material analysis, as well as for advancements in medical physics, accelerator technology, and radiation protection. Consequently, stopping power is a fundamental parameter in numerous scientific, medical, and industrial applications[1]. charged particles interact with electrons and nuclei via the Coulomb interaction, resulting in multiple ionization[2-3]. During ionization, primary electrons produce secondary electrons, and the processes of ionization and excitation lead to the breaking of chemical bonds between the molecules that make up matter [4].

Charged particles, such as protons and alpha particles, are classified as heavy, being much heavier than electrons. At a certain energy, their speed is slower than that of an electron, but their momentum is greater, and they are less susceptible to deflection upon collision. The mechanism of its deceleration in matter is the interaction of the electrostatic Coulomb force with atomic electrons and nuclei, which varies by $\left(\frac{1}{r^2}\right)$ with the separation distance (r) between the incident particles and the target particles [5]. Stopping power is one of the most important mechanisms by which the energy of charged particles is transferred to the target particles, it is defined as the amount of energy lost by a charged particle along its path through a material. It increases with decreasing particle velocity, and is denoted by $\left(-\frac{dE}{dx}\right)$ [6], and depends on the charge, the velocity of the projectile, and the target material [6,7]. Bethe-Bloch conducted the first quantum mechanical study of stopping power. The Bethe-Bloch theory of stopping power is valid when the projectile speed is greater than the Bohr speed [2]. Bethe-Bloch's analysis of energy loss is based on the Born approximation applied to collisions between a heavy particle and atomic electrons [7].The litertues [8-13]summarize some of important past studies about stopping powers of heavy charged particles.

2. Energy Loss Mechanism of Heavy Charged Particles

Importance of Studying the Stopping Power of Protons and Alpha Particles[14].

a. Understanding the interaction of radiation with matter. It illustrates how energy is transferred from particles to the atoms of the material through ionization and excitation.It helps explain the mechanisms of energy loss during penetration.
b. Determining particle penetration range. The higher the stopping power, the shorter the particle's range within the material. Consequently, alpha particles have a very short range compared to protons and electrons.
c. Radiation protection: It is used in designing protective shields and selecting appropriate materials for radiation absorption .It helps estimate the material thickness required to stop protons or alpha particles.
d. Proton Radiation Therapy. Stopping power is fundamental in determining the location of dose deposition within the body.Proton therapy relies on delivering the majority of the energy to the tumor at the Bragg Peak, thereby minimizing damage to healthy tissue.
e. Radiation Detector Design: The response of many detectors depends on the amount of energy a particle loses within the sensitive material. Therefore, stopping power is used in the design and performance analysis of nuclear detectors.
f. Materials Analysis:It is used in techniques such as: PIXE (Particle-Induced X-ray Emission) The accuracy of this techniques depends on the correct calculation of energy loss.
g. Nuclear and Accelerator Physics. Essential for determining beam energy after it passes through nuclear targets.Assists in designing nuclear experiments and selecting target thicknesses.
h. Space Science: Used to study the impact of cosmic-ray protons and heavy ions on spacecraft, electronics, and astronauts.

When a heavy charged particle moves through a material, it will encounter collisions with the atom as a whole and with its orbit electrons per unit volume of matter. The incoming particle often interacts with the orbit electrons due to the large number of electrons in the atom, while the particle rarely interacts with the atom as a whole. This interaction between a heavy charged particle and an electron can be studied classically. In this type of collision, the incoming heavy charged particle moves in a straight line, while the electron is scattered at a large angle after the collision. The incoming charged particle loses energy (ΔE) with each collision with an electron, and the energy difference between two collisions is given by [6,15]:

$$\Delta E = \frac{4m}{M} E \qquad (1)$$

Where m(amu) is the mass of the electron, and E(MeV), M(amu) are the kinetic energy and rest mass of the incident particle, respectively.

3. Mathematical Methods

This lost of energy of the incident particles are significantly changes the linear path of the particle within the matter. The stopping power of charged particles (such as a proton or an alpha particle) is calculated using the following Bethe-Bloch quantum formula [16-18]:

$$-\frac{dE}{dx}\left(\frac{\text{MeV}}{\text{m}}\right) = \frac{4\pi r_\circ^2 z^2 m_\circ c^2}{\beta^2} NZ \left[\ln\left(\frac{2m_\circ c^2 \beta^2 \gamma^2}{I^2}\right) - \beta^2\right] \qquad (2)$$

Since the classical radius of an electron is:

$$r_\circ = 2.818 \text{ fermi} = 2.818 \times 10^{-15} \text{ m}.$$

The rest of the constants in the equation are calculated as follows:

$$4\pi r_\circ^2 \approx 9.98 \times 10^{-29}\text{m}^2 = 10^{-24}\text{cm}^2 = 1 \text{ barn}.$$

$$m_\circ c^2 = 0.511 \text{ MeV}.$$

The Lorentz factor is calculated as:

$$\gamma = \frac{E + Mc^2}{Mc^2} = \frac{1}{\sqrt{1-\beta^2}} \qquad (3)$$

E: The Kinetic Energy.

$$E = (\gamma - 1)Mc^2 \qquad (4)$$

M: Rest mass of the incident particle.

$$\beta^2 = \left(\frac{v}{c}\right)^2 = 1 - \frac{1}{\gamma^2} \qquad (5)$$

Where: v is speed of incident of particle, c is speed of light in vacuum.

$$c = 3 \times 10^8 \frac{\text{m}}{\text{s}}.$$

N: Number of atoms per m^3 in the material through which the particle moves:

$$N = \rho\left(\frac{N_A}{A}\right) \qquad (6)$$

N_A: Avogadro’s number:

A: Atomic Weight.

Z: Atomic number of the material.

z: Charge of the incident particle:

$$z = 1 \text{ for electron, positron, proton, deutron; } z = 2 \text{ for } \alpha \text{ particle.}$$

I(eV): Mean excitation potential of the material, it is given by [11]:

$$I(\text{eV}) = 16Z^{0.9} \qquad (7)$$

Some values for each element under study have been recorded in Table (1), and these quantities include the mass density $\rho\left(\frac{\text{g}}{\text{cm}^3}\right)$, the mass number A, the atomic number Z, and the ratio $\left(Z/A\right)$.

Table 1. Shows the values of the variables for the elements under study [20].

Elements	$\rho\left(\frac{g}{cm^3}\right)$	A	Z	Z/A
Be – 9	1.848	9	4	0.444444
Al – 27	2.6989	27	13	0.481481
Ti – 48	4.540	48	22	0.458333
Cu – 63	8.960	63	29	0.460317

4. Results and Discussion

From Bethe-Bloch formula referred to in Equation (1), which describes the energy loss of a heavy charged particle as it passes through a material medium, it is clear that the stopping power of a proton and an alpha particle depends on two relativistic variables: The Lorentz factor (γ) and the beta factor (β), as shown in the simplified Bethe-Bloch partial formula:

$$-\frac{dE}{dx}\left(\frac{\text{MeV}}{\text{m}}\right) \propto \frac{NZ}{\beta^2}\left[\ln\left(\frac{\beta^2\gamma^2}{I^2}\right) - \beta^2\right] \qquad (8)$$

Relationship (8) has been reduced in this way to show the extent of each effect regardless of other effects. At low energies, the value of (β) is small. At the lowest energy, it becomes clear that ($\beta < 1$), i.e., when the difference between the speed of light and the speed of the particle is large, the stopping power increases. This effect is observed at an energy of (5 MeV) for both the proton and the alpha particle, which is the lowest energy used under study. The value of (β^2), which can be calculated from equation (5), is equal to $(0.010573, 0.002670141)$ for both the proton and the alpha particle, respectively. The stopping power of the element Copper, as shown in tables (2,3), is $(46.69306, 447.4968)$ measured in units of $\left(\frac{\text{MeV.cm}^2}{\text{g}}\right)$. This is because the particle moves slowly, so it has more time to interact with the electrons, and the energy lost by the incident particle is greater. As the energy increases, the value of the relative factor (β) gradually increases and becomes more effective. We find that at the highest amount of energy incident particle on the Copper (50 MeV), the value of the stopping power decreases, and the value of (β^2) is equal to $(0.098627, 0.026227547)$. The value of the stopping power for both the proton and the alpha particle, as shown in Tables (2,3), at this energy is $(8.220773, 94.93063)$ measured in units $\left(\frac{\text{MeV.cm}^2}{\text{g}}\right)$, respectively. That is, the particle has a greater penetration range because the reaction time decreases when the energy increases, and the penetration range increases with the increase in the kinetic energy of the incident particle.

Table 2. Represents the values of the proton stopping power in the elements under study and compares them with the PSTAR code and shows the percentage error between them [20-21].

E (MeV)	**Stopping Power** $\left(\frac{\text{MeV . cm}^2}{\text{g}}\right)$					
	Beryllium (Z= 9)			**Aluminum (Z= 27)**		
	This work	**PSTAR**	**Error%**	**This work**	**PSTAR**	**Error%**
5	68.14873	65.72	3.56	58.96049	56.95	3.41
10	38.81409	37.69	2.90	34.55584	33.76	2.30
15	27.82361	27.09	2.64	25.1076	24.66	1.78
20	21.95963	21.41	2.50	19.98396	19.69	1.47
25	18.28114	17.84	2.41	16.73629	16.52	1.29
30	15.74526	15.38	2.32	14.48063	14.31	1.18
35	13.88499	13.57	2.27	12.81641	12.68	1.06
40	12.4588	12.18	2.24	11.53465	11.42	0.99

45	11.32872	11.08	2.20	10.51515	10.41	1.00
50	10.41006	10.18	2.21	9.68372	9.594	0.93

Table 3. Represents the values of the proton stopping power in the elements under study and compares them with the PSTAR code and shows the percentage error between them [20-21]. (Continued).

E (MeV)	**Stopping Power $\left(\frac{MeV\ .\ cm^2}{g}\right)$**					
	Titanium(Z=48)			**Copper (Z=63)**		
	This work	**PSTAR**	**Error%**	**This work**	**PSTAR**	**Error%**
5	49.80887	49.43	0.76	46.69306	44.18	5.38
10	29.7109	29.69	0.07	28.16056	27.09	3.80
15	21.76133	21.83	0.32	20.72739	20.1	3.03
20	17.40621	17.5	0.54	16.62881	16.2	2.58
25	14.62798	14.73	0.70	14.00377	13.68	2.31
30	12.68961	12.8	0.87	12.16716	11.91	2.11
35	11.25458	11.36	0.94	10.80458	10.6	1.89
40	10.1463	10.25	1.02	9.750498	9.577	1.78
45	9.262817	9.359	1.04	8.909071	8.76	1.67
50	8.540945	8.632	1.07	8.220773	8.09	1.59

From Table (3) and Figure (1) and by comparing the results of the current work with the results of the PSTAR database for proton stopping power, it is clear that there is a good agreement in the obtained results, but there are some anomalies at low energies, especially at the energy of (5 MeV) for all elements, where it is clear that the percentage error at this energy for the elements under study $(\mathrm{Be, Al, Ti, and\ Cu})$ are equal to $(3.56, 3.41, 1.07.\ \mathrm{and}\ 5.38)\%$, respectively, except for the element Titanium, which was at the energy of $(50\ \mathrm{MeV})$. While the lowest percentage error were for the elements $(\mathrm{Be, Al, Ti, and\ Cu})$ equal to $(2.20, 0.93, 0.07, \mathrm{and}\ 1.59)\%$ and at energies $(50, 10, 50, 45)$ MeV, respectively. It is clear from Table (2) that the amount of decrease in the stopping power in each element is at the expense of the increase in the amount of energy of the incident proton. In return, there is a decrease in the results of the PSTAR database for the stopping power of the proton corresponding to each of its own energy. For example, when the proton falls on the element Beryllium with energies $(10, 20, 30, 40, 50)$ MeV, respectively, we notice the amount of decrease in the stopping power in both the current work are $(38.81409, 21.95963, 15.74526, 12.4588, 10.41006)\left(\frac{MeV.cm^2}{g}\right)$ and the results of the PSTAR database are $(37.69, 21.41, 15.38, 12.18, 10.18)\left(\frac{MeV.cm^2}{g}\right)$ respectively [21].

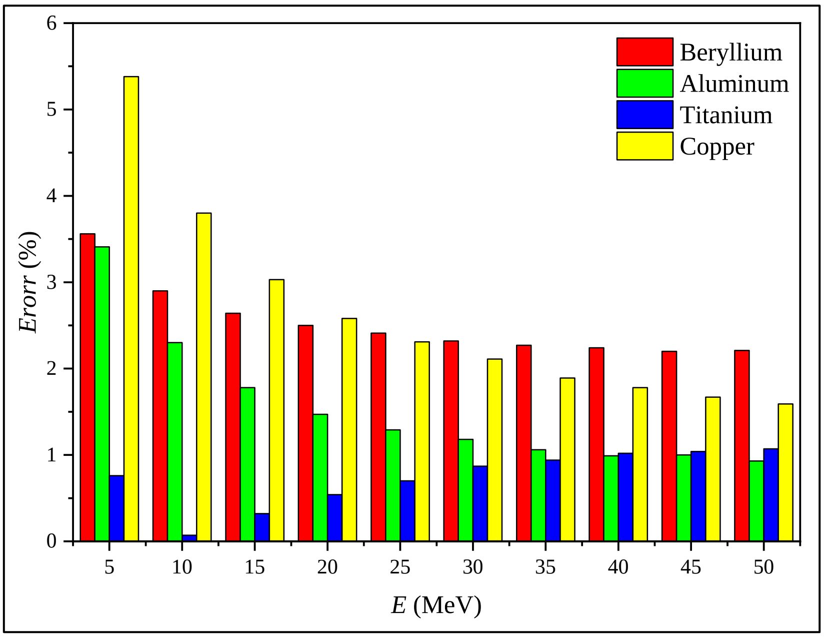

Figure 1. Shows the percentage error of the proton between the results of the current study and the PSTAR database.

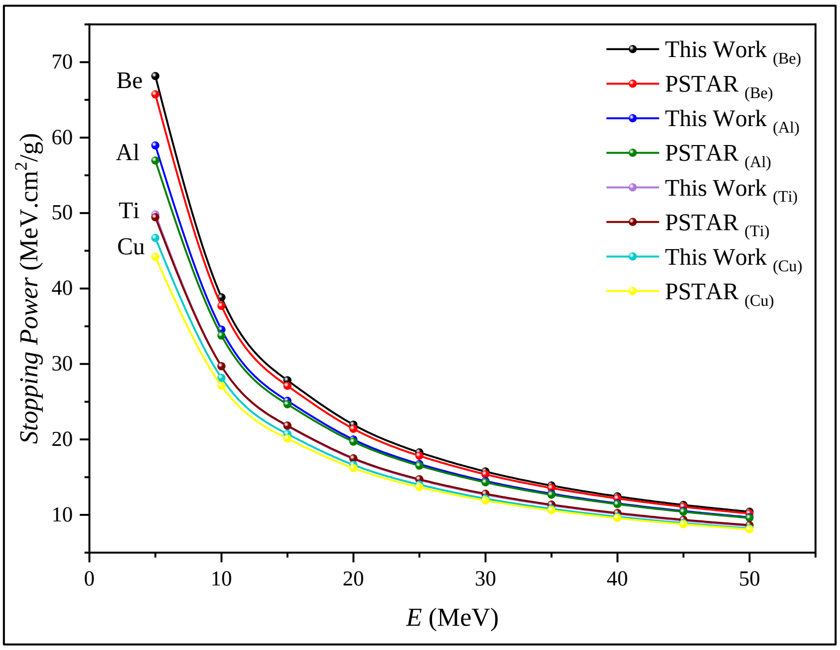

Figure 2. Shows the decrease in stopping power values as a function of proton kinetic energy between the results of the current study and the PSTAR database.

The charge of heavy particles is of great importance as it directly and explicitly affects the stopping power. As shown in the Bethe-Bloch equation, the stopping power is proportional to the square of the charge of the incident particle [4]:

$$-\frac{dE}{dx}\left(\frac{\text{MeV}}{\text{m}}\right) \propto z^2 \qquad (10)$$

This means that charged alpha particles lose their energy much faster than a proton, meaning that the distance penetrated in the same medium for a proton is longer than for an alpha particle at the same amount of energy.

Table 4. Represents the values of the stopping power of the alpha particle in the elements under study and compares them with the ASTAR code and shows the percentage error between them [20-21].

E (MeV)	Stopping Power $\left(\frac{\text{MeV . cm}^2}{\text{g}}\right)$					
	Beryllium – 9			Aluminum – 27		
	This work	ASTAR	Error%	This work	ASTAR	Error%
5	797.4119	738	7.45	628.3751	605.3	3.67
10	470.4615	446.1	5.18	391.6868	376.2	3.95
15	341.9392	327.2	4.31	291.6235	280.9	3.68
20	271.6915	261.2	3.86	235.1064	227.2	3.36
25	226.9242	218.8	3.58	198.3593	192.3	3.05
30	195.7021	189	3.42	172.369	167.6	2.77
35	172.5876	167	3.24	152.9238	149	2.57
40	154.7322	149.8	3.19	137.7771	134.5	2.38
45	140.4927	136.2	3.06	125.615	122.8	2.24
50	128.8518	125	2.99	115.6153	113.2	2.09

From Table (4) and Figure (2) and by comparing the results of the current work with the results of the ASTAR database for alpha particle stopping power, it is clear that there is a good agreement in the obtained results, but there are some anomalies at the low energies that were relied upon in our current study and for almost all elements, as it is clear that the percentage error shown in Figure (3) at this energy for the elements under study $(\text{Be, Al, Ti, and Cu})$ are equal to $(7.45, 3.95, 3.33, 5.10\,)\%$ at energies $(5, 10, 5, 10)$ MeV. While the lowest percentage error were for the elements (Be, Al, and Cu) equal to $(2.99, 2.09,\ 3.32)\%$ and at energy $(50\ \text{MeV})$, except for the element Titanium, the lowest percentage error was (0.02%) at energy $(45\ \text{MeV})$. Table (4) shows the amount of decrease in the stopping power of an alpha particle in each element at the expense of the increase in the amount of energy of the incident alpha. In return, there is a decrease in the results of the ASTAR database for the stopping power of an alpha particle corresponding to each of its own energy. For example, when an alpha particle falls on the element Beryllium with energies of $(10, 20, 30, 40, 50)$ MeV, respectively, as shown in Table (5), we note the amount of decrease in the stopping power in both the current work $(470.4615, 271.6915, 195.7021, 154.7322, 128.8518)\left(\frac{\text{MeV.cm}^2}{\text{g}}\right)$ and the results of the ASTAR database $(446.1, 261.2, 189, 149.8, 125)\left(\frac{\text{MeV.cm}^2}{\text{g}}\right)$ respectively [13]. The main reason for the decrease in the stopping power of the alpha particle is the effect of the relativistic factors $(\beta^2 \text{and}\ \gamma^2)$ in the natural logarithm term $\left[\ln\left(\frac{2m_\circ c^2\beta^2\gamma^2}{I^2}\right)\right]$ in the Beth-Bloch formula, which becomes negative at low energies [14]. The increase in the value of the relativistic factor (β) is a result of the gradual increase in the kinetic energy of the alpha particle, and the factor (β) becomes more influential. At the energy of $(50\ \text{MeV})$ for the alpha particle, i.e. the highest energy estimate among the energies under study, we obtain the lowest stopping power, as shown in the data in Table (3) for the elements under study $(\text{Be, Al, Ti, and Cu})$ are equal to $(128.8518, 115.6153, 99.87038, 94.93063\,)\left(\frac{\text{MeV.cm}^2}{\text{g}}\right)$ respectively.

Table 5. Represents the values of the stopping power of the alpha particle in the elements under study and compares them with the ASTAR code and shows the percentage error between them [20-21]. (Continued).

E (MeV)	Stopping Power $\left(\frac{MeV\ .\ cm^2}{g}\right)$					
	Titanium – 48			Copper – 63		
	This work	ASTAR	Error%	This work	ASTAR	Error%
5	498.1081	514.7	3.33	447.4968	431.3	3.62
10	322.7271	323.5	0.24	297.6875	282.5	5.10
15	244.1172	243.3	0.33	227.5143	216	5.06
20	198.6386	197.9	0.37	186.2273	177.4	4.74
25	168.6509	168.1	0.33	158.7428	151.7	4.44
30	147.2387	146.9	0.23	138.9933	133.2	4.17
35	131.1058	130.9	0.16	124.0444	119.2	3.91
40	118.4704	118.4	0.06	112.2947	108.2	3.65
45	108.2799	108.3	0.02	102.7914	99.21	3.48
50	99.87038	99.97	0.10	94.93063	91.78	3.32

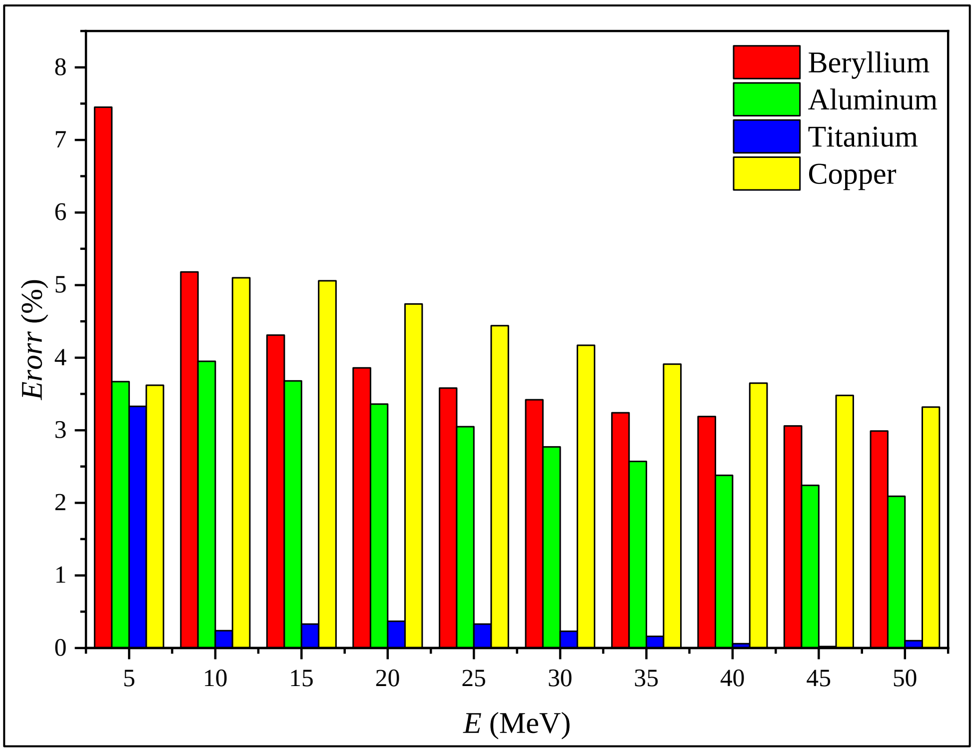

Figure 3. Shows the percentage error of the alpha particle between the results of the current study and the ASTAR database.

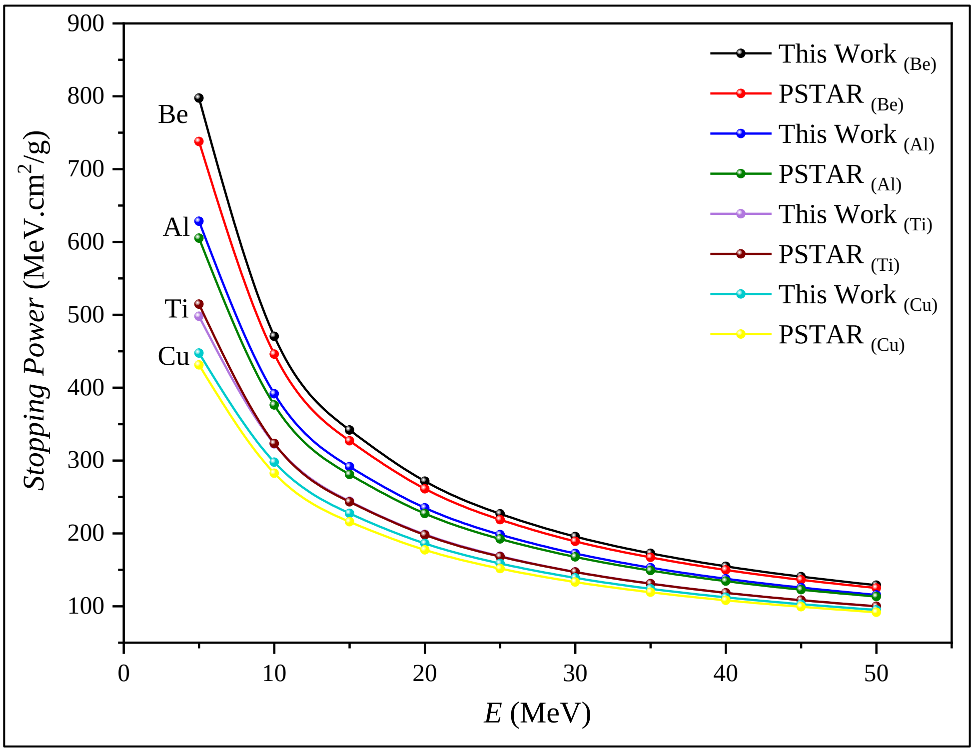

Figure 4. Shows the decrease in stopping power values as a function of the kinetic energy of the alpha particle between the results of the current study and the ASTAR database.

In the Bethe-Bloch formula for calculating the stopping power, it is shown that it increases with the increase in the charge of the incident particle because it is directly proportional to the square of the charge of the incident particle. For example, from Tables (2,3) at the energy of (50 MeV) for the element Aluminum, the stopping power of the proton is $\left(9.68372\,\frac{\mathrm{MeV\,.cm^2}}{\mathrm{g}}\right)$, while for the alpha particle it is $\left(115.6153\,\frac{\mathrm{MeV\,.cm^2}}{\mathrm{g}}\right)$ [6].

5. Conclusion

The aim of this study was to calculate the stopping power of heavy charged particles (protons and alpha particles) using the corrected Bethe-Bloch formula and compare these results with the National Institute of Standards and Technology (NIST) databases (PSTAR & ASTAR) when these particles fall with kinetic energies ranging from $(5-50)$ MeV on the elements Beryllium, Aluminum, Titanium, and Copper, respectively.

The study demonstrated good agreement between the stopping power values and those in these internationally recognized programs, due to their reliance on relative correction factors. We also observed a significant decrease in stopping power values with increasing kinetic energy of the incoming particles due to decreasing interaction time with the orbital electrons of the target atoms. It was also shown that the stopping power does not depend on the mass of the incident particle, and it is directly proportional to the square of the charge (z^2) of the incident particle. Therefore, we see that the stopping power for an alpha particle is much greater than the stopping power of a proton at the same kinetic energy of the incident particle, which depends directly on the speed of the particle. It was also shown that the amount of stopping power is directly proportional to the electron density (n) of the target material [6,22].

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