J. Myanmar Acad. Arts Sci. 2026 **Vol. XXIII. No.2**

INVESTIGATING PROTON STOPPING POWER AND RANGE IN ALUMINUM TARGETS

Zin Zin Phyoe[1], Thandar Oo[2], Htun Htun Oo[3]

Abstract

Proton beams biological effects depend on their stopping power, defined as the rate at which a material absorbs the kinetic energy of a charged particle. The Bethe-Bloch formula is used for the calculations of stopping power of proton in aluminum, the incident proton energies ranging from 0.1 MeV to 100 MeV. The mean excitation energy which is a crucial parameter is also explored for accurate stopping power calculations. Stopping power and range values were computed using a FORTRAN-90 program, showing close agreement with SRIM-2013 databases.

Keywords: proton, Bethe-Bloch formula, aluminum, mean excitation energy, stopping power

Introduction

The interaction of energetic charged particles, such as protons, with matter spans in various fields including particle physics, medicine, and materials science. Among the fundamental quantities characterizing this interaction, stopping power and range are of paramount importance. Stopping power denotes the rate of energy loss experienced by a charged particle as it traverses a material, while range represents the distance a particle can travel before coming to rest. Understanding these parameters is crucial for a wide range of applications, including proton therapy, ion implantation and particle detection.

In this research, we focus on elucidating the stopping power and range of protons in aluminum, a widely used material in various technological and industrial domains. Despite its seeming simplicity, the interaction of protons with aluminum involves complex physical phenomena, including electronic and nuclear stopping mechanisms, scattering processes, and energy transfer mechanisms. The dependence of stopping power and range on factors such as proton energy, target material properties and experimental conditions necessitates a comprehensive investigation for precise modeling and practical utilization [1][2][3].

The motivation behind this study stems from the necessity to enhance our understanding of proton-matter interactions in aluminum and to provide accurate data for applications spanning from materials engineering to radiation therapy. By employing state-of-the-art theoretical models, computational simulations, and experimental techniques, we aim to discern the intricate interplay of factors governing proton penetration into aluminum and unravel the underlying physics governing stopping power and range [4][5][6].

This research paper is organized as follows: We begin by presenting a brief overview of the theoretical framework underpinning proton stopping power and range calculations. Subsequently, we delve into the specific characteristics of aluminum as a target material, outlining its structural properties and relevance in various technological domains. Following this, we detail the methodologies employed in our investigation, encompassing computational simulations and experimental setups designed for precise measurements. We then present and analyze our results, highlighting the dependence of stopping power and range on key parameters

[1] Department of physics, Meiktila University
[2] Department of physics, Meiktila University
[3] Department of physics, Yadanabon University

such as proton energy and target thickness, with a comparison to established databases like SRIM-2013. Finally, we discuss the implications of our findings and their significance for applications ranging from proton therapy to materials science.

Through this interdisciplinary endeavor, we aspire to contribute to the burgeoning field of proton-matter interactions, offering valuable insights into the behavior of charged particles in aluminum and paving the way for advancements in diverse technological realms.

Background Theory

Bohr's formula for stopping power is derived from a classical perspective and provides a fundamental understanding of the energy loss of heavy charged particles, such as protons, as they traverse a material. The formula is expressed as [7]:

$$-\frac{dE}{dx} = \frac{Z^2 e^4 n}{4\pi\varepsilon_0^2\, m_e\, v^2}\left[\ln\left(\frac{2m_e v^2}{\langle I\rangle}\right)\right] \quad (1)$$

This equation can be simplified as

$$-\frac{dE}{dx} = \frac{4\pi(\hbar c)^2 Z^2 \alpha^2 n}{m_e c^2 \beta^2}\left[\ln\left(\frac{2m_e c^2 \beta^2}{\langle I\rangle}\right)\right] \quad (2)$$

This relation was first derived by Bohr and is known as Bohr's relation for stopping power. Complete relativistic calculations were performed by Bohr and Bethe and they modified Bohr's stopping power relation as

$$-\frac{dE}{dx} = \frac{4\pi(\hbar c)^2 Z^2 \alpha^2 n}{m_e c^2 \beta^2}\left[\ln\left(\frac{2m_e c^2 \beta^2}{\langle I\rangle(1-\beta^2)}\right) - \beta^2\right] \quad (3)$$

This relation is also known as the Bethe-Bloch formula.

where:

- $\frac{dE}{dx}$ represents the energy loss per unit path length.
- $\hbar$ is the reduced Planck's constant.
- c is the speed of light.
- α is the fine structure constant.
- n is the electron density in the stopping material.
- m_e is the electron rest mass.
- Z is the atomic number of the incident particle.
- β is the velocity of the incident particle relative to the speed of light.
- $\langle I \rangle$ is the mean excitation energy of the target material.

This formula illustrates the complex interplay between various factors such as atomic properties, particle velocity, and material characteristics in determining the energy loss of charged particles in matter. An approximate equation of $\langle I \rangle$ for $Z > 12$ [8] is,

$$\langle \mathrm{I} \rangle\ \mathrm{eV} = (9.76 + 58.8\ \mathrm{Z}^{-1.19})\ \mathrm{Z} \quad (4)$$

Range of Charged Particles

Heavy charged particles lose small fraction of energy in each collision and suffer a large number of collisions before they are finally stopped by the medium. During this motion, they move in a straight line in the forward direction. The average distance travelled by a charged particle before it comes to rest is called the range of the charged particle. To derive an expression for the range of charged particle, let $\boldsymbol{E_i}$ be the kinetic energy at the time of entry in the medium and assume that it loses *dE* energy in travelling a distance *dx*. So, the range R is

$$R = \int_{E_i}^{0} dx = -\int_{0}^{E_i} dx \tag{5}$$

By changing variable,

$$\boldsymbol{R} = \int_{0}^{\mathrm{E_i}} \left(-\frac{\mathrm{dE}}{\mathrm{dx}}\right)^{-1} (-\mathrm{dE}) = \int_{0}^{\mathrm{E_i}} \left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)^{-1} \mathrm{dE} \tag{6}$$

This equation cannot solve analytically and we use numerical method.

Results and Discussions

The stopping power for protons traversing in material is similar to that for heavy charged particles. The interaction of incident protons with atomic electrons in aluminum, leading to excitation and ionization, can be calculated from Bethe's theory, and it is called the "Collisional Stopping Power" such as the electronic stopping power. For these calculations, we use the Eq. (3) with the help of FORTRAN-90 program. The incident energies of protons 0.1 MeV-100 MeV are used in the stopping power calculation. In running the program for calculation, the density of aluminum 2.702 gcm^{-3} and electron charged density ($\mathbf{n = 7.841 \times 10^{23}} \, \boldsymbol{\frac{atoms}{cm^3}}$) are used, these values are shown in Table 1. This study also explores the mean excitation energy for aluminum, essential for accurate stopping power calculations. Thus, firstly in running the program, we use the mean excitation energy $\langle \mathbf{I} \rangle$ in Eq. (4) for aluminum targets. But, the data results are little different when the comparison with the databases in SRIM-2013 code. Thus, when we fit the mean excitation energy at $\langle \mathbf{I} \rangle = \mathbf{166\ eV}$, the results are observed that good in agreement with the results in SRIM-2013 code which are shown in Table 2. In which, we also present the error percentage between these two results. Figure 1 shows the two results are observed that good in agreement in the energy range from 0.1 MeV - 100 MeV. According to this figure, the incident energy of proton increases, the stopping power decreases in material. For the calculations of proton range, Eq. (6) is used. Table 3 shows the difference between the values of the range of proton in aluminum with the FORTRAN-90 program and SRIM-2013 code values. According to these results, increases the range of proton in target material while increasing the incident energy of the proton. The results are good in agreement as shown in Figure 2 between 0.1 MeV - 100 MeV.

Table 1. Basic Data Used in Calculations

Target	Density(ρ) g/cm^3	Atomic number Z	Mass number A	n ($\frac{atoms}{cm^3}$)
Aluminum	2.702	13	26.98154	7.841×10^{23}

Table 2 The proton energy in MeV and comparison between the FORTRAN-90 program and SRIM-2013 code for the stopping power of proton in aluminum

Energy of proton (MeV)	Stopping Power of proton in aluminum (MeVcm^{-1})		
	Results by FORTRAN-90	Results by SRIM-2013	Error%
0.1	509.61	1215.62	58.07
0.2	904.72	1007.84	10.23
0.3	856.74	858.69	0.22
0.4	777.52	754.39	3.06
0.5	705.83	677.66	4.15
1	483.20	472.57	2.25
2	307.04	299.38	2.55
3	230.38	225.23	2.28
4	186.56	182.95	1.97
5	157.86	155.20	1.71
6	137.46	135.45	1.48
7	122.14	120.56	1.31
8	110.18	108.92	1.15
9	100.55	99.51	1.04
10	92.61	91.76	0.93
20	53.60	53.39	0.39
30	38.85	38.80	0.14
40	30.95	30.93	0.09
50	25.99	25.99	0.01
60	22.56	22.57	0.00
70	20.05	20.06	0.01
80	18.13	18.13	0.00
90	16.60	16.62	0.07
100	15.36	15.37	0.03

Table 3 Proton range in aluminum target and energy for proton in 0.1 MeV - 100 MeV

Energy of proton (MeV)	Ranges of proton in aluminum (cm)		
	Results by FORTRAN-90	Results by SRIM-2013	Error%
0.1	2.0×10^{-4}	8.45×10^{-5}	136.60
0.2	3.3×10^{-4}	1.73×10^{-4}	90.75
0.3	4.3×10^{-4}	2.80×10^{-4}	53.57
0.4	5.6×10^{-4}	4.03×10^{-4}	38.95
0.5	6.9×10^{-4}	5.42×10^{-4}	27.30
1	1.57×10^{-3}	1.43×10^{-3}	9.79
2	4.24×10^{-3}	4.16×10^{-3}	1.84
3	8.06×10^{-3}	8.04×10^{-3}	0.27
4	1.29×10^{-2}	1.29×10^{-2}	0.15
5	1.88×10^{-2}	1.88×10^{-2}	0.16
6	2.56×10^{-2}	2.58×10^{-2}	0.89
7	3.33×10^{-2}	3.35×10^{-2}	0.59
8	4.19×10^{-2}	4.22×10^{-2}	0.61
9	5.14×10^{-2}	5.18×10^{-2}	0.67
10	6.18×10^{-2}	6.22×10^{-2}	0.61
20	2.09×10^{-1}	2.11×10^{-1}	0.52
30	4.32×10^{-1}	4.33×10^{-1}	0.23
40	7.24×10^{-1}	7.23×10^{-1}	0.06
50	1.08×10^{0}	1.08×10^{0}	0.20
60	1.49×10^{0}	1.49×10^{0}	0.20
70	1.96×10^{0}	1.96×10^{0}	0.25
80	2.48×10^{0}	2.48×10^{0}	0.29
90	3.06×10^{0}	3.06×10^{0}	0.26
100	3.68×10^{0}	3.68×10^{0}	0.27

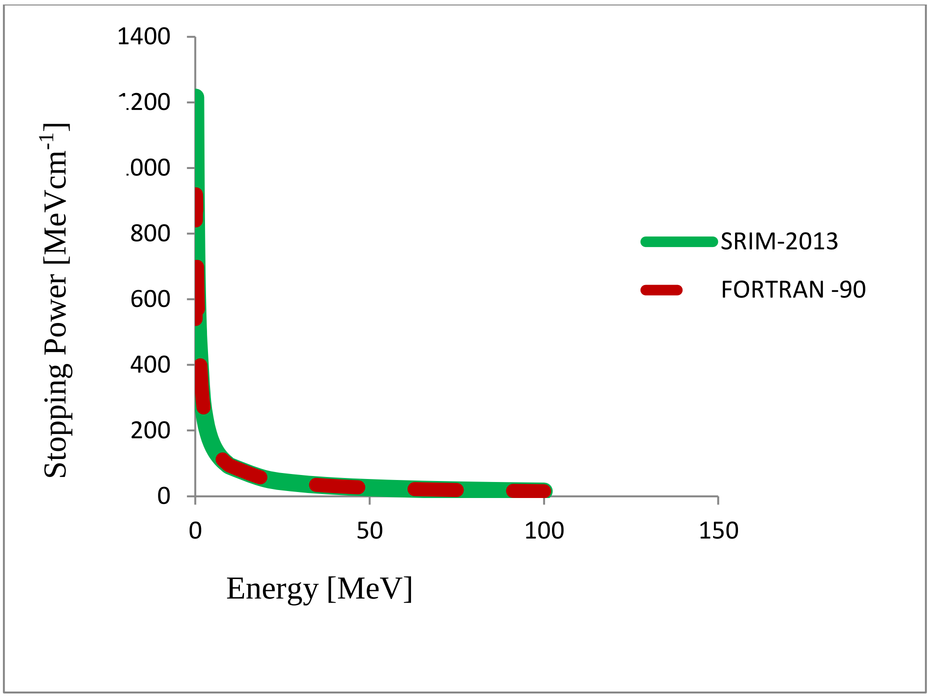

Figure 1 Plot of the stopping power of proton versus energy in aluminum for the FORTRAN-90 results with the mean excitation energy ⟨ I ⟩ = 166 eV and SRIM-2013 code

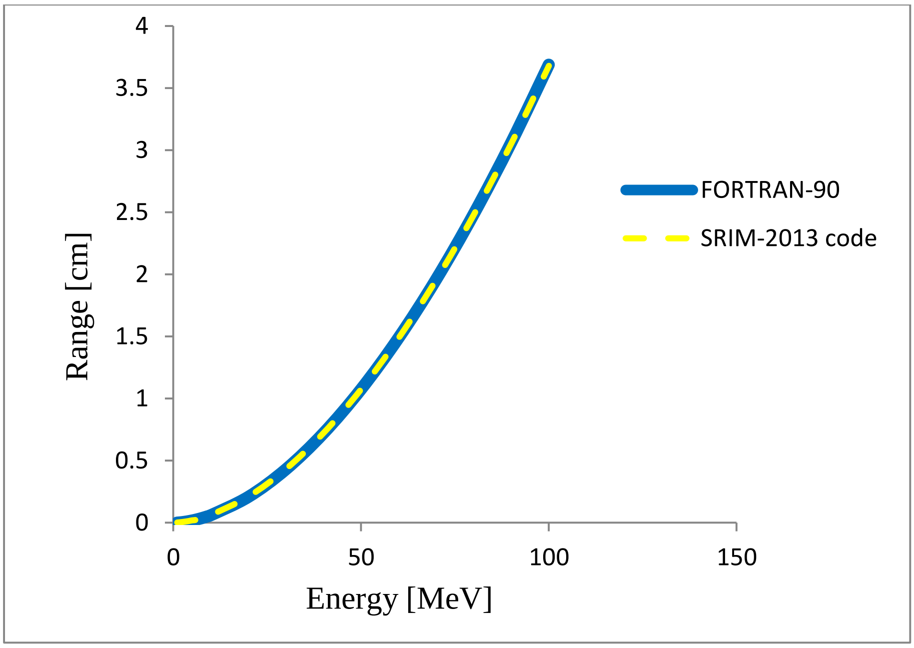

Figure 2 Plot of the proton range values versus proton energy in aluminum with the mean excitation energy ⟨ I ⟩ = 166 eV for the FORTRAN-90 results comparison with SRIM-2013 code

Conclusion

This research has effectively demonstrated the use of the Bethe-Bloch formula to determine the stopping power and range of protons in aluminum targets. The calculated values using the FORTRAN-90 program which are align closely with the standard values provided by the SRIM-2013 code. Our results confirm that as the incident energy of protons increases, their stopping power decreases, while the protons range in the target material increases. Aluminum is strong and durable which is much lighter than other materials, providing effective protection against radiation without compromising structural integrity. Compared to other materials, aluminum is relatively inexpensive and widely available, making it a cost effective choice for radiation shielding. These properties make aluminum which is a popular choice for radiation shielding in many industries, including medical, aerospace, and nuclear applications. In radiation therapy, aluminum is used to shield certain parts of the body from unnecessary radiation exposure. This helps to protect healthy tissues and organs while focusing the radiation on the cancerous cells. The study underscores the robustness of the Bethe-Bloch formula for calculating the stopping power of heavy charged particles. Proton energy ranges and target thickness must be carefully selected for applications like radiation therapy, where protons need to stop precisely within the target area. Future research will extend these findings to other target materials and more complex interactions, advancing medical physics and materials science. The methodologies and the results presented in this study can provide a solid foundation for future work aimed at optimizing proton beam applications.

Acknowledgement

We would like to tender our sincere thanks to Professor Dr. Khin Khin San, Head of Department of Physics, Meiktila University for her kind permission and encouragement in preparing this research paper. Special thanks to Professor Dr. Daw Hla Win (Retire) from Meiktila University for her advice that made this research paper easier. Finally, we are extremely thankful to Professor Dr. Htun Htun Oo, Department of Physics, Yadanabon University, for his supervision and guidance to carry out this research paper.

References

Berger, M.J., and Seltzer, S. M., NASA SP-3012, (1964).

Kornberg, R. D. "The Stopping Power of Aluminum in Proton Beams." Nuclear Physics A, 119(2), 333–344 (1968).

Mittal, V.K., Verma, R.C., & Gupta, S.C. "Introduction to Nuclear and Particle Physics" (3rd printing). PHI Learning Private limited (2013)

Phelps, A. V., & Gemmell, D. S. "Proton Beam Characterization and Calibration." Medical Physics, 21(4), 549–563 (1994).

Sigmund, S. "Stopping of Ions in Matter." Journal of Applied Physics, 32(3), 566–578 (1961).

Trellue, H. R., & Howerton, L. M. "Stopping Power of Aluminum for Protons." Physical Review, 127(3), 768–773 (1962).

Wehner, G. K., & McLean, D. A. "Aluminum: Properties and Physical Metallurgy." ASM International (1984).

Ziegler, J. F. "The Stopping and Range of Ions in Matter." Pergamon press (1985).