Dependence of Energy Loss in Polymethylmethacrylate (PMMA) on Charge of Incident Ions

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Abstract: ***The interaction of energetic ions with matter is of fundamental importance in nuclear physics, radiation shielding, and biomedical applications. In the present work, a systematic study of energy loss and transport parameters for ions ranging from protons to potassium traversing in Polymethylmethacrylate (PMMA) has been carried out. Key interaction parameters, including ion energy loss, projected range, longitudinal straggling, and lateral straggling, were calculated to quantify the ion–matter interactions in PMMA. The results demonstrate a clear dependence of energy loss processes on ion charge and energy. Light ions such as protons predominantly lose energy through electronic stopping, resulting in longer projected ranges and relatively smaller straggling. In contrast, moderately heavy ions, particularly potassium ions, exhibit significantly enhanced nuclear stopping contributions, leading to reduced penetration depths. The calculated range and straggling parameters reveal the progressive increase in spatial dispersion of ion tracks with increasing ion energy. These findings provide valuable insights into ion transport behavior in polymeric media and are relevant for applications such as particle detector design, space and cosmic radiation shielding, and radiobiological dose estimation.***

Keywords: Projected Range, Energy loss, spatial dispersion, polymers

1. Introduction

Ions penetrating target materials suffer significant energy losses due to the interactions it encounters with electrons and nuclei of the target atoms. Neil's Bohr identified two components of energy loss in ion interaction; electronic stopping and nuclear stopping. Ion interaction with electrons of the target atom leading to excitation or ionization of electrons thereby reducing the energy of the incident ion is termed as electronic stopping power. The elastic collision of incident ion with the atomic nuclei leading to recoiling of nuclei at projectile speeds less than the orbital velocity of target electrons is termed as nuclear stopping power. Nuclear interaction produces angular deflection of the incident ions affecting the energy loss and hence their range in the target material [1, 2].

Polymers are macromolecular materials composed of repeating molecular units (**monomers**) linked by covalent bonds. Polymers are easy to synthesize materials and are known for their versatility. They are light weight, flexible, thermally stable and typically cost effective materials. Polymethylmethacrylate (PMMA) is an amorphous polymer with no long range order. It is synthesized from monomer methacrylate (MMA). Multiple monomers are connected together to form PMMA chain. PMMA ($C_5H_8O_2$) has a density of 0.95gm/cm^3 and used widely as bone cement, intraocular lens and as a glass substitute in industries. The hydrogen content in PMMA makes it an effective shielding material. PMMA shielding property can be enhanced by combining it with other materials such as bismuth trioxide (Bi_2O_3) or tungsten trioxide (WO_3) [3].

The gamma ray radiation shielding property of PMMA can be enhanced by combining it with other materials such as tungsten trioxide (WO_3). Tungsten trioxide is a high atomic number composite material, when a small concentration of the material is combined with PMMA, can significantly increase gamma ray attenuation coefficient retaining high optical transparency making the composite suitable for radiation screening windows, eye wears, and industrial panels [3]. Radiation shielding is crucial in space missions involving astronauts; payloads etc., Polymers such as PMMA play an important role when they are reinforced with materials, particularly multiwall carbon nanotube (MWCNT), to improve shielding effectiveness. The filler material improves thermal stability and greatly reduces the secondary neutron generation over the pristine polymer making it ideal for space industry [4]. Recent reports have emphasized the importance of PMMA doped with bismuth oxide (Bi_2O_3) in shielding X-ray and gamma radiation and hence can be considered for medical field, in the design of medical aprons. Bismuth oxide contains high atomic number atoms and its high refractive index can increase the density and optical properties of polymer composite. The high density materials are good in shielding X-rays and gamma rays [5]. Effective shielding system is crucial for longevity and performance of satellites as they are exposed to harsh environmental conditions. The use of PMMA doped with WO_3, significantly improves gamma shielding abilities, which can be made use of in improving the performance of satellites and to safeguard the components of satellites [6].

2. Materials and Methods

The transport parameters such as Range, total energy loss, straggling for the ions Hydrogen, Helium, Lithium, Boron, Carbon, Silicon and Potassium in the target material, PMMA, are computed and analyzed in the present study.

SRIM (THE STOPPING & RANGE OF IONS IN MATTER) version 2013, Monte Carlo simulation code is used to compute range, total energy loss and straggling of the impinging ions in the target. Ion energies ranging from 10keV to 1000keV are used in the present study.

The theory of stopping and range of ions in matter has been described by Bethe (1930), Bloch (1933), Fano (1963), Sigmund (2004), and Zeigler (2008).

The formula for stopping power as given by Bethe-Bloch has the following expression:

$$\frac{-dE}{dx}=\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\frac{4\pi z^2 N_A z\rho}{mc^2\beta^2 A}\left[\ln\left(\frac{2mc^2\beta^2}{I}\right)-\ln(1-\beta^2)-\beta^2\right]$$

……….. (1)

The term -dE/dx is termed as the stopping power, the negative sign indicating fall in energy with length, I being the excitation energy of the bound electron, N_A is the Avogadro's number, (Z/A) is the ratio of atomic number to the atomic mass, **ρ** is the target density and β is the ratio of velocity of the particle to the speed of light [7]. Stopping power is measured in units of Mev /(mg/cm^2) is called mass stopping power i.e., energy loss per unit mass-thickness.

The expression for the range of the projectile is given by the following formula.

$$R(E)=\int_0^E\left(\frac{dE}{dx}\right)^{-1}dE \quad …….. (2)$$

The formula for the range straggling has the following expression:

$$\sigma_R^2=\int_0^E\left(\frac{d\sigma_E}{dx}\right)\left(\frac{dE}{dx}\right)^{-3}dE \quad ……… (3)$$

Where σ_E^2 is the variance of energy straggling [7].

The stopping power of energetic ions in matter has great research interest as it has potential applications in ion implantation in semiconductors, radiation physics, nuclear detectors, and space radiation shielding and medical physics. Closely related to stopping power is the range of ions in the target material which depends on initial energy losses. In the present work we have tried to analyse the dependence of charge of ions on stopping power and range of incident light ions in a polymer- based target material called Polymethylmethacrylate (PMMA).

3. Results and Discussions

The following properties were studied for different ions ranging from Proton to Potassium, in the target material PMMA.

Range variation studies: Energies of ions from proton to potassium are varied from 100keV to 1000keV and the range of ions in the target material PMMA are studied and are found to vary with charge and incident energy as shown in Figure 1. Range is defined as the path length of the ions in the target material until they come to rest. The penetration depth of the implanted ions can be estimated if the instantaneous energy losses are known [6].

It is evident from the Figure 1., that the penetration depth decreases as the ion charge increases. Electronic stopping power increases with charge as Coulomb repulsion exists between incident charge and target electrons. The penetration depth increases as the energy of ion increases as the ions can overcome Coulomb and nuclear interactions with increase in energy. The penetration depth of the bombarding ions can be obtained if the instantaneous energy losses are known. Range is inversely related to energy loss or stopping power as is evident from equation 2. [8]. Range values are given in units of A^0.

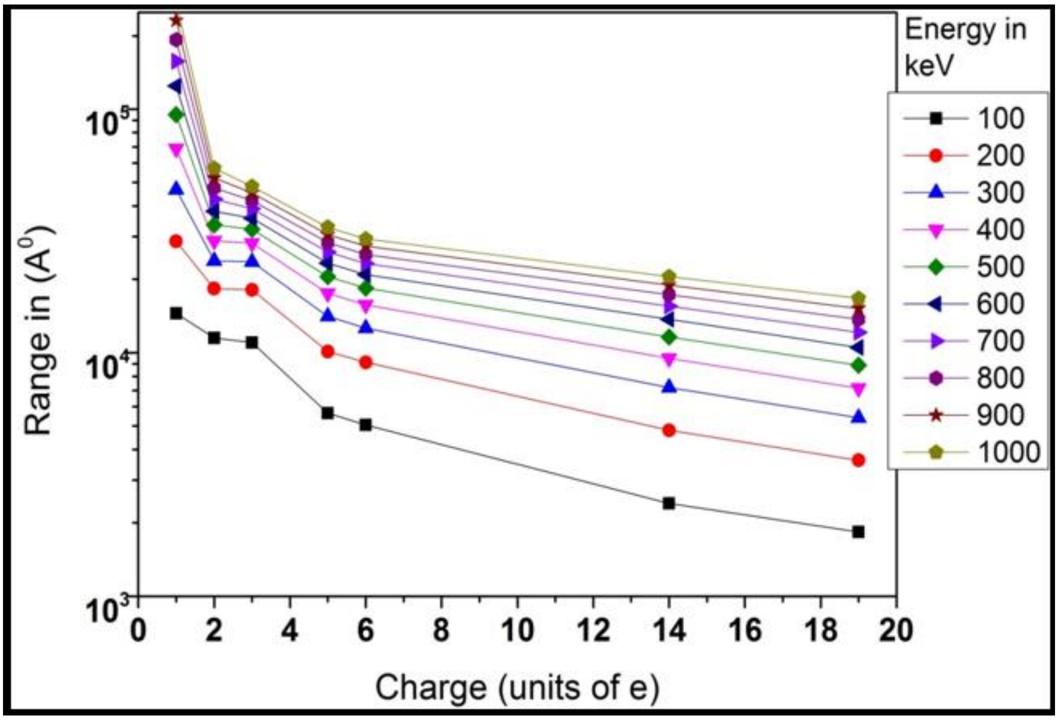

Figure 1: Variation of range with ion charge and energy for different ions

Total stopping power (Electronic and Nuclear):
Total stopping power refers to sum of electronic and nuclear stopping power. Some ions may experience both inelastic and elastic collisions due to electrons and atomic nuclei of target material. Figure 2., indicates variation of total stopping power with ion energy. Interaction of incident ions with the target electrons and thereby loss in its energy is called electronic stopping power. This interaction can result in excitation or ionization of electrons of the target atom. This interaction can happen at ion velocities which are comparable or greater than the orbital electron velocity of the target atom. Therefore electronic stopping is dominant at high energies. Electronic stopping controls range of ions in the target. Nuclear stopping can be considered to be elastic collision between two charged particles that of ion and atomic nucleus. The energy lost by the projectile to the target atom depends on the scattering angle. Nuclear stopping also refers to the transfer of energy to the recoiling nucleus at speeds less than the orbital velocity of the target electrons. Thus at lower speeds nuclear stopping is dominant for heavy ions as is evident from Figure 2. The interaction involves angular deflection of the incident ions affecting their range and energy loss [7, 9]. The deflection of energetic ions causes collision cascades which results in damage or modification (displacement, vacancies and interstitials) of the structure of the target material [10].

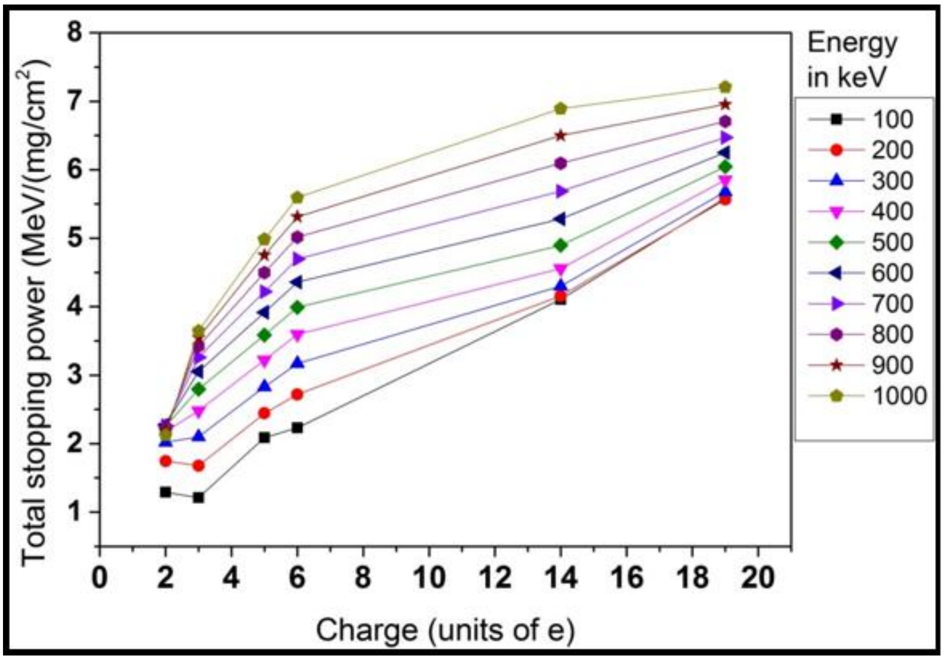

Figure 2: Variation of stopping power with ion charge and energy

Longitudinal and Lateral Straggling:
Ion straggling refers to statistical fluctuations in stopping powers due to various factors such as target density, atomic number, screening charges etc., The dispersion of energy in the target material is known as straggling. Lighter ions exhibit greater straggling due to stronger nuclear stopping which is referred to as nuclear straggling. Multiple scattering increases longitudinal straggling [11]. Longitudinal straggling refers to the spread of ions along the incident direction. The lateral straggling is the spread of ions perpendicular to the incident direction. Lateral straggling happens due to collisions with nuclei of target atoms. Lighter ions exhibit greater straggling due to stronger nuclear stopping, which is referred to as nuclear straggling, as is evident from Figure 3(a) and (b). Light ions undergo multiple scattering, which increases longitudinal straggling, whereas moderately heavier ions tend to move in focused trajectories and suffer small angular deflections, resulting in smaller straggling [12].

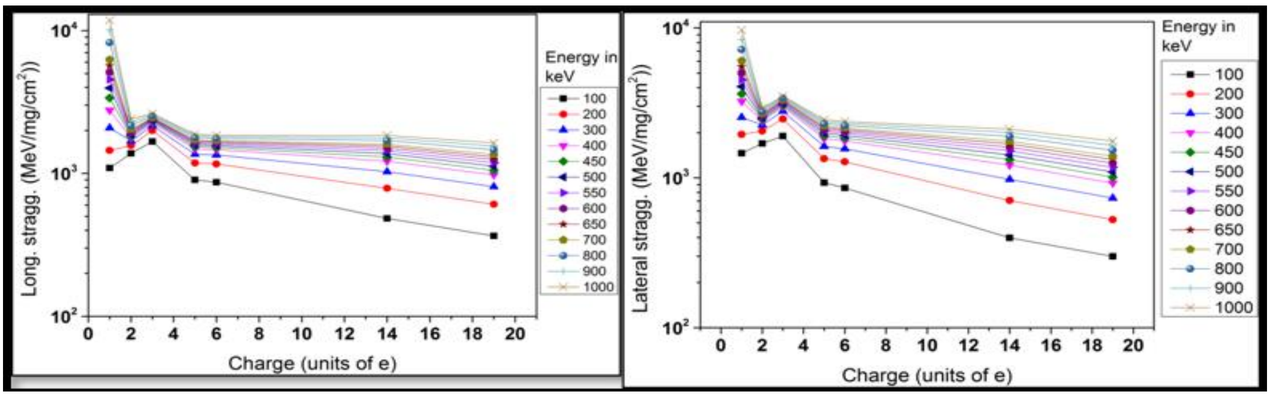

Figure 3: (a) Variation of longitudinal straggling with ion charge and energy (b) variation of lateral straggling with ion charge and energy

4. Conclusions

The following conclusions can be drawn from the current study.

Lighter ions have higher ranges compared to heavier ions. Range increases as the energy of the impinging ion increases. Range is strongly connected with stopping power. Electronic stopping is dominant in ions moving with high velocities whereas nuclear stopping is dominant in ions moving with low velocities. Moderately heavy ions lose energy intensely and locally (high stopping power), while light ions lose energy gradually and diffusely due to strong scattering and radiative losses. Light ions can be scattered easily resulting in larger straggling values.

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