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A Comparison between the Range of Electron and the Range of the Heavy Charged Particles in Some Human Body Tissues

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Abstract: In this research, the range and stopping power of light particles (electron) and heavy particles (P, Be4 and Ne10) that interact with three human tissues were calculated within the energy range (o.o1-1000Mev). Through the results we obtained, we found that the stopping power of light particles decreases rapidly at low energies and reaches the lowest value and then increases at high energies and the stopping power of heavy particles increases rapidly at low energies and reaches the maximum and then gradually decreases with increasing energy. The stopping power was found as a function of energy and the stopping power of incident particles was compared with each other. We found that the stopping power is directly proportional to the atomic number of the incident particle and also depends on the energy of the incident particle and the nature of the target material, and then employing the continuous slowing down approximation (CSDA) to calculate the path length (Range), and we found that the range depends on the energy of the incident particle, the density of the target material, the atomic number of the incident particle, and the atomic number of the target. It decreases with increasing atomic number of the incident particle. All equations have been programmed to present work using FORTRAN-90 and a program has been written for numerical calculations.

Keywords: charge particle, stopping power, range, electron, human body.

Introduction:

The loss of energy of charged particles when they penetrate matter occurs through ionization and excitation of atoms or molecules. Charged particles act on the atomic electrons of the target substance through electromagnetic force and the energy is transferred to the target electrons. Energy transferred from charged particles to orbital electrons may cause excitation (the electrons move to higher orbits) or cause ionization of the atom by releasing an orbital electron outward. Heavy charged particles lose a small portion of energy during a single collision, and constantly lose a small portion of energy when colliding with atomic electrons. It moves in an almost straight line, and in some cases the path bends due to Rutherford scattering with the nucleus [1]. Electrons and positrons, when they collide with the electrons orbiting the target, lose a large portion of their energy during a single collision. They lose their energy almost continuously as they slowdown in matter, the path is not a straight line but is curved because the scattering angle is large, in general electrons are scattered by elastic scattering with the nucleus, electrons and positrons do not propagate in a straight line but rather in a zigzag line. In addition, electrons emit bremsstrahlung photons when the path is sharply bent. The contribution of bremsstrahlung to the stopping power becomes important at high-energy regions [2].

The average energy loss of charged particles per unit length is called the stopping power (-dE/dx) of the particle, and the negative sign means that the loss of energy increases as the projectile enters the target [3]. And it is important in the field of radiation physics and dosimetry. Recently, interest in studying the stopping power and range of charged particles has increased significantly in radiation physics (theoretical and experimental studies). Many studies have been conducted on this subject with great efficiency due to the importance of these studies in treating cancerous diseases [4]. According to the World Health Organization, approximately seven million people die from cancer, which is the second cause of death after cardiovascular diseases. The number of cancer cases is expected to rise to fifty percent. Radiation therapy (using charged particles) is one of the most important treatment methods, along with chemotherapy and surgery. Clinical radiotherapy works to destroy cancer cells without harming healthy tissue, using high ionization radiation, Ionizing radiation has sufficient energy to break any chemical bond and cause ionization in all materials. We need high accuracy in dose delivery to maintain the integrity of healthy tissues, charged particles used in radiotherapy are produced by accelerating nuclei or ions in cyclotrons and synchrotrons [5].

Literature Review

The theoretical part:

(i) Calculating the stopping power and range of light charged particles:

The stopping power for light particles (electrons) consists of two components: the first is the collision stopping power, which is the most important and results from the collision interaction between the incident electrons and the atomic electrons, it is calculated from the following equation [6]:

$$\left(\frac{dE}{dx}\right)_c = \left(\frac{e^2}{4\pi\varepsilon_o}\right)^2 \left[\frac{2\pi N_o Z\rho}{mc^2\beta^2 A}\right] \left[\begin{array}{l} \frac{T\left(T+mc^2\right)\beta^2}{2I^2mc^2} + \left(1-\beta^2\right) - \left(2\sqrt{1-\beta^2}\right) \\ -1+\beta^2 \ln 2 - \frac{1}{2}\left(1-\sqrt{1-\beta^2}\right)^2 \end{array}\right] \ldots\ldots\ldots\ldots\ldots\ldots.(1)$$

The second component is: radiative stopping power, which is less important than the first. It results from the deviation of the incident electron from its path when approaching the target nucleus, and this deviation is tantamount to acceleration, and this acceleration causes radiation called bremsstrahlung radiation. bremsstrahlung radiation occurs when the energy of the incident electrons is high($E\rangle\rangle m_o c^2$), but at low energies the radiative stopping power is neglected. This type of energy loss does not occur in heavy particles because the mass of heavy particles is much greater than the mass of the electron, and therefore no bremsstrahlung radiation occurs for charged particles. We can calculate the radiative stopping power from the following equation [7]:

$$\left(\frac{dE}{dx}\right)_r = \left(\frac{e^2}{4\pi\varepsilon_o}\right)^2 \left[\frac{N_o Z^2 \rho\left(T+mc^2\right)}{137m^2c^4A}\right] \left[4\ln\frac{2\left(T+mc^2\right)}{mc^2} - \frac{4}{3}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

To obtain the total stopping power, this is done by summing: collision stopping power and radiative stopping power[8] and measured in units MeV.cm^2/g :

$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_c + \left(\frac{dE}{dx}\right)_r \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Mass collision stopping power is widely used to reduce the dependence on the mean density [8] (ρ). Many physicists have calculated the stopping power, but the basic, classic derivation was due to Bloch who improved a calculation by Bethe; hence the Bethe-Bloch Formula. The rate of energy loss is given by (– dE/dx); dE/dx being a loss of energy, is a negative quantity The full expression for the Bethe-Bloch formula can be written as [9]:

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

Where: T kinetic energy of electron, I: is the ionization, ρ: density the important dependence, the subscripts c is: the energy losses due to collisions, the subscripts r is: the energy losses due to radiations, e= electronic charge, v= velocity of the particle, m= electron rest mass, z= multiple of electron charge, β= v/c (v is the speed of the particle and c is the speed of light in a vacuum) ,$I = \hbar\omega$: is mean excitation potential of the absorber, N_A: Avogadro's number.

Range Calculations:

Range: It is the distance that the charged particles travel inside the target material until they stop, and it is assumed that the charged particles continuously slow down until they completely lose their initial energy, and this is called ((The Continuous Slowing Down Approximation range)) (CSDA). However, the term electron range means CSDA range [10]. This determines the average path length extending from the beginning to the end of the breakout. It is different from the distance traveled along the path of an electron, In our experiments, we do not use meters to measure length, but rather we use units of mass per square meter(multiplying the length parameter by the density of the material [11] . The CSDA range R is written by equation following :[12]

$$R = \int_0^E \left[\left(\frac{dE}{dx} \right)_c + \left(\frac{dE}{dx} \right)_r \right] dE \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

(ii) Calculating the stopping power and range of heavy charged particles:

The stopping power of heavy charged particles is similar to the stopping power of electrons, but the difference is: the stopping power of the heavy particles consists of two components. The first is the collision stopping power, which results from the interaction of the incident particles and the target electrons. The second component is: nuclear stopping power, which is less important than the first. Resulting due to elastic scattering of heavy charged particles with the nucleus. The nuclear stopping power is neglected at high energies and cannot be neglected at energies less than (10kev). The first collision lead to energy loss without significant deflection of the primary particle, whereas the latter lead to a large-angle scattering process . The total stopping power is the sum of: collision loss and nuclear loss [13].

$$\frac{dE}{dx} = \left(\frac{dE}{dx} \right)_c + \left(\frac{dE}{dx} \right)_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

We can find the nuclear stopping power through the following equation[7]:

$$\left(\frac{dE}{dx} \right)_n = \frac{2\pi N_A \rho}{A} \int_0^{\pi} \frac{d\sigma}{d} W(\theta, T) \sin\theta d\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Where:

$$W(\theta, T) = 4T \frac{M_t M}{(M_t + M)^2} \sin^2 \frac{\theta}{2} \;,\; \frac{d\sigma}{d} = \frac{N_A Z_1^2 Z_2^2 r_e^2}{} \frac{mc^2}{\mathrm{P}\beta} \frac{1}{\sin^4 \frac{\theta}{2}} \;,\; \mathrm{P} = \frac{1}{c}\sqrt{\left(T + Mc^2\right)^2 - \left(Mc^2\right)^2}$$

$W(\theta, T)$:is the recoil energy, M: mass of the particle, M_t: mass of the target, P: momentum of the heavy charged particle, $\frac{d\sigma}{d}$:the differential cross section for elastic scattering.$Z_1 Z_2$: The atomic number of the incident particle and the target, respectively.

For range of the heavy charged particles, unlike electrons, the effect of multiple scattering is not considered. It is approximated those continuously slow down nearly on a straight line. It can be found through the equation [7]:

$$R = \int_0^E \left[\left(\frac{dE}{dx} \right)_c + \left(\frac{dE}{dx} \right)_n \right] dE \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

Methodology

The methodology employed in this study involves the computational analysis of the stopping power and range of light (electrons) and heavy (protons, beryllium, and neon) charged particles interacting with human tissues, specifically breast, lung, and muscle. The study utilizes the Continuous Slowing Down Approximation (CSDA) to determine the path length of these particles. To achieve precise calculations, FORTRAN-90 was used for programming the mathematical models and numerical computations. The stopping power, defined as the average energy loss per unit distance traveled by a charged particle, was computed using the Bethe-Bloch formula for both light and heavy particles. The study distinguishes between collisional and radiative stopping power for electrons, whereas for heavy particles, collisional and nuclear stopping power were considered. The range of each particle was obtained by integrating the reciprocal of the stopping power over the energy spectrum. The effect of atomic number, energy, and target material density on stopping power and range was evaluated through simulation. The study emphasizes that the range of electrons is significantly larger due to their lower mass, whereas heavy particles travel in straighter trajectories with reduced scattering. The methodology ensures accuracy in modeling energy loss and penetration depth in biological tissues, providing insights valuable for applications in medical physics, particularly in radiotherapy for cancer treatment. This computational approach allows for the systematic analysis of particle interactions in human tissues, offering critical data for optimizing radiation therapy and understanding the fundamental properties of charged particle behavior in biological matter.

Results and Discussion:

To calculate the range of electrons and heavy charged particles moving in matter, the total stopping power of each of them must be found, where the force resulting from the interaction of the incident electrons with the atomic electrons leading to excitation or ionization can be calculated from Bethe's theory and this force is called the collisional stopping power, the force resulting from the acceleration of electrons in the Coulomb field of the nucleus is called the radiation stopping power, there is a force resulting from the elastic scattering of heavy charged particles with the nucleus called the nuclear stopping power. The total stopping power of the electron and heavy charged particles is found from the equation (3) and (6) respectively. The figures below show the stopping power of electron and heavy charged particles in body tissues .

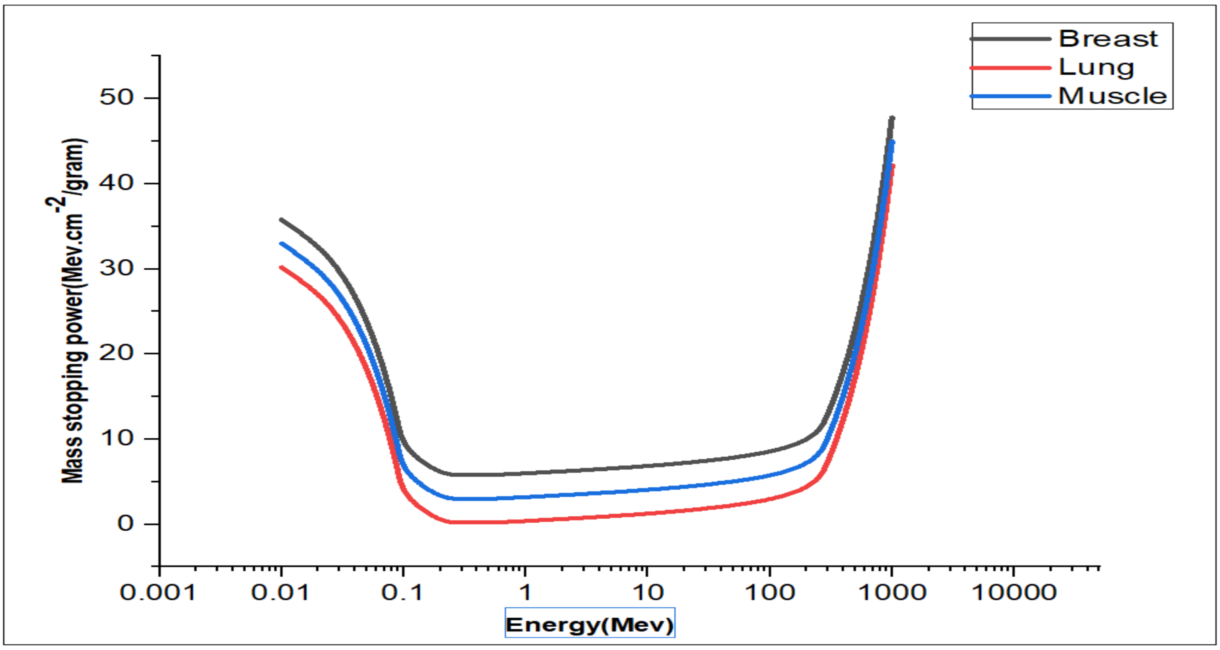


Fig (1) Stopping power of Electron in human body tissues (Breast, Lung and Muscle).

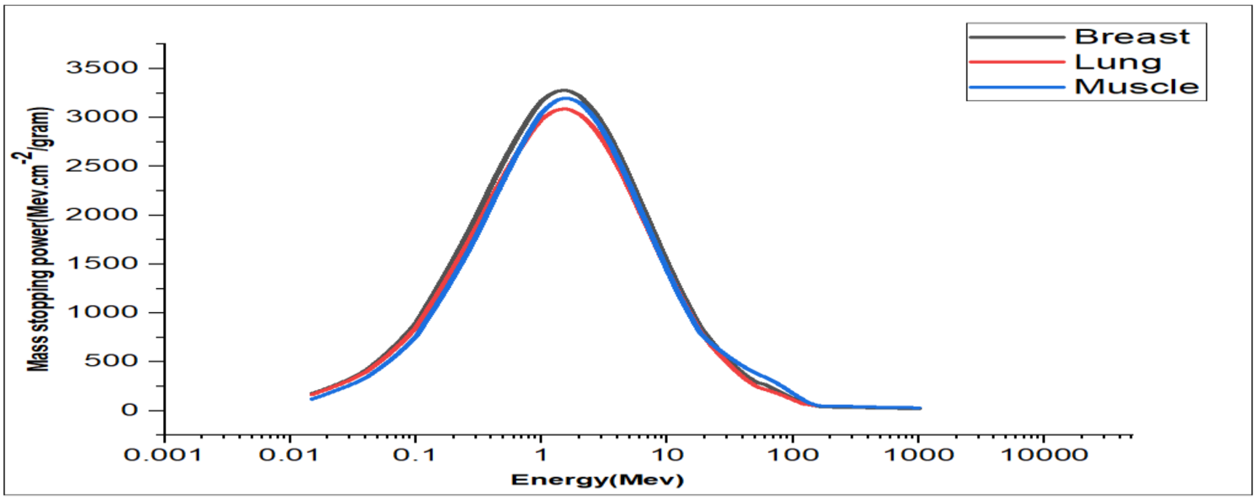
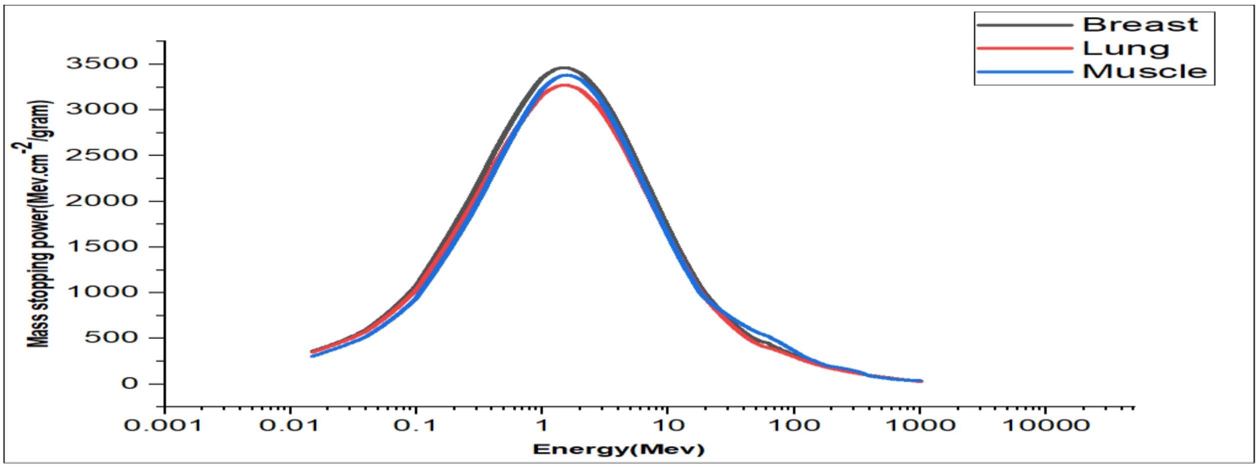
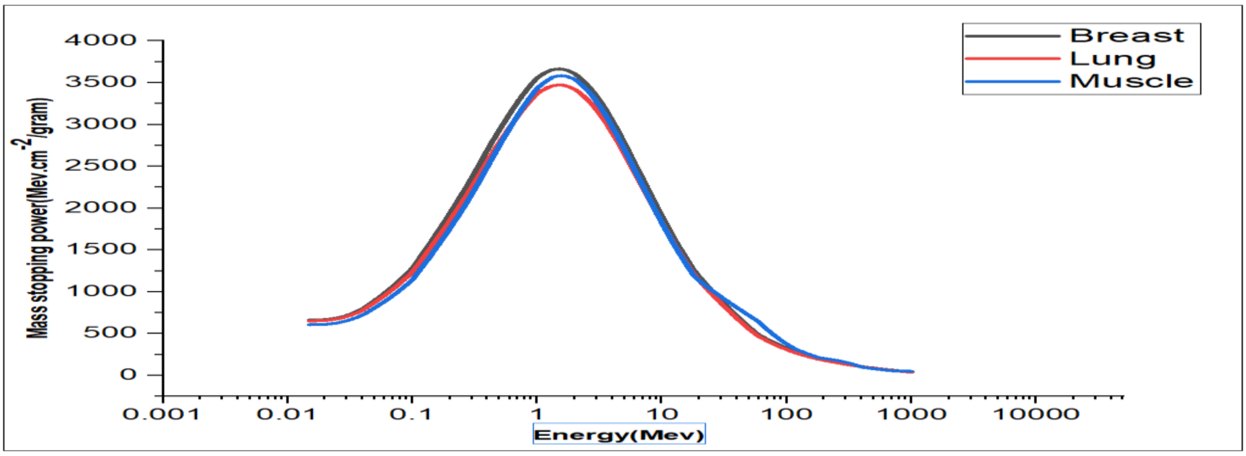


Fig (2) Stopping power of Proton in human body tissues (Breast, Lung and Muscle).



Fig(3) Stopping power of Alpha particles in human body tissues (Breast, Lung and Muscle).



Fig(4) Stopping power of Beryllium in human body tissues (Breast, Lung and Muscle).

As for the range (the distance that the charged particle travels inside the target material until it stops), light particles such as electrons and positrons spread at a large angle due to their low weight. As for the path of heavy charged particles, it is a straight line. The range of electrons and heavy charged particles can be found through the equation (5) and (8) respectively. The figures below show the range of electron and heavy charged particles in body tissues (Breast, Lung and Muscle).

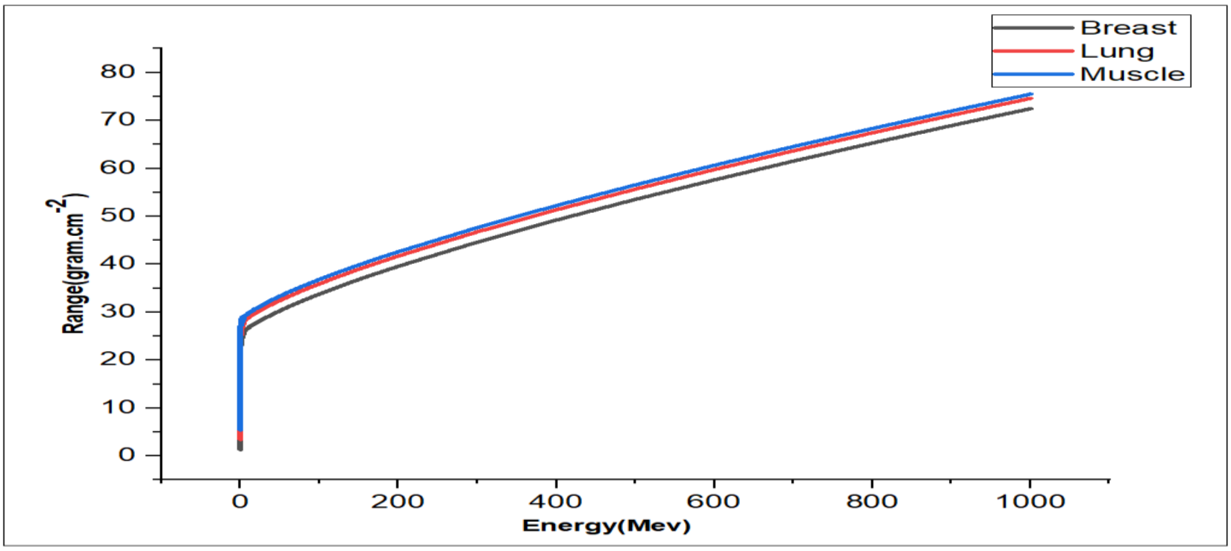


Fig (5) Range of Electron in human body tissues (Breast, Lung and Muscle).

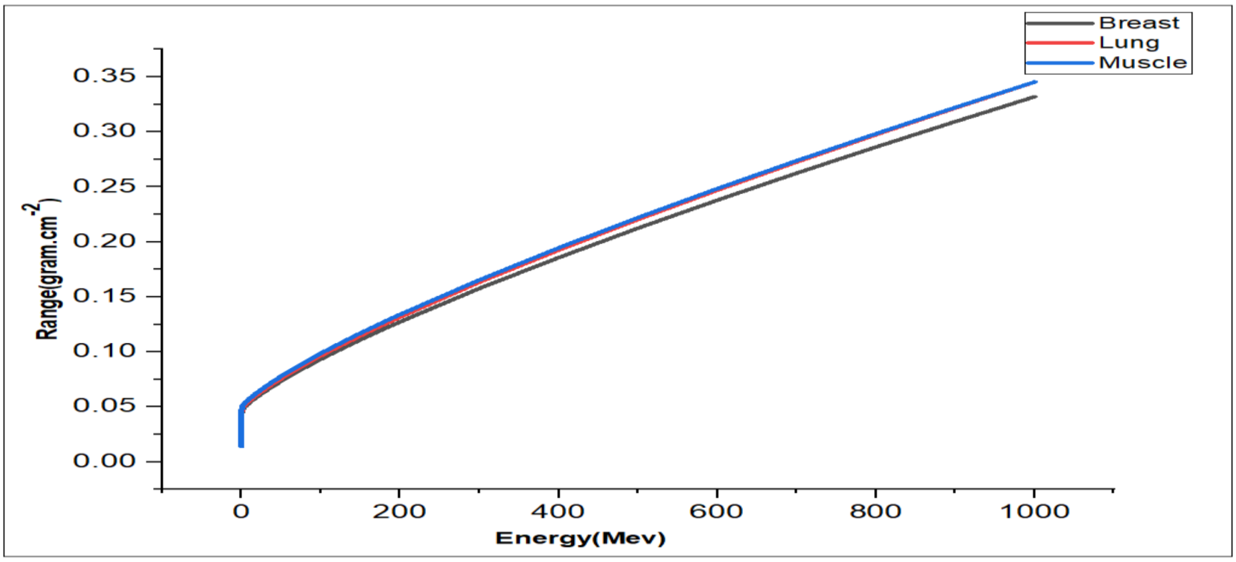


Fig (6) Range of Proton in human body tissues (Breast, Lung and Muscle).

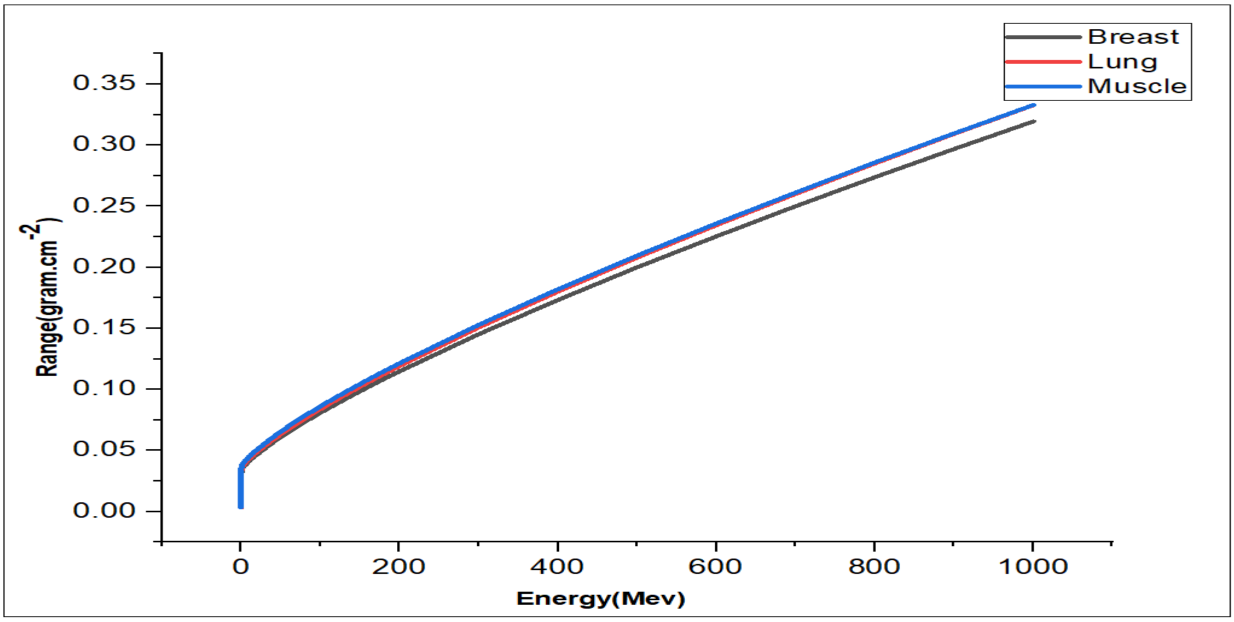


Fig (7) Range of Alpha particles in human body tissues (Breast, Lung and Muscle).

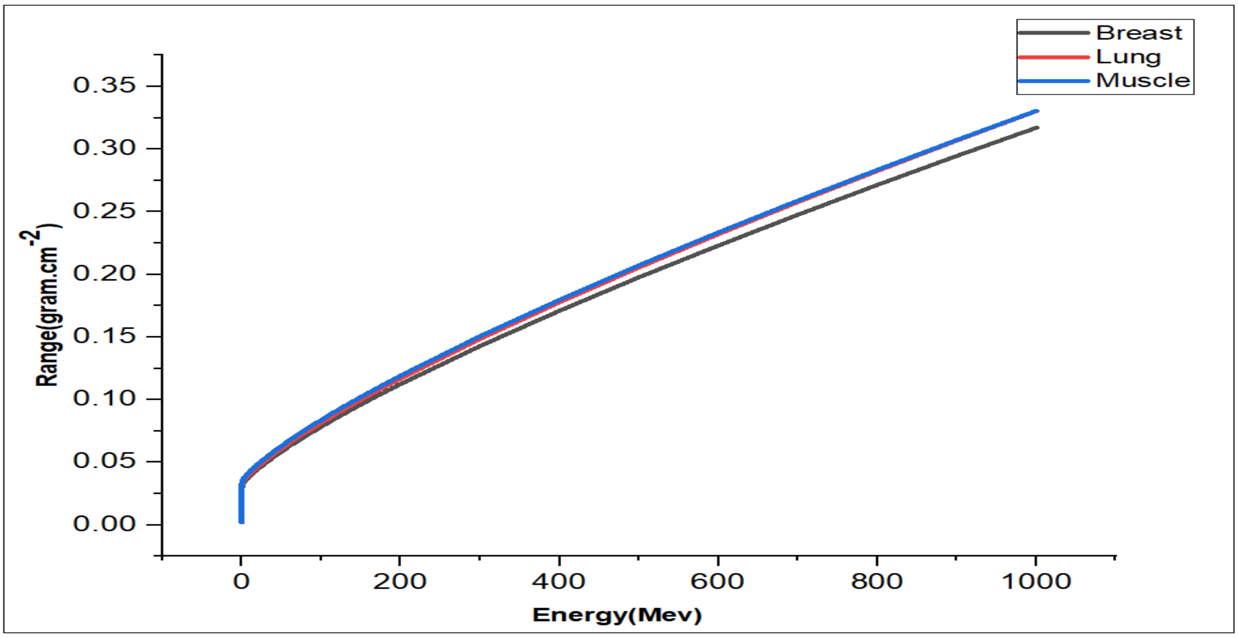


Fig (8) Range of Beryllium in human body tissues (Breast, Lung and Muscle).

Conclusion:

Through this study we can conclude:

- The stopping power depends on the energy of the incident particle, its type, the type of target material, and the atomic number of the incident particle (it increases with increasing atomic number of the incident particle). but its dependence is weak on the atomic number of the target.
- In heavy charged particles, the total stopping power increases rapidly at low energies, reaches a maximum, and gradually decreases with increasing energy, the reason for this is that the nuclear stopping power is effective only at low energies, while at high energies it is ineffective. Therefore, the total stopping power decreases at high energies according to the equation (6).
- In light particles (electrons)The total stopping power decreases with increasing energy of the incident particle (electron) at energies (0.01-10Mev). The reason for this is that only the collision stopping power is effective, while the radiation stopping power is ineffective at this range of energies. The total stopping power increases at high energies (greater than 10 Mev) because the radiative stopping power is effective in addition to the collision stopping power, according to the equation (3).
- Heavy particles are less scattered than electrons due to their heavy.
- In heavy charged particles, the energy loss is maximum when the particles slow down at the top of the curve.
- The magnitude of the range depends on the energy of the incident particle, the nature of the target material, and the atomic number of the incident particle and the target.
- The range of heavy charged particles is the same as the penetration depth because heavy charged particles travel in straight lines.
- The penetration of the particle into the target depends on the density of the target, so the penetration of the particle in the target with high density less than its penetration for the target with low density.

The range of the electron is higher than the range of the heavy particles because the mass of the electron is less than the mass of the heavy particles.

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