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Characterizing Scattering Cross-Sections and Stopping Power of Ionizing Radiation in Matter

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ABSTRACT

As the space travel industry continues to grow, it is important to better understand the increased radiation that astronauts, spacecraft, and satellites are exposed to in space. A deeper understanding will allow manufacturers to improve designs in order to protect their craft and their astronauts. Using models for the scattering cross sections and stopping distances of particles that interact in Lower Earth Orbit (LEO), plots were created to display the behavior of particles as they impact materials commonly implemented on spacecraft. The resulting impacts and degradation from the radiation exposure are analyzed in this research, and a further interpretation of the results applied to future research is discussed.

Index Terms **—** *radiation, stopping power, ionization, scattering, alpha particles, beta particles, electrons, protons, Bethe*

I. INTRODUCTION

The private sector (companies such as Blue Origin, SpaceX, Orbital ATK) has increased interest in the commercial space industry, leading to government agencies such as NASA to contract private companies to build suborbital spaceships and aid scientific missions. Additionally, the possibility of a ‘space tourism’ industry provides long-term goals for many in the private sector [Reifert, 2009]. However, the majority of these missions, including trips to the International Space Station, are in low earth orbit (LEO).

LEO poses a unique environment where solar flares, Earth’s magnetic field, and even cosmic rays (high-energy radiation, typically from outside the Solar System) trap energetic particles. This environment leads to increased levels of radiation for spacecraft, astronauts, and satellites to be subjected to as they travel in or through LEO [Pisacane, 2008]. Evaluating the dangers of extended radiation exposures in this environment is necessary in order to mitigate them.

This analysis can be broken down into radiation exposure based on the particle, and susceptibility of certain materials to said particle. Existing models can simulate the radiation environment, using the material properties of the shielding materials used on the spacecraft, astronauts, or satellites (in this research, these shielding materials will be considered the targets), and the properties of the potential damage particles.

With rise in the commercial space industry, dependence on commercial off-the-shelf (COTS) devices may rise as well. COTS devices are not generally designed for use in space; therefore, they are particularly susceptible to radiation events. The LEO environment is recognized as a considerable risk with COTS electronic and optoelectronic devices and systems [Martinez, 2011].

While LEO’s radiation environment has been taken into account when designing spacecraft in the past, satellite failures have still been linked to radiation effects. The Hipparcos, a scientific satellite of the European Space Agency, is an example of this. After functioning at expected capabilities for three years, the Hipparcos began to experience communication difficulties, a problem attributed to radiation damage to certain components. This damage ultimately led to mission operation termination within a few months after the problems began [Bedingfield et al., 1996]. Similarly, the Japanese Engineering Test Satellite (ETS-6) failed within a year of deployment, due to erosion of its solar panels from solar radiation [Martinez, 2011]. These are merely a couple of examples of many missions that have been compromised due to radiation effects. This is why thorough consideration of radiation must be taken into consideration to ensure mission success.

In order to engineer materials able to withstand the radiation environment, it is important to understand the environment, such as through empirical models. A common reference is NASA's AP and AE radiation belt models that show proton fluxes and electron fluxes for solar minima and maxima. Once LEO's radiation environment is mapped out, the microscopic interactions between the impact particles and target materials can be modeled and observed.

While there has been significant progress in radiation hardening, a deeper understanding of the radiation effects that lead to failure is needed, particularly in light of COTS devices, in order to aid the success of future commercial missions to LEO. This research studies the interactions of the impact particles and target materials on a microscopic level, analyzing and plotting the behavior of the interactions. An effective continuation of this research would be to use the results to find the average range of the impact particles, and to detail the effect of this radiation on a variety of shielding materials.

II. INTERACTIONS

The addressed radiation types are a result of charged particles: alpha particles, electrons (beta particles), and protons. Key characteristics of these radiation types can be found in Table 1. At 1MeV, the electron is relativistic, however the heavier particles are slower, easier to stop, and deposit all of their energy over a shorter distance [Martinez, 2011].

A. Cross Sections

The way these energetic particles interact with matter can be described as a scattering process. Depending on a radiation type, energy, and the target atom, there are a variety of processes that may occur. For each process, the probability of its occurrence can be found.

Characteristic	Alpha (α)	Beta (β)	Proton (p)
Symbol	${}^{4}_{2}He^{2+}$	${}^{0}_{-1}e$ or β	${}^{1}_{1}p$ or H^{1+}
Charge	+2	-1	+1
Ionization	Direct	Direct	Direct
Mass (amu)	4.001506	0.0005485	1.00727
Velocity (cm/s)	6.944×10^{8}	2.82×10^{10}	1.38×10^{9}
Velocity (*c*)	2.35%	94.1%	4.6%
Range in Air (cm)	0.56	319	1.81

Table 1. Characteristics of charged particles- alpha, beta, and protons.

This can be done by actually treating the scattering process as an equivalent series of stationary ones, with many occurring from a continuous current of particles incident on the target atom, rather than as dynamic, or time-dependent, sets of individual interactions.

In the late 19th century, J. J. Thomson developed the plum pudding model, stating that negatively charged electrons were distributed throughout the atom in a uniform sea of positive charge. Ernest Rutherford, wanting to test Thomson's postulate, conducted a scattering experiment by bombarding thin gold foil with alpha particles. While most of the alpha particles passed straight through or were deflected by very small amounts, a very small fraction experience deflection by a large angle. Using scattering theory, Rutherford was able to conclude that 99.9% of the atom is empty space, and that in consists of centralized, positively charged nucleus surrounded by a cloud of orbiting electrons.

The scattering cross section, σ, a measure of the rate of reactions that occur per target atom for a given flux of the incident radiation, is used as a parameter for this analysis. The target is assumed to be at rest, while the incident particles have a specific energy. In order to find the reaction rate, it is necessary to sum over all possible directions into which the particle scatters, which is why σ is called the total cross section. Measured in barns (1 barn = 10^{-28} m^2), the cross section is also strongly dependent on the angle of the scattering. Therefore, the differential cross section

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v_0^2}\right)^2 csc^4\left(\frac{\theta}{2}\right) \tag{1}$$

was used to model Rutherford type scattering, as shown in Figure 1.

B. Charged Particle Interactions

Charged particles are classified as *directly ionizing*, because they interact strongly with the orbital electrons of the material they move through. Heavy charged particles (alpha particles and protons) lose energy in small steps, through interactions with the electrons. Once the particle has lost too much energy to ionize the material, it loses energy by nuclear collisions, capturing electron(s) as it slows to form a neutral atom (an alpha particle becomes helium, a proton becomes hydrogen) [Martinez, 2011].

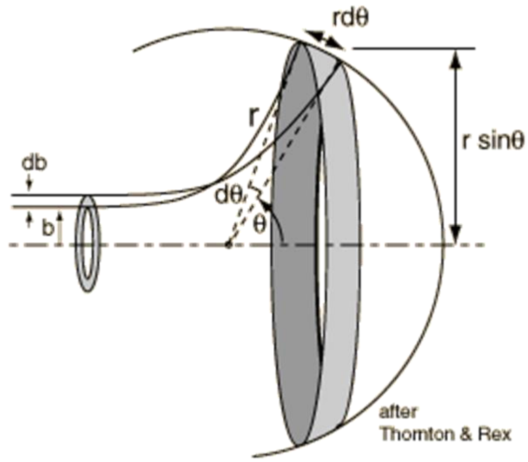

Fig. 1. Scattering cross section.

The coulombic interactions with the atomic electrons slow the particles almost to a stop, and because of the high number of interactions, the slowing down is nearly continuous [Martinez, 2011]. Atomic electrons cannot typically deflect ions, so their path of travel is relatively straight. Heavy particles, even particularly energetic ones, have a well-defined range of merely a few centimeters in air.

Heavy charged particles have such a large mass, that any single scattering interaction does not result in a significant fractional loss of the particle's kinetic energy, and cannot significantly affect its momentum vector. Therefore it would take a great deal of collisions, on average, for a heavy charged particle to come to a rest in a medium. Because such little energy is lost per collision, and the stopping medium is assumed to be isotropic, the trajectory of a heavy charged particle is assumed to be linear, and in any single collision the velocity can be considered constant [Prussin, 2007].

Using Hans Bethe's derivation by quantum mechanics (the "Bethe equation")

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 \right] \quad (2)$$

where, by the low energy approximation seen in equation (3)

$$T_{max} = 2m_e c^2 \beta^2 \gamma^2 \tag{3}$$

the researcher created a model in MatLab to describe the mean rate of energy loss by charged heavy particles. This energy loss is referred to as the *stopping power* due to ionization, and can essentially be considered the total stopping power for heavy ions [Prussin, 2007]. While the limits are partially dependent on the projectile velocity (v), the particle mass (M), and the atomic number of the absorber (Z), therefore depending on different targets), ultimately $\left\langle \frac{dE}{dx} \right\rangle$ is a function of β. The input values used to calculate the curves shown in Figures 2 and 3 can be found in Table 2.

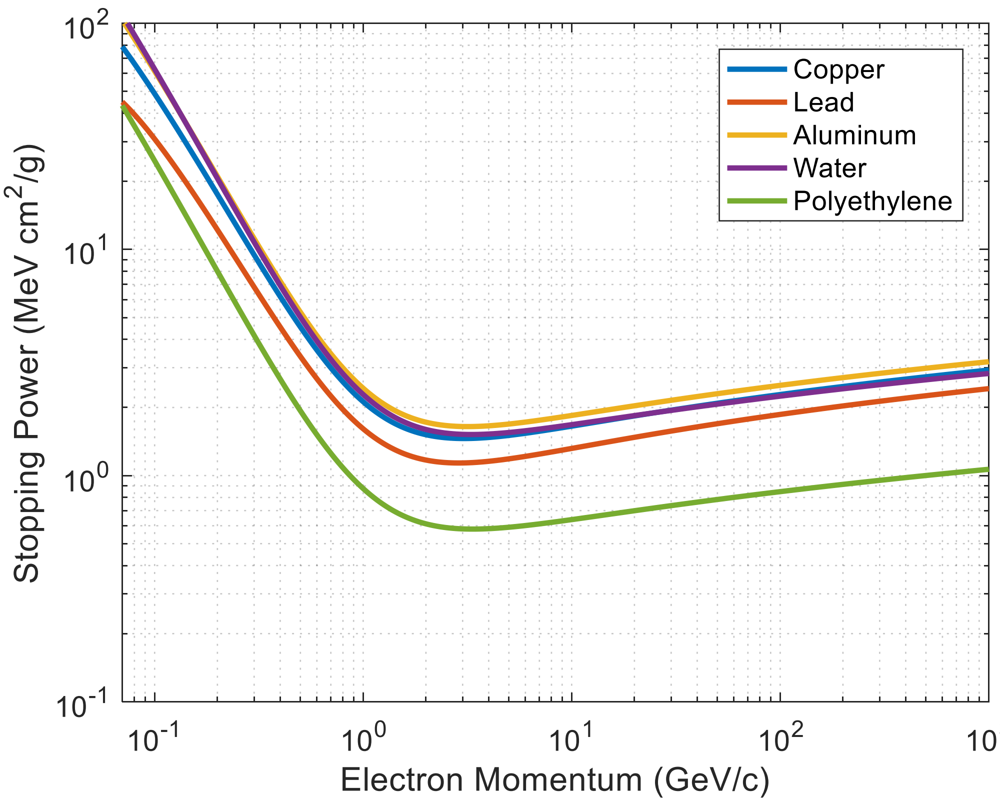

Figure 2. Stopping power of common materials used in spacecraft, with respect to electron (β) momentum.

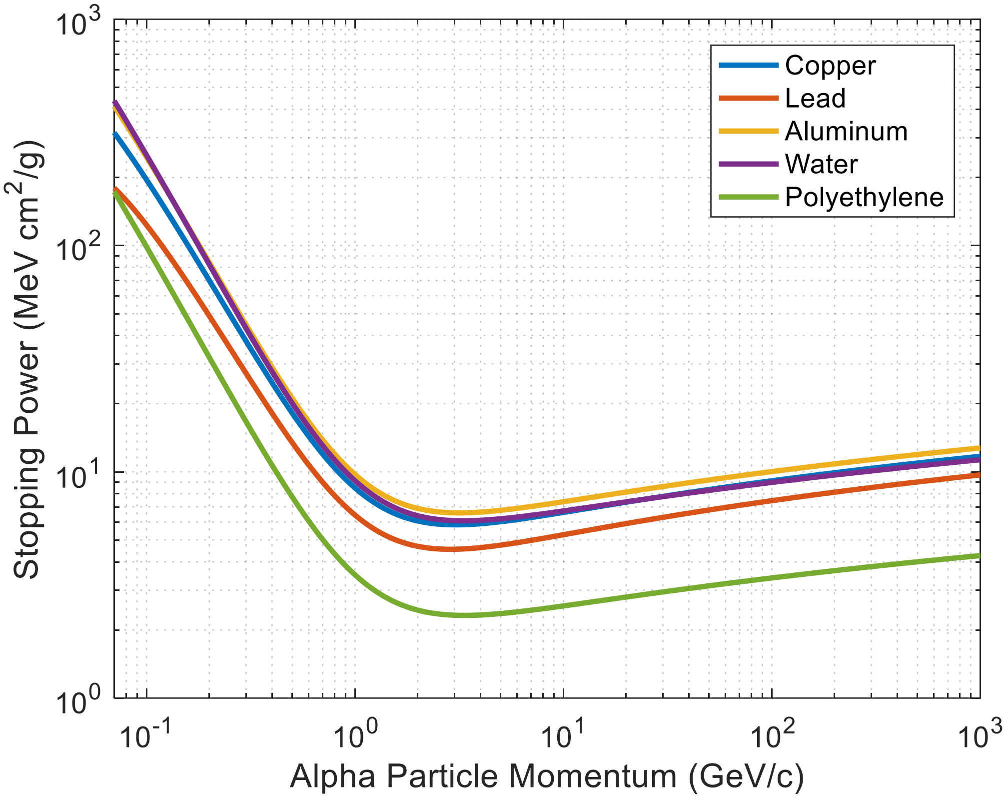

Figure 3. Stopping power of common materials used in spacecraft, with respect to α particle momentum.

Material	Atomic Number (z)	Atomic Mass [g/mol]	Mean Excitation energy [eV]
Copper	29	63.5	322
Lead	82	207.2	823
Aluminum	13	26.9	166
Water	7.42	18	75
Polyethylene	4.299	28	57.4

Table 2. Values used to model the Bethe equation and create stopping power curves.

III. Discussion

A. Results

For protons, it was found that the best shielding material would be water. However, this is obviously a difficult shield to implement in space travel. The best material was lead, for energies close to 1 MeV. Aluminum, for energies greater than 1 MeV, was the following material, due to its high density of electrons and high ionization constant.

For alpha particles, it is evident that they deposit greater amounts of energy per unit distance. These heavier particles are expected to travel shorter distances. However, the results are similar to protons in that for energies below 2MeV, the best material is polyethylene, and for energies greater than 10 MeV, aluminum and water are shown as the best shielding materials.

B. Implications

An effective continuation of this research would be to expand analysis on average range due to stopping power. The results found from the models created in this research can be used to calculate average range, the distance that the impact particles penetrate their target materials. While this value, known as the *average range* of the particle in a particular medium, was not derived and modeled in the scope of this research, it is still important in interpreting the results of this research. Therefore, the discussion will reference the average ranges (R)

$$R = \int_{E_0}^{0} \left(\frac{dE}{dx}\right)^{-1} dE \tag{4}$$

found using a model by Martinez in her dissertation [2011]. For protons, it was found that lead had the smallest average range function, an expected conclusion due to lead’s higher stopping power. For alpha particles (with average ranges almost an order of magnitude smaller than protons, due to slower movement leading to shorter distances), water was shown to be good shielding.

We learn from these models that the range of heavy charged particles in matter is quite small, due to the great amount of collisions with the electrons. While the heavy ions move through the matter, there is some probability that they will pick up electrons, or even that an electron bound to them may be taken up once again by the medium. The probability of capture/release is dependent upon the electrons' binding energies and the energies of the electrons in the medium. Typically, particularly for ions of higher atomic numbers, there will be a continuous reduction in ionic charge as they slow.

This research merely models the behavior of these high energy particles. As discussed, further research supported from these models can make greater findings that will impact the industry's future decision making. Based on discussions from factors such as the average range, recommendations for shielding materials can be made towards manufacturers in the private sector.

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