Tantalum based polymers for cosmic radiation shielding

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Abstract. Cosmic radiation poses a significant challenge for long-duration space missions by inducing biological damage and degradation of spacecraft materials and electronics. In this study, the radiation shielding performance of tantalum-based polymers, $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$, is investigated using the Stopping and Range of Ions in Matter (SRIM) framework. Key interaction parameters, including stopping power, projected range, and straggling, are evaluated for protons, alpha particles, and representative heavy ions (C, O, and Fe), and compared with a hydrogen-rich reference polymer, C_2H_4. While hydrogen-rich materials exhibit higher stopping power for light ions, tantalum-based polymers significantly reduce ion penetration depth, enabling compact shielding. The results indicate that tantalum-based polymers are promising candidates for hybrid or multilayer cosmic radiation shielding applications.

1 Introduction

Cosmic radiation shielding is essential to protect astronauts, spacecraft electronics, and materials from high-energy particles such as galactic cosmic rays and solar energetic particles. These radiations can penetrate biological tissue, causing DNA damage, increased cancer risk, and neurological effects during long-duration space missions [1]. Radiation also induces single-event upsets and long-term degradation in electronic components, threatening mission reliability [2]. Advanced shielding using hydrogen-rich polymers and composite materials helps reduce both primary radiation and secondary particle production, enabling safer human space exploration and improving the operational lifetime of space systems [3].

Cosmic radiation is composed mainly of energetic ions originating from galactic and solar sources. Protons (hydrogen nuclei) dominate the cosmic-ray spectrum, contributing about 85–90% of the total flux, followed by alpha particles (helium nuclei) at nearly 10–12%. Heavier ions ranging from lithium to iron and beyond constitute the high-charge and high-energy (HZE) component. Although their abundance is small (~1%), HZE ions possess high linear energy transfer and are responsible for significant biological and material damage in space environments [1]. Solar cosmic radiation additionally includes low-energy protons and helium ions released during solar particle events [4].

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Polymers are extensively investigated for cosmic radiation shielding because of their high hydrogen content, low mass density, and ability to suppress secondary particle production. Hydrogen-rich polymers such as polyethylene (PE) and ultra-high molecular weight polyethylene (UHMWPE) effectively attenuate galactic cosmic rays through elastic scattering with hydrogen nuclei, thereby reducing the absorbed dose [1]. Comparative experimental studies have demonstrated that UHMWPE provides superior shielding performance compared to conventional aluminum shields against high-energy protons and heavy ions. Recent advances in polymer composites, including hydrogen-rich benzoxazine resins and UHMWPE-fiber-reinforced systems, show improved mechanical integrity and enhanced radiation resistance under simulated and real space environments [5].

Stopping power is a key parameter in selecting materials for cosmic radiation shielding because it determines how efficiently energetic charged particles lose energy while passing through matter. It is defined as the energy loss per unit path length, $-dE/dx$, and governs dose reduction inside shielding materials. For cosmic radiation dominated by protons and heavy ions, materials with appropriate stopping power can significantly attenuate particle energy and associated biological damage [1]. However, high-Z materials, despite exhibiting large stopping power, tend to generate harmful secondary radiation. Hence, low-Z, hydrogen-rich polymers are preferred for space radiation shielding, as they provide effective energy loss with minimal secondary particle production [6].

Motivated by the growing demand for lightweight, compact, and efficient radiation shielding materials for long-duration space missions, the present work aims to systematically investigate the shielding potential of tantalum-based polymers against cosmic radiation. While hydrogen-rich polymers are well known for their superior stopping efficiency for protons and light ions, high-Z constituents such as tantalum can significantly reduce ion penetration depth and enhance structural robustness. Therefore, this study focuses on a detailed analysis of stopping power, projected range, and straggling characteristics of dominant cosmic-ray ions in $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$, using the SRIM framework, with the objective of assessing their feasibility in hybrid and multilayer shielding designs for space applications.

2 Theory

The *Stopping and Range of Ions in Matter (SRIM)* program, developed by Ziegler *et al.*, is based on a semi-empirical description of ion–matter interactions. The total stopping power is expressed as the sum of electronic and nuclear components,

$$-\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{\mathrm{e}} + \left(\frac{dE}{dx}\right)_{\mathrm{n}} .$$

Electronic stopping, dominant at medium and high ion velocities, arises from inelastic collisions with target electrons. At high energies it follows a Bethe-type form,

$$\left(\frac{dE}{dx}\right)_{\mathrm{e}} \propto \frac{Z_1^2}{v^2} \ln\left(\frac{2m_e v^2}{I}\right),$$

while at low energies it is described using the Lindhard–Scharff–Schiøtt (LSS) theory.

Nuclear stopping, important at low energies, is due to elastic ion–nucleus collisions and is treated using the binary collision approximation with the Ziegler–Biersack–Littmark (ZBL) screened Coulomb potential,

$$V(r) = \frac{Z_1 Z_2 e^2}{r}\,\phi(r/a).$$

Ion ranges and straggling are obtained by Monte Carlo simulations of successive collisions, yielding statistically averaged penetration depths and damage profiles.

3 Results and discussions

The figure 1 illustrates the stopping power (dE/dx) as a function of particle energy for two tantalum-based polymers, $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$, compared with a hydrogen-rich reference material, C_2H_4. This comparison is directly relevant to cosmic radiation shielding, since galactic cosmic rays are dominated by protons (~90%), followed by alpha particles (~9%), with the remaining fraction consisting of high-Z and high-energy (HZE) ions such as carbon, oxygen, and iron. For protons, both tantalum-based polymers exhibit the expected

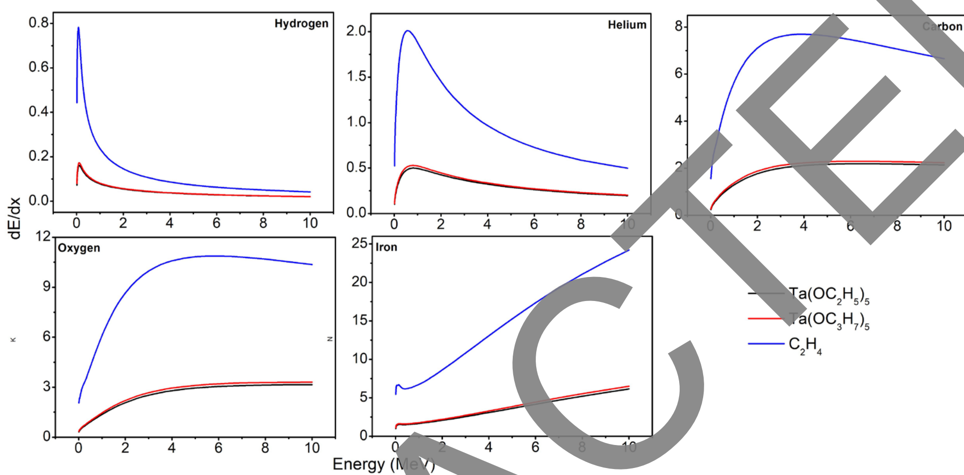

Figure 1. Stopping power (dE/dx) as a function of particle energy (0–10 MeV) for protons (H), alpha particles (He), and representative HZE ions (C, O, and Fe) in tantalum-based polymers $Ta(OC_2H_5)_5$ (black) and $Ta(OC_3H_7)_5$ (red), compared with the hydrogen-rich reference material C_2H_4 (blue). The figure highlights the systematically lower stopping power of Ta-based polymers relative to hydrogen-rich materials across all ion species, emphasizing their limited effectiveness as standalone cosmic radiation shielding materials.

decrease in stopping power with increasing energy, characteristic of electronic stopping in the non-relativistic regime. However, their dE/dx values are consistently much lower than those of C_2H_4 across the entire energy range. This behavior reflects the reduced hydrogen content in tantalum-based polymers, since hydrogen is highly effective in slowing down protons through ionization losses. Consequently, for the dominant proton component of cosmic radiation, hydrogen-rich materials provide superior shielding performance.

A similar trend is observed for alpha particles. All materials show a low-energy maximum in dE/dx, corresponding to enhanced ionization losses near the Bragg peak region. Nevertheless, C_2H_4 exhibits significantly higher stopping power than both Ta-based polymers. The curves for $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$ are very close to each other, indicating that variations in the organic ligand length have only a minor influence on alpha-particle energy loss. This confirms that light, hydrogen-rich materials are intrinsically more effective against helium ions.

For medium-mass HZE ions such as carbon and oxygen, the stopping power increases rapidly with energy and approaches a saturation region at higher energies. In this regime, C_2H_4 shows substantially larger dE/dx values than the tantalum-based polymers. The Ta-polymers exhibit smoother and lower-magnitude curves, indicating weaker electronic stopping. Despite the high atomic number of tantalum, the reduced hydrogen fraction limits the overall energy dissipation efficiency for these HZE ions.

The behavior for iron ions, representing the heaviest and most biologically damaging component of cosmic radiation, is distinct. The stopping power increases strongly with energy for all materials, but C_2H_4 again shows the highest values. The tantalum-based polymers display a more moderate and nearly linear increase in $\mathrm{d}E/\mathrm{d}x$. Although high-Z elements such as tantalum can enhance nuclear interactions and fragmentation, this does not translate into higher stopping power and may instead increase the production of secondary particles, such as neutrons, which are undesirable in space radiation shielding.

Overall, the figure 1 demonstrates that tantalum-based polymers alone are not optimal for primary cosmic radiation shielding, particularly against protons, alpha particles, and HZE ions. Their relatively low stopping power compared to hydrogen-rich materials limits their effectiveness in directly reducing particle energies. However, they may play an important role in multilayer or hybrid shielding concepts, where hydrogen-rich polymers provide efficient energy loss and fragmentation suppression, while tantalum-based polymers contribute mechanical strength, thermal stability, and attenuation of secondary photons.

The figure 2 shows the projected range as a function of particle energy (0–10 MeV) for

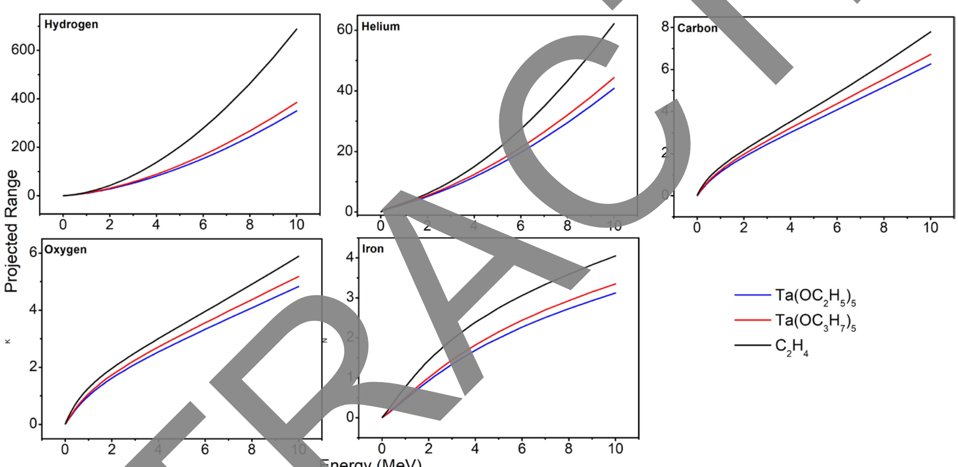

Figure 2. Projected range versus energy (0–10 MeV) for H, He, C, O, and Fe ions in $Ta(OC_2H_5)_5$, $Ta(OC_3H_7)_5$, and C_2H_4, showing the reduced particle penetration in tantalum-based polymers compared to the hydrogen-rich reference material.

the main components of galactic cosmic radiation, namely protons (hydrogen), alpha particles (helium), and representative heavy ions (carbon, oxygen, and iron), interacting with two tantalum-based polymers, $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$, in comparison with a hydrogen-rich reference material, C_2H_4. Since cosmic radiation is dominated by protons (~90%) and alpha particles (~9%), with a smaller but biologically significant contribution from high-Z and high-energy (HZE) ions, the projected range provides a direct measure of penetration depth and hence shielding effectiveness.

For protons, the projected range increases rapidly with energy in all materials, reflecting the reduced stopping efficiency at higher energies. However, C_2H_4 consistently exhibits the largest proton range, indicating deeper penetration in hydrogen-rich polymers. In contrast, both tantalum-based polymers substantially reduce the proton range, with $Ta(OC_2H_5)_5$ showing the shortest penetration depth. This behavior arises from the higher effective atomic number and density associated with tantalum, which enhances energy loss per unit path length. From a shielding perspective, this implies that tantalum-based polymers can achieve comparable proton attenuation with thinner layers, an important advantage for mass- and volume-limited space applications.

A similar trend is observed for alpha particles. The projected range of helium ions in C_2H_4 is significantly larger across the entire energy interval, whereas both Ta-based polymers strongly suppress the penetration depth. The difference between $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$ remains modest, indicating that the shielding behavior is dominated by the presence of tantalum rather than by variations in the organic ligand length. Since alpha particles constitute the second most abundant component of cosmic radiation, the reduced ranges in tantalum-based polymers demonstrate their effectiveness in compact shielding configurations.

For medium-mass HZE ions such as carbon and oxygen, the absolute projected ranges are much smaller than those of protons and helium because of their higher charge and stronger interactions with matter. Nevertheless, C_2H_4 again allows the deepest penetration, while tantalum-based polymers significantly limit the range. This is particularly relevant because carbon and oxygen ions produce dense ionization tracks and contribute disproportionately to radiation damage in space. The reduced ranges in Ta-based polymers indicate improved localization of energy deposition and a lower probability of ion traversal through sensitive regions.

The iron-ion case, representing the heaviest and most damaging HZE component, exhibits the smallest projected ranges overall. Here, the advantage of tantalum-based polymers is most pronounced, with iron ions penetrating substantially less than in C_2H_4 at the same energy. This highlights the strong attenuation capability of high-Z tantalum-containing materials against very heavy ions, although such materials may also enhance nuclear fragmentation and secondary particle production.

Overall, figure 2 demonstrates that tantalum-based polymers are effective in reducing the penetration depth of cosmic-ray ions across the entire spectrum, from protons to heavy HZE ions. While hydrogen-rich polymers allow larger particle ranges and are advantageous for minimizing secondary radiation, tantalum-based polymers provide superior compactness and range reduction. These results support the use of hybrid or multilayer shielding concepts that combine hydrogen-rich materials with tantalum-based polymers to optimize protection against both primary cosmic radiation and secondary effects in space environments.
The figure 3 illustrates the lateral straggling as a function of energy (0–10 MeV) for the principal components of cosmic radiation, namely protons, alpha particles, and representative heavy ions (carbon, oxygen, and iron), in two tantalum-based polymers, $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$, compared with a hydrogen-rich polymer, C_2H_4. Lateral straggling quantifies the transverse spread of charged particles as they traverse matter and is a key parameter for assessing the spatial extent of radiation damage in shielding materials. For protons, which dominate the cosmic-ray spectrum, lateral straggling increases rapidly with energy. The tantalum-based polymers exhibit significantly larger lateral straggling than C_2H_4, with $Ta(OC_3H_7)_5$ showing the highest values. This behavior reflects enhanced multiple Coulomb scattering in the high-Z tantalum matrix, leading to stronger angular deflections and a broader transverse spread. For alpha particles, a similar but less pronounced trend is observed, with Ta-based polymers again exhibiting larger lateral straggling than the hydrogen-rich material.

For heavier ions such as carbon, oxygen, and iron, lateral straggling rises sharply at low energies and then gradually approaches saturation. In this regime, the difference between tantalum-based polymers and C_2H_4 becomes particularly pronounced, with Ta-containing materials producing substantially greater transverse spreading. This indicates stronger scattering and interaction of HZE ions in high-Z media. Overall, while tantalum-based polymers enhance scattering and reduce straight-line penetration, their increased lateral straggling sup-

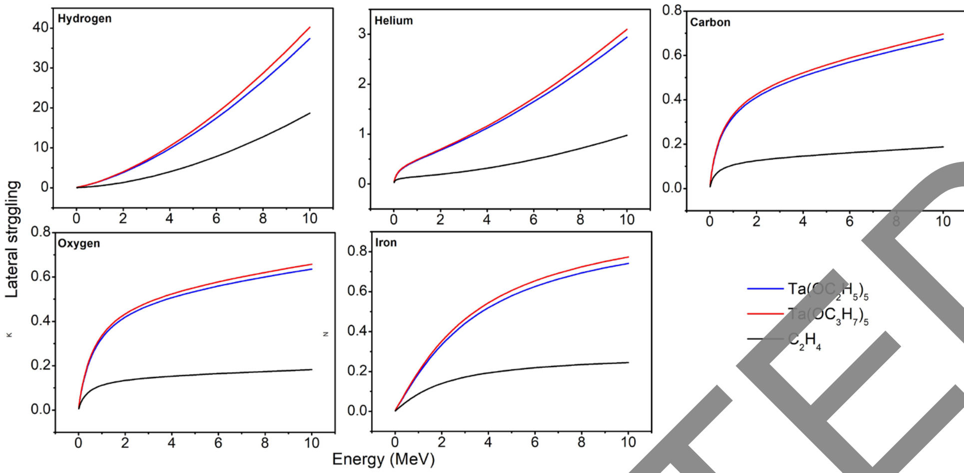

Figure 3. Lateral straggling as a function of particle energy (0–10 MeV) for protons (H), alpha particles (He), and representative HZE ions (C, O, and Fe) in tantalum-based polymers $Ta(OC_2H_5)_5$ (blue) and $Ta(OC_3H_7)_5$ (red), compared with the hydrogen-rich reference material C_2H_4 (black). The enhanced transverse spreading observed in Ta-based polymers reflects stronger multiple Coulomb scattering in the high-Z tantalum matrix, particularly for heavier ions, with important implications for radiation damage localization and hybrid cosmic-radiation shielding design.

ports the use of hybrid shielding designs that combine hydrogen-rich polymers with tantalum-based layers to optimally control both penetration depth and transverse radiation spread.

The figure 4 shows the longitudinal straggling as a function of energy (0–10 MeV) for the major components of cosmic radiation, namely protons, alpha particles, and representative heavy ions (carbon, oxygen, and iron), in two tantalum-based polymers, $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$, compared with a hydrogen-rich polymer, C_2H_4. Longitudinal straggling quantifies the spread in penetration depth around the mean range and is an important indicator of how localized and predictable energy deposition is within a shielding material. For protons, which constitute about 90% of cosmic radiation, the longitudinal straggling increases strongly with energy. C_2H_4 exhibits the largest straggling at higher energies, implying a broader distribution of proton stopping points. In contrast, both tantalum-based polymers show reduced straggling, with $Ta(OC_2H_5)_5$ giving the smallest values. This indicates that tantalum-containing polymers confine proton penetration more effectively, leading to more localized and predictable energy deposition.

A similar trend is observed for alpha particles. Although the absolute straggling values are smaller than for protons, C_2H_4 again shows larger straggling than the tantalum-based polymers. The small difference between $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$ suggests that the presence of tantalum largely governs the straggling behavior.

For heavier ions such as carbon, oxygen, and iron, the tantalum-based polymers exhibit significantly larger longitudinal straggling than C_2H_4. This reflects stronger energy-loss fluctuations and enhanced interactions in the high-Z tantalum matrix. Overall, tantalum-based polymers are advantageous for reducing straggling of light ions, while for HZE ions a hybrid shielding approach remains preferable.

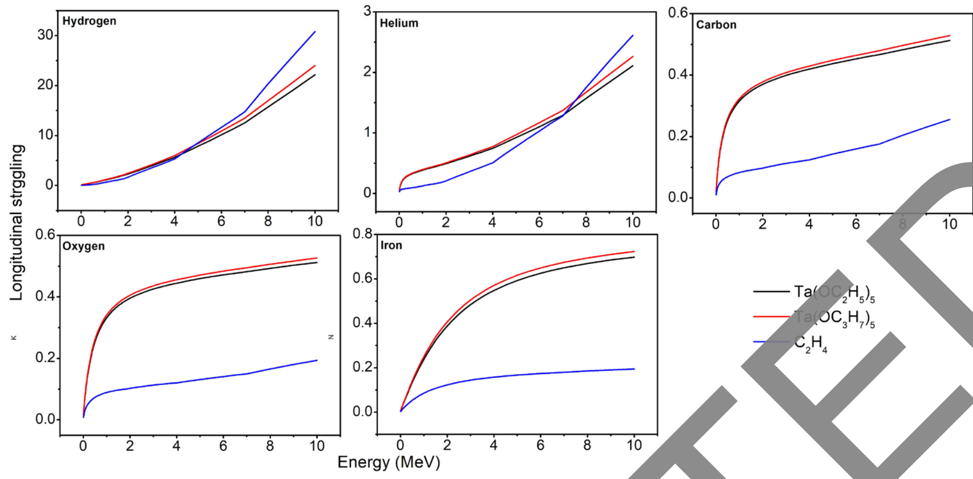

Figure 4. Longitudinal straggling as a function of particle energy (0–10 MeV) for protons (H), alpha particles (He), and representative HZE ions (C, O, and Fe) in tantalum-based polymers $Ta(OC_2H_5)_5$ (black) and $Ta(OC_3H_7)_5$ (red), compared with the hydrogen-rich reference material C_2H_4 (blue). The figure illustrates the enhanced spread in penetration depth for Ta-based polymers, particularly for heavier ions, highlighting differences in range predictability and energy-deposition localization relevant to cosmic-radiation shielding.

4 summary

This paper investigates the suitability of tantalum-based polymers, $Ta(OC_2H_5)_5$ and $Ta(OC_3H_7)_5$, for cosmic radiation shielding, using the SRIM (Ziegler et al.) framework to analyze ion–matter interactions. Stopping power, projected range, lateral straggling, and longitudinal straggling are systematically studied for the dominant components of galactic cosmic radiation: protons (90%), alpha particles (9%), and representative heavy ions (C, O, Fe). The results show that hydrogen-rich C_2H_4 exhibits significantly higher stopping power for protons and alpha particles, confirming the superior role of hydrogen in dissipating ion energy. However, tantalum-based polymers substantially reduce the projected range of ions, enabling more compact shielding. For heavy ions, Ta-based polymers enhance scattering and energy-loss fluctuations, reflected in increased lateral and longitudinal straggling. Overall, the study concludes that tantalum-based polymers alone are not optimal primary shields but are highly valuable in hybrid or multilayer shielding designs, where hydrogen-rich materials suppress secondary radiation while tantalum-based polymers provide structural strength, compactness, and enhanced attenuation of heavy ions.

References

[1] Durante Physical basis of radiation protection in space travel. Reviews of Modern Physics **83**, 1245-1281

[2] Li, Xiaoyu et al., Evaluation of shielding materials against galactic cosmic rays for protecting astronauts. Radiation Protection Dosimetry **201**, 361-377 (2025).

[3] Blachowicz, Tomasz et al., Shielding of Cosmic Radiation by Fibrous Materials. Fibers **9**, (2021).

[4] Simpson Elemental and Isotopic Composition of the Galactic Cosmic Rays. Annual Review of Nuclear and Particle Science **33**, 323-382

[5] Iguchi, Daniela et al., Development of Hydrogen-Rich Benzoxazine Resins with Low Polymerization Temperature for Space Radiation Shielding. ACS Omega **3**, 11569-11581 (2018).

[6] R. Chandrasekharan et al., Detection of VUV light at high quantum efficiency with large area avalanche photodiodes (LAAPDs). Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **567**, 45-47 (2006).