PTCOG-AO2025-ABS-0139

Refining Track Structure Modeling with Quantum Uncertainty for RBE Calculation of Light Ion Beams(H–O)

JiHuai Chi[*,1], MingZhang Lin[2], Hsiao-Ming Lu[1]

[*,1] Hefei Ion Medical Center, The First Affiliated Hospital of USTC, Division of Life Sciences and Medicine, University of Science and Technology of China, China, [2] School of Nuclear Science and Technology, University of Science and Technology of China, China

Objectives

The spatial distribution of energy deposition at nanometer and micrometer scales plays a critical role in determining the ultimate biological response. In the classical amorphous track structure model, the dose is assumed constant in the core, with an artificially sharp transition to the penumbra for analytical simplicity. This work aims to improve the amorphous model by incorporating quantum uncertainty into track structure modeling, with the goal of enhancing both physical accuracy and applicability in Relative Biological Effectiveness (RBE) modeling.

Methods

We introduce a quantum-mechanically motivated uncertainty correction to the Kiefer–Chatterjee (KC) model by replacing the constant core with a Gaussian-shaped dose distribution, reflecting the spatial uncertainty of ionization due to quantum effects at nanometric scales. The core and tail regions are smoothly connected via a hyperbolic tangent modulation, ensuring a continuous transition with Gaussian dominance near the core and 1/r^2 behavior at larger radii. To assess biological implications, we applied the modified Microdosimetric Kinetic Model (mMKM) framework to compute the RBE, using the saturation-corrected specific energy Z_{1D}^* as the key quantity for RBE modeling.

Results

The quantum-uncertainty-refined model provides a smooth transition from the core to the penumbra region, and better reproduces the central dose distribution observed experimentally across various ion species. The proposed model eliminates the artificial discontinuity, yielding a more realistic and continuous radial dose profile (See Figure 1). The resulting Z_{1D}^* values show consistency with KC model predictions in light ions, while gradually deviating for heavier ions at higher energies, reflecting the growing role of spatial uncertainty (See Figure 2 and Figure 3).

Conclusions

By introducing a Gaussian core into the KC model, we incorporate spatial uncertainty of ionization events at nanometric scales, leading to more physically realistic radial dose distributions. The refined model demonstrates good agreement with experimental data. This consistency reflects a more accurate physical description of ion track structure and supports the reliability of the uncertainty-refined model for extrapolation to heavier ions and higher energies. This refined track structure model offers a more robust foundation for biological modeling and provides a physically grounded basis for future developments in RBE modeling and biologically optimized ion therapy planning.