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Introduction

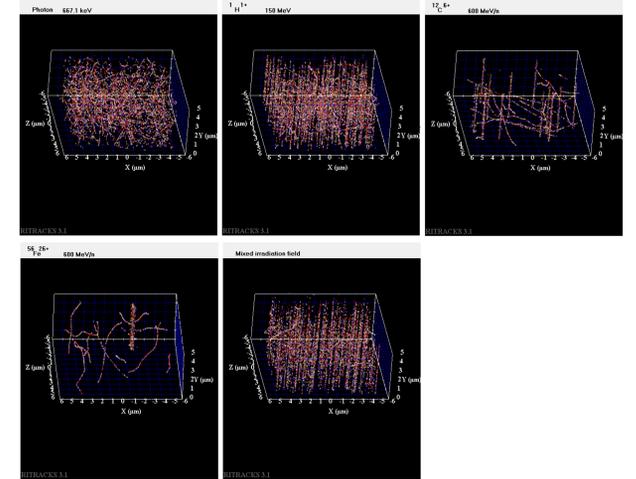
- Energy deposition by ionizing radiation in micrometric targets representative of cells is very important to understand the effect of radiation and the cellular and biological response.
- Microdosimetry is used to estimate quality factors for risk assessment in radiation protection [1] and quantify Relative Biological Effectiveness (RBE) for treatment planning of hadron radiation therapy [2].
- Radiation physics has shown that ionizing radiation deposits energy in a complex manner, referred to as the track structure.
- Consequently, energy deposited in a target is a function of variables such as the ion type, its energy, and the irradiated volume.

Simulation setup: volume irradiation with stochastic tracks

- The code RITRACKS (Relativistic Ion Tracks) [3] simulates detailed stochastic radiation track structures of ions of different types and energies.
- A parallelepiped volume is defined. Its bottom surface is irradiated by n tracks, determined by sampling the Poisson distribution, $p(n) = \lambda^n \exp(-\lambda)/n!$ where $\lambda = \phi A$ is the average number of tracks, A is the area of the irradiated surface, and ϕ is obtained from a given dose using

$$D(\text{Gy}) = 1.6 \times 10^9 \phi (\text{cm}^{-2}) \times LET (\text{keV}/\mu\text{m})$$

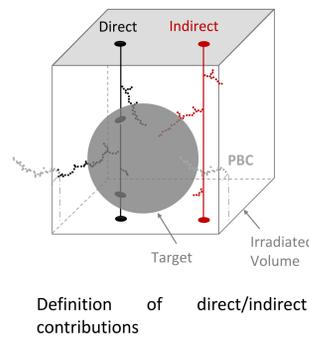
- The LET of an ion is calculated using the Bethe's equation.
- To mimic the contribution of energy deposition of delta-rays from tracks in neighboring volumes, periodic boundary conditions (PBCs) are used. Essentially, all electrons leaving the irradiation volume are put back on the other side of the volume, with the same energy and direction vector.



Example of RITRACK simulations for photons, protons 150 MeV, Carbon 600 MeV/n, Iron 500 MeV/n and mixed irradiation field. The dose is approximately 0.2 Gy in all cases.

Simulation set-up: microtarget

- Wall-less spherical water targets are used and encompassed in the irradiated volume [4].
- The energy deposited is calculated for each individual track.
- The tracks are categorized as direct for those which the axis intercepts the target, and indirect for those that do not.
- Electrons are considered to originate from a different track after crossing a boundary.



Calculation of the dose to the target at various impact parameters

- The radial dose is given in the Kiefer-Chatterjee [5,6] parameterization by

$$D_r(r) = \begin{cases} \frac{\lambda_1}{r_{min}^2} & r \leq r_{min} \\ \frac{\lambda_2}{r^2} & r_{min} < r \leq r_{max} \\ 0 & r > r_{max} \end{cases} \quad \lambda_1^{KC} = \left(\frac{LET}{\rho} - 2\pi\lambda_2^{KC} \log \left(\frac{r_{max}}{r_{min}} \right) \right) \quad r_{min} = 11.6\beta_{ion}$$

$$\lambda_2^{KC} = 1.25 \times 10^{-4} \left(\frac{z^*}{\beta_{ion}} \right)^2 \quad r_{max} = 0.062 \times E^{1.7}$$

E is the energy per nucleon
 β_{ion} is the relativistic beta.

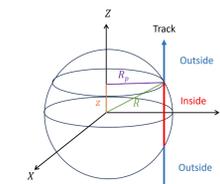
- The energy deposited in the target by one track can be calculated analytically

$$D_{sphere}^{indirect} = \frac{4\pi\lambda_2}{V_s} \left\{ R - \sqrt{b^2 - R^2} \sin^{-1} \left(\frac{R}{b} \right) \right\}$$

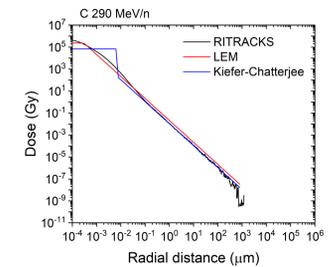
$$D_{sphere}^{in} \approx \frac{2\pi\sqrt{R^2 - b^2}}{V_s} \left[\lambda_2 \log \left(4 \frac{R^2 - b^2}{r_{min}^2} \right) + (\lambda_1 - 2\lambda_2) \right]$$

$$D_{sphere}^{out} \approx \frac{2\pi\lambda_2}{V_s} \left[2R + \sqrt{R^2 - b^2} \left(-2 + \log \left(4 \frac{(R^2 - b^2)(R - \sqrt{R^2 - b^2})}{b^2(R + \sqrt{R^2 - b^2})} \right) \right) \right]$$

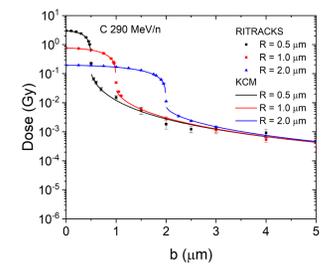
b : Impact parameter
 R : target radius
 V_s : Sphere volume



3D view of an ion track and a spherical target.



Radial dose calculated by the local effect model (LEM) and by the Kiefer-Chatterjee parameterization



Dose to spherical targets as a function of the impact parameter for one 290 MeV/n carbon track (dots), and the current model prediction with the Kiefer-Chatterjee model for targets of radius 0.5, 1 and 2 μm .

Calculation of the direct and indirect spectra

- The probability density function $P(D)$ (where D is the dose) is calculated as:

$$P(D) = \frac{df}{dD} = \frac{df}{db} \left| \frac{db}{dD} \right| = \frac{df}{db} \left| \frac{db}{dD} \right|^{-1}$$

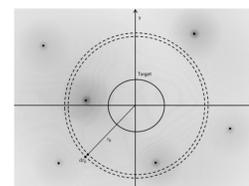
- Since the target is irradiated uniformly, the probability for a track to be found between the impact parameters b and $b + db$ is given by $\phi 2\pi b db$, where ϕ is the fluence.
- By the analytical model, each impact parameter is associated with a given dose (or energy deposition).
- The equations cannot be inverted analytically. However, an approximate relationship between b^2 and the energy deposited in the sphere can be derived.
- With this approach, an energy deposition spectra can be obtained.

$$P(D)dD = \frac{\phi DV_s^2}{2\pi^2 \left(\lambda_2 \log \left(4 \frac{R^2}{r_{min}^2} \right) + (\lambda_1 - 2\lambda_2) \right)^2} dD.$$

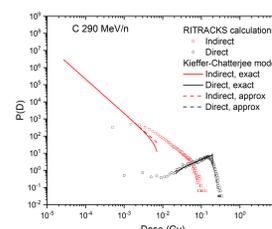
Direct spectra

$$P(D)dD = \phi \pi \frac{\lambda_2}{D^2} dD$$

Indirect spectra, 1 term



Dose to target by multiple tracks.



Dose spectra for 290 MeV/n carbon, with a target of radius of 2 μm .

Conclusions

- An analytical model based on the Kiefer-Chatterjee parameterization has been developed to calculate the energy deposition to a target by ion tracks at all impact parameters. An analytical expression was also derived for the energy deposition spectra.
- The calculations were compared with those from the code RITRACKS.
- The energy gap between the indirect and direct spectra is due to the missing calculation between $R - r_{min} < b < R + r_{min}$.

References

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