Cluster-Size Distributions for Extended Irradiation Fields: Monte Carlo simulation

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INTRODUCTION

In view of the importance of particle track structure to understand and to monitor the initiation of irradiation damage to the relevant sub-structures of living cells like the DNA and higher-order genomic structures, the properties of the tracks of ionizing radiation of quality Q must be measured. Such measurements are feasible today by counting the number of ionizations produced inside a small gas volume by ionizing particles directly crossing it, or passing nearby at a given impact parameter. The most appropriate measuring device, available at present for this purpose, is the so called track-nanodosimeter, installed at the TANDEM-ALPI accelerator complex of LNL. This track-nanodosimeter measures ionization cluster-size distributions \( P(Q, d; r_{\text{beam}}) \) in a cylindrical target volume which is defined by a non-homogeneous efficiency map (about 0.37 cm in diameter and height) and is comparable in size (at a density of 1 g/cm³) to a segment of the chromatin fibre of 20 nm in diameter and height. The impact parameter \( d \) is changed in the experiments by moving the target volume perpendicularly to the centre line of a widely homogeneous circular “pencil beam” (radius \( r_{\text{beam}} = 0.04 \) cm) of primary particles.

Due to the need of information concerning the ionization cluster-size formation in radiation fields with radii \( R \) notably larger than those generally applied in the measurements, it was the aim of the present study (i) to develop and to test a procedure to determine the relative frequencies of cluster-size formation in extended radiation fields the radius of which is notably larger than that commonly used and (ii) to investigate the influence of the spatial resolution of realistic nanodosimetric measurements, a series of Monte Carlo simulations was performed for 240 MeV \(^{12}\)C-ions penetrating through or passing by nanometre-sized target volumes at specified impact parameters. To study the spatial resolution either a needle beam \((r_{\text{beam}} \sim 0 \text{ cm})\) or a homogeneous “pencil beam” \((r_{\text{beam}} = 0.04 \text{ cm})\) was assumed in the simulations, and a homogeneous cylindrical particle beam with \( r_{\text{beam}} = 0.6 \text{ cm} \) to study the validity of the integration procedure. The target was a spherical volume, 0.37 cm in diameter, filled with propane gas at a pressure of 3 mbar (density of propane at 25°C: \( \rho = 5.47 \mu \text{g/cm}^3 \)). The impact parameter was varied between 0 cm and 0.6 cm to enable the simulation of a homogeneous extended field with a radius of \( R = 0.6 \text{ cm} \).

To give an impression of the results, Fig. 1 presents the calculated relative frequencies \( P(Q, d; r_{\text{beam}}) \) caused by the carbon ions at impact parameters \( d = 0 \text{ cm}, 0.15 \text{ cm}, 0.25 \text{ cm}, \) and 0.6 cm in the case of an irradiation with a “needle beam” \((r_{\text{beam}} \sim 0 \text{ cm})\) or with a homogeneous “pencil beam” \((r_{\text{beam}} = 0.04 \text{ cm})\). These data are compared with the relative frequencies \( P(Q, d; R | r_{\text{beam}}) \) for \( r_{\text{beam}} \sim 0 \text{ cm} \) and \( R = 0.04 \text{ cm} \), calculated according to the integration procedure described by equation (1).

\[
P_{\nu}(Q, d; R) = \frac{2}{\pi R^2} \int_0^\infty \int_0^\pi \rho_{\nu}(r, d) \int_0^\frac{\pi}{2} dr \times P_{\nu}(Q, r) \quad (1)
\]

As it is clear from the figure, there is an excellent agreement of the data for all impact parameters apart from \( d = 0.15 \) cm which is close to the border of the irradiated target sphere. Here, the \( P_{\nu}(Q, d; 0.04 \text{ cm}) \)-distribution and the \( P_{\nu}(Q, d; 0.04 \text{ cm}; 0 \text{ cm}) \)-distribution agree very well
whereas the $P_\nu(Q, d, 0 \text{ cm})$-distribution shows a different shape. This difference in shape can be explained by the fact that close to the border the number of primary particles not directly interacting with the target volume is notably larger in the case of a “pencil beam” than of a “needle beam”. At impact parameters ‘far’ from the border, however, $P_\nu(Q, d, 0 \text{ cm})$ and $P_\nu(Q, d, 0.04 \text{ cm})$ are almost the same.

As far as the validity of the procedure to determine the relative frequencies of cluster-size formation in an extended radiation field is concerned, the agreement of $P_\nu(Q, d, 0.04 \text{ cm})$ and of $P_\nu(Q, d, 0.04 \text{ cm})$ shows that, at least for small field sizes, the procedure works quite well.

To demonstrate that the procedure works correctly also for larger field sizes, figure 2 shows a comparison of $P_\nu(Q, d, 0.6 \text{ cm})$ and $P_\nu(Q, d, 0.6 \text{ cm})$ for impact parameters of 0 cm and 0.6 cm. A first glance at the figure shows that the agreement of the data is excellent.

As a further check of the spatial resolution in cluster-size measurements due to the application of “pencil beams”, Fig. 3 presents the $P_\nu(Q, d, R|_{\text{beam}})$-distributions due to 240 MeV $^{12}$C-ions at different impact parameters $d$ in an extended beam of radius $R = 0.6 \text{ cm}$ with a “needle beam” ($r_{\text{beam}} = 0 \text{ cm}$) and a “pencil beam” ($r_{\text{beam}} = 0.04 \text{ cm}$).

As can be seen in the figure, the agreement of the distributions for the spherical target volume irradiated either by a “needle beam” or by a “pencil beam” is almost the same for all impact parameters. It can, therefore be stated that the beam diameter plays a role only for impact parameters close to the border of the target volume in the case of an irradiation with “pencil beams” of small $r_{\text{beam}}$ (see Fig. 3) but can be neglected in the case of extended particle beams.

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