Track Nanodosimetry of 20 MeV Protons

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INTRODUCTION

Track nanodosimetry is the theoretical and experimental research which studies the stochastic aspects of ionization yield produced by ionizing particles in nanometer sized target volumes, positioned at different distances from the primary particle track. The STARTRACK experimental set up, mounted on the +50° beam line at the Tandem-Alpi particle accelerator of Legnaro National Laboratories, has been conceived to give an experimental basis to nanodosimetric calculations. The detection system is able to measure the cluster distributions of electrons set in motion by different ion tracks in a 20 nm propane site, with the resolution of one electron. The 20 nm site can be moved at different distances from the primary particle track. Ionization cluster distributions of 20 MeV protons have been measured and compared with Monte Carlo calculations. For a complete description of the track-nanodosimetry detection system, see Refs. [1] and [2].

ELECTRON CLUSTER-SIZE DISTRIBUTIONS

The number of ionizations produced by a primary particle (including those produced by its secondary electrons) within the SV is what we call the ionization cluster-size.

We investigate the stochastic of ionization events by evaluating the probability \( P_i(k,d,\varepsilon) \) that \( \varepsilon \) electrons are generated in the nanometric target volume SV, positioned at distance \( d \) from a particle-track of radiation quality \( k \); \( \varepsilon \) is the overall detection efficiency of the system. The first \( M_1(k,d,\varepsilon) \) and the second \( M_2(k,d,\varepsilon) \) moments of the cluster-size probability distribution \( P_i(k,d,\varepsilon) \) are of particular interest as the first moment represents the mean cluster-size, and the second one characterizes the fluctuation in the cluster-size, which is commonly expressed by the variance of the distribution.

Another quantity which is particularly relevant is the ratio of the variance to the mean of the \( P_i(k,d,\varepsilon) \) distribution \( M_2(k,d,\varepsilon)/M_1(k,d,\varepsilon) \). This ratio, as highlighted by De Nardo et al. [3], is indeed equal to the ratio \( m_2(k,d,\varepsilon)/m_1(k,d,\varepsilon) \) of the second to the first moment of the elementary cluster-size distribution \( f_i(k,d,\varepsilon) \), which is the cluster-size distribution in the case of a single primary ionization event. In microdosimetry, the ratio of the second to the first moment of the energy-imparted distribution is \( \overline{\varepsilon}_b \), the mean lineal energy dose. \( M_2/M_1 \) is equivalent to the \( \overline{\varepsilon}_b \) of the primary particle (the 20 MeV proton, here), while \( m_2/m_1 \) corresponds to the \( \overline{\varepsilon}_b \) of the single primary ionization and can be considered as the primary ionization quality. For \( d>15 \) nm, in the penumbra region, the reduced variance can be considered as the single \( \delta \)-electron quality. For a discussion on fundamentals of ionization-cluster size formation see again Ref. [3].

MONTE CARLO CALCULATIONS

Monte Carlo simulation was performed, taking into account the spatially dependent electron detection efficiency within the SV. To simulate the formation of electron clusters within the SV it was assumed that, for 20 MeV protons penetrating through material layers of mass per area of about 2 \( \mu \mathrm{g/cm}^2 \) or less, elastic scattering, impact excitation, and charge-changing processes can be neglected. In consequence, the formation of electron clusters was exclusively based on direct proton ionization processes in propane, on the spectral and angular distribution of secondary electrons set in motion by impact ionization of the protons, and on the degradation of electrons in propane. For the integrated and differential ionization cross sections used for the Monte Carlo simulation of proton track segments in propane, see the publication by De Nardo et al. [3].

In contrast to the restriction of proton interactions to ionization processes only, the formation of electron clusters due to secondary electrons was simulated by taking into account elastic electron scattering, a series of different excitation processes, and impact ionization. At each electron interaction point, the electron's flight direction after elastic scattering or its energy loss and flight direction after inelastic scattering was determined, supplemented by the energies and flight directions of potential secondary electrons. As the influence of external electromagnetic fields on the movement of electrons within the STARTRACK apparatus was not directly taken into account, it was assumed that the electrons travel along straight lines which connect successive interaction points. In the case of elastic electron interactions, the polar angle of the electron's flight direction after elastic scattering or its energy loss and flight direction after inelastic scattering was determined relative to its initial direction assuming that the azimuthal scattering angle is always uniformly distributed between 0 and \( 2\pi \). In contrast to elastic scattering, it was supposed in the case of electron excitation processes that the electron direction remains unchanged whereas the
initial electron energy is reduced by the excitation energy. On electron impact ionization (only single ionization is taken into account), it was assumed that a secondary electron is liberated which was treated in the same way as the initial electrons. The history of each electron was simulated until it left the SV, or until its energy had been degraded to a value smaller than 11.08 eV, which is equal to the lowest ionization threshold energy of propane.

RESULTS AND DISCUSSION

Previous measurements [3,4], performed with a 5.4 MeV $^{244}$Cm alpha-particle source, have pointed out an invariance of the distributions of the conditional ionization-cluster size probability $P\nu(k,d,\varepsilon)$ in the alpha-particle penumbra. Sensitive sites experience the same ionization distribution, independent of their distance from the ion track. This fact was confirmed by MC calculations.

New measurements and calculations have been performed with a 20 MeV proton beam. The sensitive volume has been moved from 0 nm up to 30 nm from the proton track, with steps of about 2.5 nm. At large distances $d$, the cluster distributions are dominated by zero-sized events. Consequently, the conditional distributions $P\nu(k,d,\varepsilon)$ with $\nu>0$ are substantially equivalent to the elementary probability distributions.

In figure 2, the ratio $M_2/M_1-M_1$ of the variance to the first moment of the distribution $P\nu$ is plotted against the impact parameter $d$. As previously mentioned, the quantity $M_2/M_1-M_1$ is equal to the ratio $m_2/m_1$, of the elementary ionization cluster-size distribution due to a single primary ionization, which in turn is equivalent to the microdosimetric quantity $\gamma_D$. It can be considered as the primary ionization quality. The primary ionization quality of proton and alpha particles are plotted together. In both cases the reduced variance increases with increasing distances, until $d$ reaches values of about 20 nm, then it becomes approximately constant.

![Fig. 1](image1.png)

Fig. 1. Conditional ionization cluster-size distributions at impact parameter $d=30$ nm. Filled circles: 20 MeV protons; open circles: 5.4 MeV alpha particles. Full line: protons MC calculation; dashed-line: alpha-particles MC calculation.

In figure 1, conditional cluster-size distributions in a site placed at 30 nm from a 20 MeV proton-track and from a 5.4 MeV alpha-particle track are plotted together. Both measured and calculated data do not show any difference between the two conditional distributions, which are independent not only of the distance from the ion path, but also of the particle type and velocity. Similar results were obtained by MC simulations of Wilson and Paretzke [5].

![Fig. 2](image2.png)

Fig. 2. Reduced variance $M_2/M_1-M_1$ of the cluster size probability distribution $P\nu$ as a function of $d$. Filled symbols: 5.4 MeV alpha particles, open symbols: 20 MeV proton beam.

We can conclude that beyond 20 nm experimental data do not show any significant change of the $\delta$-electron quality neither with $d$ nor with the ion kind and velocity.