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, the properties of the tracks of ionizing radiation of quality Q (charge state and velocity) must be measured. The track-nanodosimeter installed at the TANDEM-ALPI accelerator complex of LNL counts the number of ionizations produced inside a small gas volume by ionizing particles directly crossing it, or passing nearby at a well defined distance. The target volume, 3.7 mm in diameter and height, is filled with gaseous propane at a density of $\rho = 5.47 \text{ µg/cm}^3$ and corresponds to a mass per area of about 2 µg/cm². Hence, at a density of 1 g/cm³ the target volume is comparable in size to a segment of the chromatin fibre, 20 nm in diameter and height. The impact parameter $d$ is changed by moving the target volume perpendicularly to the centre line of a circular pencil beam of primary particles (beam radius $r_{\text{beam}} = 0.4$ mm) [1].

The beam radii $R_{\text{beam}}$ of interest in radio-biology or radiation therapy are much larger than the beam radii $r_{\text{beam}}$ which can be applied in the real experiment, but the integration of experimental data, over the azimuthal angle $\phi$ and over the impact parameter $d$, allows the reconstruction of a realistic irradiation geometry. Results are presented for 20 MeV protons and 240 MeV carbon-ions, which have the same velocity and therefore the same spectral distribution of $\delta$-electrons.

RESULTS AND DISCUSSIONS

The simple integration of the cluster size probability measured at impact parameter $d$, $P_v(Q, d)$ over the azimuthal angle $\phi$ and distance $r$ (see figure 1), lead to determine $P_v(Q, d = 0; R)$, which represent the cluster size probability at impact parameter $d = 0$, for a larger particle beam of radius $R$:

$$P_v(Q, d = 0, R) = \frac{2}{\pi R^2} \int_0^R \int_0^\pi d\phi r \times P_v(Q, R)$$

For sake of simplicity, in the following the probability $P_v(Q, d = 0; R_{\text{beam}})$ will be simply indicated as $P_v(Q, R_{\text{beam}})$. Based on this distribution, the mean ionization-cluster size caused by single ionizing particles in the target volume is given by the first moment $M_1(Q, R)$:

$$M_1(Q, R) = \sum_{v=1}^{\infty} v P_v(Q, R)$$

In the same sense, the cumulative probability of forming ionization-cluster sizes $v \geq k$ is given by the sum distribution defined by Equation (3):

$$F_2(Q, R) = \sum_{v=k}^{\infty} P_v(Q, R)$$

Fig. 1: Schematic view of the integration of $P_v(Q, d)$ over the azimuthal angle $\phi$ and distance $r$, according to equation (1).

The mean cluster size $M_1(Q, d)$ is of particular interest; It is proportional to the mean number of primary ionizations $L/\lambda$ along a travelling length $L$ of the particle track. Figure 1 shows the average cluster sized obtained for an irradiation field of 20 MeV protons and 240 MeV carbon-ions, by varying the field size, expressed here as the ratio of the field radius $R_{\text{beam}}$ to the sensitive volume radius, $R_{sv}$.

Fig. 2: Mean cluster size $M_1(Q, d)$ for homogeneous parallel irradiation fields of different radii $R_{\text{beam}}$, as a function of the ratio $R_{\text{beam}}/R_{sv}$.
It is clear in the figure that decreasing the field size $M_1(Q,R)$ increases, for both protons and carbon ions, and the values for carbons are always greater than those for protons by a factor of approximately 10.8, which reflects the ratio of the mean ionization free path-length ($\lambda_{ion} = 2.05 \, \mu g/cm^2$ for the protons and $\lambda_{ion} = 0.057 \, \mu g/cm^2$ for the carbon-ions).

The sum distributions $F_2(Q,R)$ represents the probability that at least 2 ionizations are produced in the target volume, and it is therefore intuitively related to the probability to cause a double strand break in the DNA structure. Figure 3 shows $F_2(Q,R)$ as a function of the field size. Similarly to $M_1(Q,R)$, $F_2(Q,R)$ increases for decreasing size of the irradiating field, but in contrast to $M_1(Q,R)$ $F_2(Q,R)$ shows a saturation effect in the case of carbon-ions. This is obviously due to the definition of $F_2(Q,R)$ as a probability. When the field size is smaller than the target size, the primary particle always traverses the target, producing ionizations with higher probability with respect to the case of a passage nearby. If the primary particle is densely ionizing the average cluster size $M_1(Q,R)$ reaches easily values greater than 1, and, for large $M_1(Q,R)$, the probability of $\nu \geq 2$ becomes equal to 1.

![Fig. 3: Cumulative probability $F_2(Q,R_{beam})$ due to 20 MeV protons and 240 MeV carbon ions, as a function of irradiation-field size $R_{beam}/R_{sv}$.](image)

As a consequence of the saturation of $F_2(Q,R)$, the distance between carbon-ions and protons is greater for large field sizes and becomes smaller if the particle-beam radius is smaller than the target radius.

Figure 4 shows the ratio of $F_2/M_1$ This ratio is of particular interest as it was observed that it behaves, as a function of $M_1$, in a similar way as the radiobiological cross sections do as a function of LET. It is therefore a good candidate to be representative of the radiation quality of ionizing particles. The irradiation field size is given in the abscissa, expressed by the ratio of the radii $R_{beam}/R_{sv}$.

For very narrow beams, when all the primary particles cross the target, the quality of the protons is higher than that of the carbon-ions. This is due to the saturation of $F_2$, and the reason is rather simple. In a strictly physical sense, $F_2$ can’t be greater than 1, in contrast $M_1$ continuously increases when the particle beam shrinks close to the target centre (maximum travelling length). Consequently the ratio $F_2/M_1$ decreases. In a “radiobiological” sense, if two or slightly more ionizations are sufficient to cause a complex damage to the DNA, in the case of the carbons several ionizations are misspent in the sense that they can’t produce further effect.

For larger irradiating fields the situation is reversed, and the ratio $F_2/M_1$ becomes almost constant in the studied range of radiation field radius. For $R_{beam} > 1.5 \, R_{sv}$ the value for carbon-ions is approximately 0.2 whereas the value for protons is approximately 0.135, with a ratio of about 1.5.

![Fig. 4: Ratio of the summed probability $F_2(Q,d)$ to the mean cluster size $M_1(Q,d)$, due to 20 MeV protons and 240 MeV carbon ions, as a function of irradiation-field size $R_{beam}/R_{sv}$.](image)

**CONCLUSIONS**

The track-nanodosimeter installed at LNL-INFN allows the direct measurement of track structure characteristics at defined impact parameter from a narrow-pencil particle beam of radius $r_{beam} = 0.4 \, mm$. In contrast, the beam radii $R_{beam}$ of interest in radiobiology or radiation therapy are much larger than the beam radius which can be applied experimentally. The integration of experimental data allows the determination of many characteristics of the track structure of ionizing particles coming from a homogeneous extended beam, which would be hardly measurable directly, in a real extended beam of larger sizes. Further details and a deeper analysis will be published.

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