MICRODOSIMETRIC RESULTS OBTAINED BY PROPORTIONAL COUNTER
AND IONIZATION CHAMBER METHODS: A COMPARISON

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Microdosimetric Results Obtained by Proportional Counter and Ionization Chamber Methods: A Comparison*

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Abstract

Energy deposition in one micron diameter volumes at distances of one and two microns from the ion's path has been estimated based on previously reported radial dose measurements made using a mesh wall ionization chamber. In these estimations it was assumed that radial dose varied inversely as the square of the radial distance. Ionization chamber measurements were reported for heavy ions (atomic number 1 to 53) having specific energies from 0.25 to 2.5 MeV per atomic mass unit (MeV/amu) and from 230 to 377 MeV/amu. Energy depositions were also measured using a wall-less gas proportional counter, and were reported by Kliauga and Rossi. Ions used in the proportional counter technique were 6.6 MeV/amu lithium and 10 and 23 MeV/amu protons. A comparison of results estimated from ionization chamber studies and measured using proportional counters is reported here. This comparison was facilitated by normalization in terms of $Z^2_{\text{eff}}$ and specific energy of the incident ions.

Proportional counter results were in apparent agreement with ion chamber results for 23 MeV/amu protons but were lower than ion chamber results by approximately 50% for 10 MeV/amu protons and 60% for 6.6 MeV/amu lithium ions.

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INTRODUCTION

In order to understand basic radiation mechanisms involved in cell killing or damage, and to interpret radiobiological data obtained using heavy ion irradiations, it is very important to have a good understanding of the spatial distribution of energy deposition which is produced by these ions. Microdosimetry has played an important role in this regard. Two different experimental approaches have been employed: (a) using an ionization chamber method, radial dose distribution as a function of radial distance was measured \(^{(1,4,5,6,7)}\) and (b) using wall-less gas proportional counters, event size spectra were measured. \(^{(2,3)}\)

The wall-less gas proportional counters have been used to measure both the "direct" events (energy deposited in a site when the incident particle passes through the detector) and "indirect" events (energy deposited in a site when the incident particle passes outside the site).

This article presents a comparison of energy deposited in simulated one micron diameter sites. The data analyzed in this work are from reports on radial dose measurements made using heavy ions (atomic number 1 to 53) having specific energies from 0.25 to 2.5 MeV/amu and from 230 to 377 MeV/amu, \(^{(4,5,6,7)}\) and from reports on event size measurements and average energy deposited per incident ion for 10 and 23 MeV protons and 40 MeV lithium ions. \(^{(3)}\)

EXPERIMENTAL

(a) Radial Dose Measurements: A cylindrical mesh wall ionization chamber (12.3 cm long, 1.6 cm diameter, 97% transparent) was placed inside a one meter long 30 cm diameter ionization chamber. The mesh wall ionization chamber could be placed at various radial positions from the axis of the large ionization chamber. It was used to determine radial dose as a function of radial distance from the ion's path. Details on the experimental method and data reduction and analysis are available in reference 5. Figure 1 shows the experimental chamber used. The mesh of the ionization chamber and the walls of the large ionization chamber were operated at the same voltage.

(b) Event Size Measurements: The basic apparatus consists of an aluminum container (approximately 76 cm long, 44 cm diameter) housing a one inch diameter wall-less proportional counter mounted on a positioned movable platform. This apparatus has been described elsewhere. \(^{(8)}\) The proportional counter moves on a
track perpendicular to the beam axis, and can be reproducibly positioned to within ±.002 inches. Figure 2 shows the experimental arrangement used in these measurements. The grid structure of the proportional counter is made up of concentric circles inscribed on a spherical surface along three mutually perpendicular axes. The proportional counter was operated with grid structure at -100 volts, a grounded helix, and the center wire of the counter at +550 volts, both with respect to the aluminum container. The grid structure was 90% transparent.

CALCULATION OF ENERGY DEPOSITED

Results for radial dose measurements as a function of radial distance from the ions path for 3 and 1 MeV protons and 3 MeV alpha particles were taken from Wingate and Baum. Results for radial dose measurements for 38.4 MeV oxygen ions, and 61.9 and 33.25 MeV iodine ions were taken from Varma et al., 920 MeV alpha particles from Varma et al. and 7,540 MeV neon from Varma and Baum. Table 1 presents the average dose determined at specific radial distances for various ions. From the experimental data and theoretical model calculations average dose at intermediate radial distances is given approximately by

\[ D(r) = \frac{D_0}{r^2} \]  

where \( D_0 \) is directly proportional to the square of effective charge \( (Z_{\text{eff}}^2) \) and inversely proportional to energy per atomic mass unit of the ion \( (E/m) \). Parameter \( D_0 \) in the above equation can be obtained from the information given in Table 1, and is also listed in this table.

We calculate from the above point dose function the average energy that will be deposited in a one micron diameter sphere placed at radial distances of one or two microns from the ions path.

Figure 5 shows schematically the ions path and a spherical site having diameter 'a' placed at radial distance R from the ion's path. To calculate the average energy deposited in this site, we first identify a volume element which is at some radial distance r from the ion's path. The dose at that point is determined from extrapolation of measured quantities given in Table 1. For this extrapolation it was assumed that dose varies as \( 1/r^2 \) from
the ion's path. The volume element is then multiplied by \( D_0/r^2 \) and numerically integrated over the entire volume of the site to give the average energy deposited.

RESULTS AND DISCUSSIONS

Average energy deposited in one-micron diameter sites at radial distances of one and two microns estimated from radial dose measurements, and those obtained from event spectra measurements are given in Table II. This table also lists the normalized dose, which is obtained by multiplying the energy deposited by \( E/m \) (MeV/amu) and dividing by \( Z_{\text{eff}}^2 \). This normalized energy deposition allows for convenient comparison of results for different ions at different energies, by properly accounting for the dependence on specific energy and effective charge of the incident ions. Normalized energy deposition should be approximately equal for all ions and energies studied here.

The normalized energy deposited in one micron diameter sites at radial distances of one and two microns, as a function of specific energy of incident ions is plotted in Figure 3 and 4, respectively. From data presented in Table II and Figures 3 and 4, energy deposition calculated from the experimental measurements of radial dose, show fluctuations which appear to be random. The 23 MeV proton data obtained using the gas proportional counter method was within experimental uncertainty of the estimated values determined from ionization chamber measurements. However, the 10 MeV proton and 40 MeV lithium ion data obtained using the gas proportional counter were 50 and 60\% lower, respectively, than those estimated from ionization chamber method measurements.

As pointed out earlier it was assumed, with some experimental justification, that dose varied inversely as the square of the radial distance from the ion's path. This assumption is not accurate for distances approaching the range of the secondary electrons having maximum energy. For these distances, the variation in dose with distance is faster than \( 1/r^2 \) which would tend to cause values estimated from ion chamber measurements to be elevated. However, this consideration gives errors of only a few percent and thus could not account for the differences observed.

An important factor which could have influenced the measurements made using the gas filled proportional counter was the existence of an electric...
field between the aluminum container and the grid structure of the counter. To illustrate this point, consider Figure 6 which shows an estimated plot of relative dose (percent) per logarithmic energy interval as a function of secondary electron energy.

The energies shown in this figure are approximately those expected at radial distances of interest and thus represents the slowed down secondary electron spectra (assumed here to be approximated by an $E^{-2}$ function over the energy range of interest). If no electric field existed between the grid and the container, then secondary electrons that have ranges smaller than the site diameter would deposit most of their energy in the detector; those with range greater than the site diameter would deposit energy in proportion to their LET and path length in the detector.

Now consider an electric field due to an applied -100 volts between the grid and the container (approximately the field that was present under experimental conditions). This field reduces the energy of the incident secondary electrons at the detector.

Electrons in energy interval (1) shown in the diagram are completely repelled by the -100 volt field. Electrons in energy region (2) are also repelled by the field and do not enter the detector. The fraction absorbed in the detector is shown in region (3). Energy in region (4) is not deposited in the detector as the range of the secondary electrons exceeds the diameter of the detector. The area under the regions $(1) + (2) + (3)$ represents the energy deposited in the detector with no electric field between the grid and the aluminum container. Area under region (3) represents the energy deposited in the detector under the influence of the electric field. Area under region (3) is approximately 60% of the total area under $(1) + (2)$ and (3).

In Figure 6, a cut-off energy of 10 eV was assumed for the secondary electrons, this energy is approximately equal to the ionization potential of the gases used. However, if the secondary electron spectrum was assumed to have $E^{-3}$ dependence below about 100 eV, then this would tend to increase the area under region (1). But at energies below 100 eV the average energy required to form an ion pair ($\bar{W}$) will increase and this has the effect of decreasing the energy measured in the experiment, i.e., decreasing the area under region (1). Thus, the above mentioned effects tend to cancel each other, and hence choice of 10 eV for the cut-off energy, even though arbitrary is
adequate for our approximate calculations. Using 30 eV (which is the \( W \) for approximately 1 kev electrons) as the cut-off energy in Figure 6, results in differences of only a few percent in the ratio of area under region (3) and that under \( \sum (1) + (2) + (3) \). Thus, under the influence of an electric field only about 60\% of the expected energy deposition should occur. This would account for the low proportional counter results obtained for 40 MeV lithium ions and 10 MeV protons. If the slowing down spectrum does not significantly change shape with specific energy of the incident ion, then the energy deposited obtained by proportional counter measurements when the heavy ion does not pass through the counter, i.e., for "Indirect" events should be raised by about 40\%. This correction, thus makes 40 MeV lithium and 10 MeV proton data agree within experimental uncertainty with ionization chamber measurements, but leaves 23 MeV proton data about 40\% higher than ionization chamber data. This may indicate that the secondary electron slowing down spectrum is a function of specific energy of the incident ion and is softer for lower energies.

It should be emphasized that the gas proportional counter gives correct results for direct events, i.e., when the particle passes through the detector, since in this case the electric field does not appreciably affect the energy deposition in the detector.

ACKNOWLEDGEMENT

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REFERENCES


<table>
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<tr>
<th>Ion</th>
<th>Specific Energy (MeV/amu)</th>
<th>$Z_{\text{eff}}$</th>
<th>Radial Distance ($\mu$m)</th>
<th>Dose (ergs/gm)</th>
<th>$\text{ergs.}\mu\text{m}^2/\text{gm}$</th>
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<tr>
<td>$^1\text{H}$</td>
<td>1</td>
<td>1.0</td>
<td>$5.0 \times 10^{-3}$</td>
<td>$3.0 \times 10^7$</td>
<td>$7.5 \times 10^2$</td>
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<tr>
<td>$^1\text{H}$</td>
<td>3</td>
<td>1.0</td>
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<td>$2.0 \times 10^4$</td>
<td>$2.0 \times 10^2$</td>
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<td>$2.8 \times 10^7$</td>
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<td>2.0</td>
<td>$3.0 \times 10^2$</td>
<td>$1.4 \times 10^{-4}$</td>
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Table II. Estimated and Measured Energy Deposition in One Micron Diameter Sites and Normalized Energy Deposition for Various Ions.

<table>
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<tr>
<th>Ion</th>
<th>Specific Energy (MeV/amu)</th>
<th>Energy Deposition in 1µm diameter site (eV)</th>
<th>Normalized Energy Deposition in 1µm diameter site (eV)</th>
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<td></td>
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<td>R=(1µm)</td>
<td>R=(2µm)</td>
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<tr>
<td>$^1$H</td>
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<td>3</td>
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</tr>
<tr>
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<td>$^6$Li</td>
<td>6.66</td>
<td>$1.6 \times 10^2$</td>
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* Taken from Figure 4 in Reference 3. Note, however that ordinate in this figure is mislabeled, values $10^{-3}$, $10^{-2}$ and $10^{-1}$ should be ten times larger.
FIGURE CAPTIONS

Figure 1. Experimental chamber used in radial dose measurements.

Figure 2. Experimental arrangement used in event size spectra measurements.

Figure 3. Plot of normalized energy deposition in one micron diameter site vs specific energy of incident ions at radial distance of one micron, from the ion's path.

Figure 4. Plot of normalized energy deposition in one micron diameter site vs specific energy of incident ions at a radial distance of two microns from the ion's path.

Figure 5. Sketch showing position of the site with respect to ion's path, and relevant parameters, used in calculations.

Figure 6. Plot of relative dose (percent) per logarithmic energy interval vs secondary electron energy. Also shown are the maximum energy of secondary electrons for 6.6 MeV/amu Li^3+ ions (A), 10 MeV protons (B) and 23 MeV protons (C).
Figure 1. Experimental chamber used in radial dose measurements.
Energy (MeV/amu) vs. Normalized Energy Deposited in 14 M Diameter Site (keV)

- Experimental data from Klauka and Rossi
- Estimated from radial dose measurements

A - Experimental, Klauka and Rossi
0 - Estimated from radial dose measurements
Figure 4. Plot of normalized energy deposition in one micron diameter.

- Experimental, Klauza and Rossi
- Estimated from radial dose measurements

NORMALIZED ENERGY DEPOSITED IN 1µm DIAMETER SITE (keV)

ENERGY (MeV/amu)
Figure 5. Sketch showing position of the site with respect to the ion's path, and relevant parameters, used in calculations.
Figure 6. Plot of relative dose (percent) per logarithmic energy interval.

Secondary Electron Energy (eV) vs logarithmic energy interval.