Measurements of energy deposition spectra in small sites by protons and deuterons

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Measurements of Energy Deposition Spectra
in Small Sites by Protons and Deuterons*

by
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B.A. University of Montana, 1980

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Measurements of Energy Deposition Spectra in Small Sites by Protons and Deuterons

Director: Leonard E. Porter

The effects of radiation on biological material is dependent on the amount of energy imparted by the radiation to the sensitive components of the living cells. Monte Carlo calculations are, at present, the only method of obtaining the ionization distributions at the spatial dimensions of DNA. However, developing codes for these calculations require comparisons to be made between the calculations and actual experimental results obtained at larger spatial dimensions.

Experimental measurements of ionization distributions were made using protons and deuterons with energies of 0.5 to 1.5 MeV. Propane gas was used to simulate small cylindrical sites of unit density material with diameters of 0.5 and 1.0 um. The heights of the sites equaled their diameters. The beams of protons and deuterons had cross sections much smaller than the simulated sites which allowed accurate measurements of energy deposition in the site as a function of the beam’s distance from the center of the site. Beams were positioned at distances of 0.17 to 6 times the radius from the center of the site. Both the magnitude of the energy deposited and the number of occurrences of each magnitude of energy deposited in the site were measured for a given number of protons and deuterons.

Energy deposition in the site is shown to be dependent on the number of delta rays induced by the primary ion, the distance the delta rays have to travel to reach the site and the energy of the delta rays. Comparison of dose distributions for protons and deuterons passing outside the site reveals that deuterons deposit less energy than protons of the same and, in some cases, lower stopping power. The data supports the argument that the delta rays induced by these deuterons are of lower energy, and are therefore more limited in range, than the delta rays induced by the corresponding protons.
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CHAPTER I
INTRODUCTION

Among the physical properties of radiation which have important effects on biological materials are the magnitude of the energy deposited to the material by each primary ion and the number of occurrences of each magnitude of energy deposited to the material by all the primary ions. For 1 MeV protons, about 75% of the energy lost in primary interactions is in the ionization process \(^{(1)}\). However, the energetic delta rays (or, secondary electrons) produced by the proton collisions have such a short range that energy distribution measurements using biological or unit density material in a condensed phase is not feasible. Therefore one uses the gaseous phase to simulate this material. Wilson and Paretzke \(^{(2)}\) have concluded that, at least for the hydrocarbons which they studied, there is no significant difference in the gaseous and condensed phases for proton-induced emission of delta rays with energies above 15 eV.

The proportional counter is well suited for simulating small sites of unit density material. The experimental technique was introduced by Rossi et al. \(^{(3)}\). Simulation of small sites is achieved by equating the thickness (in gm/cm\(^2\)) of the small site at unit density to the thickness (in gm/cm\(^2\)) of the gas in the sensitive volume of the proportional counter. By varying the density of the gas, the delta ray tracks can be lengthened to where they traverse a significant portion of the sensitive

\(^{*}\) The numbers in parentheses refer to numbered references in the bibliography.
volume. As the energetic delta rays cross the sensitive volume of the proportional counter, they deposit energy by ionizing the gas. Those electrons with insufficient energy to leave the sensitive volume drift toward the anode wire of the proportional counter where they gain enough kinetic energy to initiate even more ionizations, multiplying by powers of ten the number of electrons finally collected by the anode. The resultant pulse height is thereby proportional to the energy released by the original delta ray in the sensitive volume. Limitations exist as to the smallest site size that can be simulated by the proportional counter. Debate over the energy spectrum resolution versus site size continues (4,5) with general agreement that resolution degrades somewhere below 0.5 μm*. Since DNA strands are only two to three nanometers wide, Monte Carlo calculations are used in determining the ionization distributions for very small sites (less than 0.1 μm). However, developing codes for these calculations requires comparisons to actual experimental results on the larger sized sites.

One of the problems with the early proportional counters was the effect due to the solid walls. Energy deposition spectra for primary ions that traversed the site were distorted due to the ionizations taking place just at the gas-wall interface of the sensitive volume. Also, delta rays produced outside the counter could not penetrate the wall. A "wall-less" proportional counter has been developed whose walls

* A 1.0 μm site at unit density corresponds to a thickness of 10^{-4} gm/cm^2 (1.0 μm x 1 gm/cm^3).
are of the same density as the gas and defined by a grid of fine wire. Energy distributions of delta rays can now be obtained from primary particle tracks passing outside as well as inside the sensitive volume of the proportional counter. This ability to probe in and near the primary track is of interest to radiobiologists in their study of the survival of irradiated cells.

In this study, energy deposition spectra, resulting from the initial ionization of propane gas by positively charged ions, have been experimentally collected. Each individual spectrum was characterized by four parameters: the primary ion used, the initial energy of the primary ion, the simulated site size used, and the distance from the primary ion track to the center of the site. Because of the vast number of possible combinations that could be made with these four parameters, limitations were chosen in view of the accelerator capabilities, the resolution of the proportional counter, and the number of comparisons that could be made of spectra differing by only one parameter.

Previous work done using simulated small sites is limited. One experiment, by Gross and Rodgers (6), used a spherical proportional counter while another experiment, by Glass and Roesch (7), used a cylindrical proportional counter. The two experiments, however, were similar in the use of protons as the primary ion. In comparison to these earlier experiments, the work presented here features lower energy protons and includes deuterons as primary ions.
CHAPTER II
APPARATUS

The main apparatus utilized here is the same as that used by Glass and Roesch (7) in 1972, consisting basically of a large chamber containing a wall-less, cylindrical proportional counter with its charge sensitive preamplifier and a solid state detector (ORTEC Model:5-59A). A coincidence circuit is established such that only those events in the proportional counter corresponding to an event in the solid state detector are analyzed.

The beam of ions from the 2 MV Van de Graaff accelerator is collimated by two holes of 12.5 μm diameter in tantalum foil before entering the chamber. The beam cross section is thus much smaller than that of the proportional counter. The two collimator holes also serve for differential pumping between the gas filled chamber and the accelerator vacuum. At the other end of the chamber, a 0.5 mm slit is placed over the solid state detector to reduce the number of signals received due to scattering within the gas.

The wall-less proportional counter, mounted in a frame, can be moved perpendicularly to the beam line by means of a micrometer screw. The sensitive volume of the cylindrical proportional counter is defined radially by a helical grid of fine wire and longitudinally by field-shaping electrodes. The height of the sensitive volume is equal to the diameter of the cylinder with the high voltage anode wire occupying the axis. The wire grid itself provides about 95%
transparency of the radial surface. The field-shaping electrodes serve to keep the electric field lines straight along the ends of the sensitive volume (figure 1).

Low energy secondary electrons are prevented from drifting into the sensitive volume by the electric field from two low voltage anode loops outside the proportional counter, situated above and below the sensitive volume.

An aluminum x-ray source (ISOTOPE PRODUCTS LABORATORIES Model:XAN-244-AL) mounted inside the chamber is used for energy calibration (see section A of chapter III). The proportional counter is exposed to the x-rays by the removal of a shield covering the source. This shield can be operated from outside the chamber without breaking the vacuum.

The input stage of the charge sensitive preamplifier for the proportional counter is located inside the chamber and close to the counter. This method is used in order to minimize the electrical noise that can be caused by the capacitance of connecting wires. The rest of the charge sensitive preamplifier (TENNELEC Model:TC 136) is attached outside the chamber.

Signals from the proportional counter are routed via the preamplifier to two linear-amplifier/pulse-shapers (TENNELEC Model:TC 202BLR). Two amplifier/shapers are used in order to observe the same spectrum simultaneously using two different gain settings. The output of each amplifier/shaper is then connected to the signal input of
Diagram of the main apparatus with insert showing details of the wall-less proportional counter.
individual analog-to-digital converters (ADC) (NUCLEAR DATA Model: ND 560). The addresses produced by the ADCs are routed through an interface (NUCLEAR DATA Series 2200 Digiplex/Dual Parameter) to a multichannel analyzer (MCA) (NUCLEAR DATA Model: 100). This scheme allows acquisition of two spectra simultaneously, without increased dead time and loss of precision. The MCA provides a graphical spectrum of pulse height (abscissa) versus frequency (ordinate) and stores these values for retrieval in numerical form. The maximum pulse height that can be registered along the 512 channel abscissa used in this experiment is eight volts. Since pulse height is proportional to the energy deposited, the abscissa can be converted to an energy scale. Increasing the gain of the amplifier/shaper decreases the differences in energy between consecutive channels.

Signals produced as a result of the positive ions striking the solid state detector are routed through a separate charge sensitive preamplifier (TENNELEC Model: TC 136 S/PA) and amplifier/shaper (TENNELEC Model: TC 203BLR). These signals, which are used to enable the MCA for acquisition of signals from the proportional counter, are then used as inputs to a single channel analyzer (TENNELEC Model: TC 441). The single channel analyzer (SCA) provides ten volt logic pulses 1 usec wide. A discriminator on the SCA allows for the selection of only those pulses above a certain voltage to provide the logic signal. The output logic signals are divided and routed into the gate inputs of both ADCs. With the MCA in the coincidence mode, the logic signal turns the MCA on for seven microseconds to acquire a signal from the proportional counter. A
scaler, built into the MCA, is used to count the number of gate signals received during the acquisition time of the MCA.

The pressure in the chamber is maintained with a constant flow of propane gas using a feedback system controlled by a pressure meter (MKS Baratron Type: 77 with a Type: 77H-30 Pressure Head). As propane gas leaks into the chamber, the pressure meter continuously compares the chamber pressure to that in a separate reference volume. Differences in pressure are corrected by opening and closing a leak valve (GRANVILLE-PHILLIPS Series: 213) to a roughing pump. A Servo Response Controller (GRANVILLE-PHILLIPS Model: 213 015) is added to adjust the on-off timing of the leak valve motor for more stable control. A mercury manometer (GILMONT Cat. No.: G-1500) is used to measure directly the pressure in the chamber. To reduce any possible errors in the manometer's reading, it is situated out of the line of direct flow of gas.
CHAPTER III

METHODS

A. CALIBRATION

Energy calibration of the spectra is done with the use of the aluminum x-ray source. At the 1.37 μm simulated site, the aluminum x-ray spectrum is collected in a non-coincidence mode. The channel number of the peak for this spectrum corresponds to the predominant energy of the x-rays (1.487 keV). Therefore, the difference in energy between consecutive channel numbers, \((E/CH)_x\), for the x-ray spectrum is simply 1.487 keV divided by the channel of the peak, \(CH_x\).

\[(E/CH)_x = \frac{1.487 \text{ keV}}{CH_x} \quad (3.a.1)\]

For the same simulated site size, a coincidence spectrum is collected using protons with 1.5 MeV of energy at the center of the proportional counter. Taking into account the differences in the amplifier gain settings, the energy loss by the protons, \(E_l\), that corresponds to the channel, \(CH_l\), for the peak in this spectrum is

\[E_l = K_1 \times CH_l \times (E/CH)_x, \quad (3.a.2)\]

where \(K_1\) is the ratio of the gain setting used for the aluminum x-ray spectrum to the gain setting used for the proton spectrum.

Figure 2 is an example of spectra collected for aluminum x-rays and 1.5 MeV protons at the same simulated site size. The aluminum x-ray spectrum shows a considerable amount of bremsstrahlung. This is a result of the 5.9 MeV alpha particles from curium 244 exciting the gas as well as the aluminum foil in the source. Attempts were made to
Calibration spectra using aluminum x-rays (left) and 1.5 MeV protons (right) for a 1.37 μm simulated site diameter. Amplifier gain for aluminum x-rays is ten times that used for the 1.5 MeV protons.
reduce the bremsstrahlung by placing beryllium and mylar windows over
the source, but this method seriously reduced the number of aluminum
x-rays emitted as well.

Energy calibration for a smaller simulated site is determined by
collecting a coincidence spectrum for protons with 1.5 MeV of energy at
the center of that simulated site. Scaling for the difference in
simulated site sizes, the energy, \( E_2 \), of the peak for this spectrum is

\[
E_2 = K_2 \times E_1, \quad (3.a.3)
\]

where \( E_1 \) is the previously determined energy loss for 1.5 MeV protons at
the 1.37 \( \mu \)m simulated site, and \( K_2 \) is the ratio of the smaller simulated
site size to 1.37 \( \mu \)m. The difference in energy between consecutive
channel numbers, \( (E/CH)_2 \), for the smaller site is simply the value of \( E_2 \)
divided by the channel number, \( CH_2 \), of the peak corresponding to that
energy.

\[
(E/CH)_2 = E_2/CH_2 \quad (3.a.4)
\]

B. GAS GAIN

As mentioned in the introduction, electrons initially deposited in
the sensitive volume of the proportional counter are drawn toward the
anode wire by the electric field. These electrons gain sufficient
kinetic energy to cause further ionization of the gas. The ratio of the
number, \( N_f \), of electrons finally collected by the anode wire to the
number, \( N_i \), of electrons initially deposited in the site is the gas
gain, \( G \).

\[
G = N_f/N_i \quad (3.b.1)
\]
To determine the gas gain for a particular site size, a spectrum for a beam of ions passing close to the center of the site is first collected. Using the same amplifier/shaper gain setting, a second spectrum is obtained using test pulses supplied by a pulser (TENNELEC Model: TC 812) connected to the charge sensitive preamplifier of the proportional counter. The amplitude of these pulses is adjusted until the MCA registers a corresponding amplified and shaped pulse in the same channel as the peak in the first spectrum. The output voltage, \( V \), of the test pulse, when multiplied by the ratio of the test line capacitance, \( C \), to the charge per electron, \( Q_e \), gives the same number of electrons, \( N_f \), that would have to be collected by the anode wire of the proportional counter to produce the same signal.

\[
N_f = V \times \frac{C}{Q_e} \tag{3.b.2}
\]

where \( Q_e \) has the value of \( 1.6 \times 10^{-19} \) coulombs per electron. The channel number containing the peak in the first spectrum represents an energy, \( E_i \). This energy is determined by multiplying the MCA channel registering the peak by the energy calibration for that gain setting and simulated site size. \( E_i \), when divided by the mean energy needed to produce an ion pair (the \( W \)-value), gives the number of electrons, \( N_i \), initially deposited in the site.

\[
N_i = \frac{E_i}{W} \tag{3.b.3}
\]

\( W \) has been experimentally determined to be about 24 eV per ion pair for electrons in propane gas (8). The gas gain can then be calculated using equation (3.b.1). For this experiment, the gas gain is between 1000 and 2000.
C. NOISE

The electrical noise of a charge sensitive preamplifier is commonly expressed in terms of the number of electrons producing the noise at the input stage for the charge sensitive preamplifier. A root-mean-square (rms) voltmeter (HEWLETT-PACKARD Model:3400A), connected to the output of the amplifier/shaper, is used to measure the rms noise voltage, $V_n$. By determining a test pulse voltage, $V_t$, needed to produce the same output voltage as the rms noise voltage, one can determine the number of electrons needed to produce the noise by using equation (3.b.2). For this apparatus, the noise corresponds to that which 150 to 200 electrons would produce at the input stage of the charge sensitive preamplifier.

D. ENERGY RESOLUTION

The "full width at half maximum", (Fwhm), of a distribution is used to determine the energy resolution of the proportional counter. If, for a continuous Gaussian (or normal) distribution, we assume that the maximum of the distribution occurs at the average energy for the distribution, then

$$F\text{whm} = 2.35 \times \sigma_E$$  \hspace{1cm} (3.d.1)

where $\sigma_E$ is the standard deviation from the average energy. Remembering that the number of ion pairs produced is related to the energy imparted by the stopping particle by the W-value (see equation 3.b.3), one can rewrite equation 3.d.1 to read

$$F\text{whm}_N = 2.35 \times \sigma_N$$  \hspace{1cm} (3.d.2a)

or
\[ \text{Fwhm}_E = 2.35 \times \sigma_N \times W \quad (3.\text{d}.2b) \]

where \( \sigma_N \) is the standard deviation from the average number of ions, \( \langle N \rangle \), produced by the stopping particle. The variance, \( \sigma^2 \), has the relationship (9),

\[ \sigma^2 = \langle N \rangle \times F \quad (3.\text{d}.3) \]

where \( F \), the Fano factor depends on the probability of different energy losses per ionization. For propane, the Fano factor is 0.29 ± 0.03 (10).

Since the primary particle loses energy faster at the end of its track than at the beginning, one should consider all the ionizations caused by the stopping particle in order to determine the average number of these ionizations. The aluminum x-rays in a large simulated site should provide the measurable results. The x-ray transfers most of its energy (1.487 keV) to an electron (the primary particle), and, because of the large simulated site size, the electron's path length is short enough that the vast majority of the path lengths will begin and end within the site. However, as can be seen with the x-ray spectrum in figure 2, the amount of bremsstrahlung prevents the direct measurement of \( \text{Fwhm}_E \). Hence, half the width at half maximum is measured and then doubled to represent \( \text{Fwhm}_E \). A value of about 500 eV is indicated for \( \text{Fwhm}_E \) after consideration of many x-ray spectra. A calculation using a Fano factor of 0.29, the x-ray energy of 1.487 keV and a W-value of 24 eV per ion pair yields 240 eV for the value of \( \text{Fwhm}_E \). As expected, the measured value of \( \text{Fwhm}_E \) is not as small as the calculated value. However, the large difference in the two values is in part due to the
bremsstrahlung appearing in the x-ray spectrum. Other contributing factors to the difference are the electronic noise (section C of this chapter) and any lack of symmetry in the proportional counter. Lack of symmetry in the proportional counter causes non-uniformity in the gas gain along the anode wire.

E. DATA COLLECTION

Table 1 shows the primary ions, their energies and the simulated site sizes for which spectra are collected.

Table 1
Spectra ion, energy and site size

<table>
<thead>
<tr>
<th>Primary Ion</th>
<th>Energy (MeV)</th>
<th>Simulated Site Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>deuterons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Because of the density of the gas and the distance the primary ions had to traverse to reach the solid state detector, some spectra cannot be collected with this apparatus without modification. The 0.5 MeV proton in the 1.0 µm simulated site and the 0.5 MeV deuteron in the 0.5 and
1.0 µm simulated sites do not have enough energy by the time they reach the solid state detector to produce signals distinguishable from the inherent noise of the solid state detector.

The distance between the primary ion's track and the center of the proportional counter (or, impact parameter) is measured in terms of the radius of the simulated site. For each primary ion, energy and simulated site size listed in table 1, spectra for impact parameters of 0.17, 0.87, 0.95, 1.0, 1.2, 1.4, 1.6, 2.0, 3.0, 4.0 and 6.0 radii are collected.

As mentioned in the description of the apparatus and support equipment, simultaneous spectra acquisition can be performed using two different gain settings on the amplifier/shapers. A ratio of 100 to 1 is used for most of the simultaneous spectra collected in this work. At the higher gain settings, the energy calibrations are about 1.3 and 1.5 eV per channel for the respective 0.5 and 1.0 µm simulated site sizes.

Not all the primary ions reaching the solid state detector produce coincidence events in the proportional counter. So the duration of the spectrum acquisition is determined by the number of logic (or, gate) signals received by the MCA. For most of the spectra, 10,000 logic signals registered by the scaler determines the acquisition time.
A steady beam current, especially for low energy primary ions at the larger simulated site sizes, is a difficult problem. The primary ions lose a large amount of energy near the proportional counter, and a small fraction of these ions reach the solid state detector. One is at first tempted to increase the beam current to increase the count rate at the solid state detector. However, this method tends to saturate the proportional counter with electrons, thus distorting the spectrum. Also, automatic focusing and steering controls for the Van de Graaff tend to drift with time causing fluctuations in the beam current, thereby saturating the proportional counter. The solution to the problem is to reduce the beam current sufficiently so that these fluctuations will not saturate the proportional counter. This is done by first lowering the beam current of the accelerator to just above the limit where the automatic controls can hold the beam reasonably steady. Then, by slightly offsetting one of the holes of the collimator, one reduces the current within the chamber. The count rate of the solid state detector is small (in the order of 10 ions per second). However, fluctuations in the beam current will not seriously affect the proportional counter.

For the spectra collected using the higher amplifier/shaper gain, the question arose as to whether electronic noise of the charge sensitive preamplifier and/or accidental coincidences between unrelated events were influencing the lower energy end of the spectrum. Periodic spectra were therefore taken at various impact parameters. The results clearly showed that these two possibilities were occurring and indicated
the degree to which they influenced the actual experimental results. The electronic noise effect was determined by collecting a spectrum without a beam current and using the pulser to provide the gate signals. The influence of both electronic noise and accidental coincidence is determined by collecting a spectrum with a beam current and again using only the pulser to provide the gate signals. Subtraction of the electronic noise spectrum from the latter spectrum yields the accidental coincidence spectrum. Although accidental coincidences did occur, the number and random sizes of these events would not alter the distributions significantly. The electronic noise spectra, however, significantly altered the number of events appearing in the MCA channels one through eleven at the higher amplifier/shaper gain. Section D of chapter IV will describe how the data was corrected to eliminate the electronic noise.
CHAPTER IV

RESULTS

A. RATIO OF IONS TO SIGNALS

Figures 3a and 3b show the ratio of the number of primary ions producing measurable events to the number of primary ions counted by the scaler of the MCA as a function of impact parameter. Essentially every primary ion that passed near the center of the site produced an analyzable signal. Farther out, at 0.87 radii, a drop in the ratio is observable. The drop in the ratio becomes even more steep for the 0.95 and 1.0 radii impact parameters. At 1.2 radii, the ratio starts to drop off more gradually, with fewer than 1% of the primary ions producing measurable events at the 2.0 radii impact parameter for all primary ion energies and simulated site sizes shown here.

In the Glass and Roesch experiment (7), protons with 1.7, 3.0 and 4.0 MeV energies were used for a 0.23 \( \mu \text{m} \) simulated site of tissue equivalent gas. They note that between 1.04 and 1.28 radii, the ratio falls to about 15%. This corresponds to the data presented in figures 3a and 3b. However, Glass and Roesch observe that more than 80% of the protons produced analyzable signals for impact parameters less than 1.04 radii. Also, they note that the ratio drops gradually from 15% at about 1.28 radii to 1% at about 3.2 radii. The differences between the latter two findings and those that appear in the present study may be explained by the differences in the energies and simulated site sizes between the two experiments. With respect to the actual dimensions of the sensitive volume, the track lengths of delta rays become longer for
Figure 3

Ratio of the total number of events measured by the proportional counter to the number of gates provided by the solid state detector as a function of impact parameter for (a) protons and (b) deuterons of energy $E$ and simulated site diameter $d$. 

- **a.**
  - Black: $1.5$ MeV $1.0 \mu m$
  - Red: $1.0$ MeV $0.5 \mu m$
  - Green: $1.0$ MeV $1.0 \mu m$
  - Blue: $0.5$ MeV $0.5 \mu m$

- **b.**
  - Black: $1.5$ MeV $0.5 \mu m$
  - Red: $1.0$ MeV $0.5 \mu m$
  - Green: $1.0$ MeV $1.0 \mu m$
increasing primary ion energies and for decreasing simulated site sizes (see table 2 in section B of this chapter). The lengthening of the delta ray track increases the probability that at least part of it will cross the sensitive volume of the proportional counter. Evidence for this can be seen in figure 3b. For the 1.0 MeV deuteron at the 0.87 radii impact parameter, about 11% more deuterons produce analyzable signals in the 0.5 \( \mu \text{m} \) site than in the 1.0 \( \mu \text{m} \) site. And, for the 0.5 \( \mu \text{m} \) site at 0.87 radii, about 3% more analyzable signals appear in the 1.5 MeV deuteron spectrum than in the 1.0 MeV deuteron spectrum. Figure 3a shows similar increases in the ratio when the proton energy is increased and/or the simulated site size is decreased.

A curious note about figures 3a and 3b is the crossing over of the lines at about 1.18 radii. For impact parameters greater than 1.18 radii, the higher ratios appear to be favored by the lower primary ion energies and by the larger site sizes (i.e., by short delta ray tracks). The explanation for this may be in the way the delta ray tracks lie with respect to the primary ion track. When the primary ion ionizes the gas, the delta rays tend to be scattered in the forward direction. So, for large energy transfers between the primary ion and the electron, the electrons' track may be close enough to the beam line that it does not enter the sensitive volume. Further ionization caused by the high energy electron may also produce an electron whose track is close to the beam line. Also, since more ionization occurs at the end of a track than at the beginning, using a smaller simulated site lengthens the electrons' track and increases the distance between
subsequent ionizations, thereby decreasing the number and likelihood that delta rays will enter the sensitive volume.

B. MEAN ENERGY

Figures 4a, 4b and 4c show the mean energy deposited in the site as a function of impact parameter. The mean energy, \( \langle E \rangle \), of a spectrum is determined by summing the products of the deposited energy, \( E_i \), times the number of events for that energy, \( N(E)_i \), and then dividing by the total number of events in the spectrum.

\[
\langle E \rangle = \frac{\sum (E_i \times N(E)_i)}{\sum N(E)_i} \quad (4.b.1)
\]

The smooth curved lines that appear in the figures are the theoretical mean energy losses in the site for each primary ion energy and simulated site size used. The theoretical curves are calculated by simply multiplying the appropriate stopping power (11) for the various primary ions by the simulated chord lengths across the proportional counter. The observed mean energies fall close to the theoretical means when primary ions pass through the site. However, at the edge of the site and beyond, the observed mean energies are larger than the theoretical means. This is expected since the primary ion's path length in the site is zero; yet associated delta rays may enter the site and deposit energy. All but one of the plots show a minimum in the mean energy just outside the site before a slight increase and then taper off at larger impact parameters. This can be explained by the numbers of events in the spectra and by the range of the delta rays. As mentioned in section A of this chapter, just outside the site the number of events...
Figure 4

Mean energies of events occurring in the 0.5 μm diameter site due to (a) protons and (b) deuterons of energy E as a function of impact parameter. Straight lines are drawn to guide the eye. Smooth curves represent the theoretical means.
Mean energies of events occurring in the 1.0 μm diameter site due to protons and deuterons of energy E as a function of impact parameter. Straight lines are drawn to guide the eye. Smooth curves represent the theoretical means.
drops off. However, the low energy delta rays make up the majority of the events. For successively larger distances outside the site, the range of the low energy delta rays prohibits more and more of these delta rays from reaching the site. The number of events by the more energetic (i.e., long-range) delta rays then starts to make up a larger percent of the total number of events in the spectrum.

Difficulties arise in determining the maximum range of a delta ray since a definition of the range for low energy electrons is not agreed upon. Several methods for determining these ranges include:

1) summing the individual path lengths as the electron wanders around,

2) resolving individual path lengths along the line of the initial velocity vector,

and

3) measuring the path length for certain initial and final electron energies.

The method used to determine the range of the delta rays in this study is the continuous slowing down approximation (cSda). The definition of the range using the continuous slowing down approximation, \( \text{R}_{\text{csda}} \), is as follows: "\( \text{R}_{\text{csda}} \) is the path length a particle would traverse when slowing down to a stop, if its rate of energy loss along the track were equal to the mean energy loss defined by the stopping power" (12). Therefore,

\[
\text{R}_{\text{csda}} = \frac{E_e}{S_e(E_e)}
\]  

(4.2.b)

where \( S_e(E_e) \) is the stopping power of the electron with initial energy,
Ee, in a particular absorber. Table 2 shows the calculated values of Rsda in terms of the radius of the simulated site size.

<table>
<thead>
<tr>
<th>Primary Ion</th>
<th>E\text{max} (keV)</th>
<th>S (E) in propane (MeV cm(^2)/gm)</th>
<th>Rsda (gm/cm(^2)) for simulated site size 0.5 (\mu)m</th>
<th>Rsda (radii) for 1.0 (\mu)m</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>0.5</td>
<td>1.0</td>
<td>149</td>
<td>6.7x10(^{-6})</td>
</tr>
<tr>
<td>d</td>
<td>1.0</td>
<td>1.5</td>
<td>112</td>
<td>1.3x10(^{-5})</td>
</tr>
<tr>
<td>p</td>
<td>1.5</td>
<td>2.0</td>
<td>90.7</td>
<td>2.2x10(^{-5})</td>
</tr>
<tr>
<td>p</td>
<td>2.0</td>
<td>3.0</td>
<td>66.9</td>
<td>4.5x10(^{-5})</td>
</tr>
</tbody>
</table>

The maximum energies for the delta rays are determined using the conservation laws of energy and momentum for elastic collisions.

As can be seen in table 2, the shortest range (in radii) occurs for delta rays with 1.0 keV initial energy and for the 1.0 \(\mu\)m simulated site size. For the 1.0 MeV deuteron and 1.0 \(\mu\)m site in figure 4c, this may explain why one does not see the characteristic mean energy minimum just outside the site which one sees for other energies, primary ions, or site sizes.
C. ANALYSIS OF SPECTRA WITH IMPACT PARAMETERS LESS THAN OR EQUAL TO THE SIMULATED SITE RADIUS

Figures 5a, 5b and 5c are samples of some of the spectra collected for impact parameters less than or equal to the radii of the simulated sites. Each spectrum is normalized so that the area under the spectrum represents the fraction of the total number of ions producing measurable events in the proportional counter (see section A of this chapter). Therefore, at the smallest impact parameter, where every primary ion should produce an analyzable signal, the area under the spectrum would be unity.

Figure 6a demonstrates the similarity in the energy deposition pattern by different primary ions with the same energy per nucleon. The ratio of the mean energy deposited by the deuteron to the mean energy deposited by the proton is 1.1.

As can be seen in figure 6b, doubling the energy of the primary ion does not simply decrease the energy deposition pattern by a factor of two. Here, the ratio of the mean energy deposited by the low energy proton to that by the high energy proton is 1.5. However, for primary ions with the same energy, figure 6c demonstrates that doubling the site size does increase the mean energy deposition by a factor of two. Here, the ratio of the mean energy deposited in the larger site to that deposited in the smaller site is 2.0.
Normalized spectra at various impact parameters, b, for (a) 1.0 MeV protons within a 0.5 μm diameter site and (b) 1.5 MeV protons within a 1.0 μm diameter site. Curves fitted by eye.
Normalized spectra for 1.5 MeV deuterons at various impact parameters, b, within a 0.5 μm diameter site. Curves fitted by eye.
Normalized spectra for 1.0 MeV deuterons (black) and 0.5 MeV protons (red) at the 0.042 μm impact parameter of a 0.5 μm diameter site. Curves are fitted by eye.

Normalized spectra for 0.5 MeV (red) and 1.0 MeV (black) protons at the 0.042 μm impact parameter of a 0.5 μm diameter site. Curves are fitted by eye.
Normalized spectra for 1.5 MeV protons at the 0.042 μm impact parameter of a 0.5 μm diameter site (left) and at the 0.085 μm impact parameter of a 1.0 μm diameter site (right).
As the primary ions cross near the center of the site, the large number of delta rays produced and the short range of these delta rays insure that most of the energy lost by the primary ion will remain within the site. However, as the impact parameter is enlarged up to and including the radius of the site, changes in the spectra are due to the decrease in the number of primary ion induced delta rays within the site and to the increase of energy transported outside the site by the delta rays.

D. ANALYSIS OF SPECTRA WITH IMPACT PARAMETERS GREATER THAN THE RADIUS OF THE SIMULATED SITE

For impact parameters greater than the radius of the simulated site size, the amount of energy deposited within the site is due solely to energy transported to the site by delta rays produced outside the site. The shape of the distribution changes from those that appear in figures 5a, 5b and 5c to monotonically decreasing spectra (figure 7). As the impact parameter is lengthened, the likelihood increases that each measured event (and thereby the spectrum in general) represents individual interactions of the primary ion. However, as can be seen in figure 7, the area under such distributions is quite small reflecting the decreasing probability that the delta rays will reach the site because of insufficient energy. Also, outside the site, the solid angle subtended by the sensitive volume with respect to a point on the beam line decreases with increasing impact parameter. The direction in which the delta rays are emitted is therefore important to whether energy is deposited in the site or not.
Figure 7

Example of a normalized spectrum for an impact parameter just outside the radius of the site.
For the spectra with impact parameters greater than the radius of the site, I have chosen to represent the distributions using microdosimetric quantities. One such distribution is a dose distribution using linear energy. Linear energy, \( y \), is the energy, \( \varepsilon \), deposited in the site by a single event divided by the mean chord length, \( l \), of the site.

\[
y = \frac{\varepsilon}{l} \quad (4.d.1)
\]

The mean chord length for a convex body is:

\[
l = 4 \times \frac{V}{A} \quad (4.d.2)
\]

where \( V \) is the simulated volume and \( A \) is the simulated surface area of the site. For a cylinder, equation 4.d.2 reduces to

\[
l = 2 \times \frac{d}{3} \quad (4.d.3)
\]

where \( d \) is the simulated diameter of the proportional counter. The quantity \( N(y) \) is the linear energy distribution, or, the ratio of the number of primary ions that actually deposit a specified amount of linear energy, \( y \), to the number of primary ions that were available for such a deposition. Dose distributions weight the distribution by multiplying the linear distribution by the linear energy, \( y \). On a linear scale a dose distribution appears as in figure 8a. Putting the abscissa on a logarithmic scale, the distribution takes the form as in figure 8b. In order more easily to visualize the shape of the distribution, the spectrum is divided into four groups (by channel numbers). Since these spectra are collected with higher amplifier gain settings, electronic noise produces events at the lower end of the spectra that are not really part of the energy deposition pattern from delta rays (see section E of chapter III). Therefore, the first group,
Examples of a dose distribution (a) on a linear scale and (b) on a logarithmic scale.
Example of a dose distribution on a logarithmic scale after averaging.
channels one through eleven, are assigned the value that is the average for channels twelve through fourteen. The second group, channels twelve through thirty-two, are averaged in groups of three. The third group, channels thirty-three through sixty-eight, are averaged in groups of nine. And the last group, channels greater than sixty-eight, are averaged in groups of twenty. The result can be seen in figure 8c. This averaging process may, at first, seem arbitrary. However, it had been developed after trying different combinations on many spectra and provided the best representation for the general shape of the distribution. The area under any part of the dose distribution curve between \( y_1 \) and \( y_2 \) is proportional to the ratio of the total linear energy deposited by events within the \( y_1 \) and \( y_2 \) interval to the total linear energy deposited due to all the events in the distribution.

Figures 9 through 15 depict, for each specific primary ion and primary ion energy, the linear energy dose distributions for impact parameters greater than the radius of the site. Information from dose distributions comes from differences in the area under distributions and general shifts along the abscissa between distributions.

A difference in area under two distributions indicates a change in the total number of events within the site (figures 9c and 9d). However, small changes in area may be due to the stochastics of the number of events rather than to a fundamental change in the distribution (figures 14a and 14b). A change in area may be restricted to a certain range of linear energy sizes for the events such as those below about 100 eV/\( \mu \)m between figures 10b and 10c.
Dose distributions for 0.5 MeV protons at various impact parameters, $b$, outside the 0.5 $\mu$m diameter site.
Dose distributions for 1.0 MeV protons at various impact parameters, b, outside the 0.5 \( \mu \text{m} \) diameter site.
Dose distributions for 1.0 MeV deuterons at various impact parameters, b, outside the 0.5 \( \mu \text{m} \) diameter site.
Dose distributions for 1.5 MeV deuterons at various impact parameters, \( b \), outside the 0.5 \( \mu \text{m} \) diameter site.
Dose distributions for 1.0 MeV protons at various impact parameters, $b$, outside the 1.0 $\mu$m diameter site.
Dose distributions for 1.0 MeV deuterons at various impact parameters, $b$, outside the 1.0 $\mu$m diameter site.
Dose distributions for 1.5 MeV protons at various impact parameters, $b$, outside the 1.0 $\mu$m diameter site.
A general shift along the abscissa between two distributions indicates an overall change in the number of occurrences of each event size (figures 10a and 10c), resulting in an altering of the mean energy deposited.

Each of figures 16 through 20 compares dose distributions for the two simulated site sizes at the same ratios of impact parameter to site radius. The first thing one notices is that for figures 16 through 19 the area under the distributions for the same primary ion and primary ion energy is smaller for the 0.5 \( \mu \)m radius sites (labelled b in each of the figures) than for the 0.25 \( \mu \)m radius sites (labelled a). This situation suggests a decrease in the number of events within the site and therefore a decrease in the total energy deposited when the simulated site size is doubled.

Because of the differences in stopping powers between 0.5 MeV and 1.0 MeV protons, one expects less energy deposition for the 1.0 MeV protons than for the 0.5 MeV protons. This expected decrease in deposited energies is shown by the differences in areas for their respective dose distributions at impact parameters 0.30 \( \mu \)m, 0.35 \( \mu \)m and 0.40 \( \mu \)m in figures 16a, 17b and 18a, respectively. However, the two distributions indicate that about the same energy was deposited at the 0.50 \( \mu \)m impact parameter (figure 19a), and that the energy deposited in the site for the 1.0 MeV protons is greater than that for the 0.5 MeV protons at the 0.75 \( \mu \)m impact parameter (figure 20a). These latter two results are expected when one considers that the maximum energy of a delta ray emitted by a 0.5 MeV proton interaction is smaller than the
Dose distributions for protons and deuterons of various energies at 1.2 radii outside the simulated sites of diameter (a) 0.5 μm and (b) 1.0 μm.
Dose distributions for protons and deuterons of various energies at 1.4 radii outside the simulated sites of diameter (a) 0.5 \( \mu \text{m} \) and (b) 1.0 \( \mu \text{m} \).
Dose distributions for protons and deuterons of various energies at 1.6 radii outside the simulated sites of diameter (a) 0.5 μm and (b) 1.0 μm.
Dose distributions for protons and deuterons of various energies at 2.0 radii outside the simulated sites of diameter (a) 0.5 μm and (b) 1.0 μm.
Dose distributions for protons and deuterons of various energies at 3.0 radii outside the simulated sites of diameter (a) 0.5 \( \mu \text{m} \) and (b) 1.0 \( \mu \text{m} \).
maximum energy of a delta ray emitted by a 1.0 MeV proton interaction. Although the 0.5 MeV protons deposit more energy per unit path length than the 1.0 MeV protons deposit, many of the delta rays emitted in the direction of the site by the 0.5 MeV proton interactions have insufficient energy to reach the site at the 0.75 \( \mu \text{m} \) impact parameter. On the other hand, delta rays emitted in the direction of the site by the 1.0 MeV proton interactions may have sufficient energy to reach the site at the 0.75 \( \mu \text{m} \) impact parameter. The same general process can be seen between the dose distributions for the 1.0 MeV and 1.5 MeV deuterons at the 0.5 \( \mu \text{m} \) diameter site, and between the 1.0 MeV and 1.5 MeV proton distributions at the 1.0 \( \mu \text{m} \) diameter site. However, the transitions in areas beneath the distributions take place between 0.40 \( \mu \text{m} \) and 0.75 \( \mu \text{m} \) impact parameters for the deuterons and around the 1.0 \( \mu \text{m} \) impact parameter for the protons.

As was discussed in section C of this chapter and shown in figure 6a, the spectra produced by 0.5 MeV protons and 1.0 MeV deuterons passing close to the center of the 0.5 \( \mu \text{m} \) diameter site were very nearly the same in shape and in mean energy. This was expected since the 1.0 MeV deuterons have the same energy per nucleon and therefore the same stopping power as the 0.5 MeV protons. However, the dose distributions of these two primary ions for impact parameters greater than the radius of the site are quite different. Although the two distributions appear similar in shape at the 0.3 \( \mu \text{m} \) impact parameter (figure 16a), the general shift of the 1.0 MeV deuterons to the lower end of the abscissa represents a decrease in the energy deposited
compared to the distribution for the 0.5 MeV protons. For the larger impact parameters (figures 17a, 18a and 19a), the difference in energy depositions is even more noticeable by the differences in area under the distributions. But at the 0.75 μm impact parameter (figure 20a), the two distributions indicate that essentially the same amount of energy has been deposited.

The 1.5 MeV deuteron, which has an energy per nucleon of 0.75 MeV, has a larger stopping power than the 1.0 MeV proton. Yet, less energy is deposited in the 0.5 μm diameter site by these deuterons than by the protons at impact parameters 0.30 μm, 0.35 μm and 0.40 μm (figures 16a, 17a and 18a, respectively). And again, it is at the 0.75 μm impact parameter (figure 20a) where one sees the closest similarity in energy deposition.

Finally, the 1.0 MeV deuteron has an energy per nucleon of 0.5 MeV. Therefore, the difference in stopping power for these deuterons and for 1.0 MeV protons is even larger than in the previous case. Dose distributions for these two primary ions can be seen for both the 0.5 μm and 1.0 μm diameter sites in figures 16 through 20. For the 0.5 μm diameter site, the 1.0 MeV deuterons deposit more energy in the site than do the 1.0 MeV protons at the 0.30 μm impact parameter (figure 16a). However, a transition occurs at about the 0.35 μm impact parameter (figure 17a) and one sees much the same conditions at the following impact parameters (figures 18a and 19a) as one does in the previous cases. For the 1.0 μm site diameter, the 1.0 MeV protons deposit more energy than do the 1.0 MeV deuterons at all impact
parameters (figures 16b through 20b).
CHAPTER V
CONCLUSIONS

A literature search yields very little for possible comparisons with the present work. Many of the earlier experiments (14,15,16) are concerned with the radial distribution of energy. These experiments measure the total energy deposited within a defined radial distance around the primary ion track (i.e. the restricted stopping power), and therefore do not readily lend themselves for direct comparison to this work. However, as mentioned in the introduction of this paper, two previous experiments (6,7) are concerned with energy deposition by protons in simulated small volumes. The Glass and Roesch experiment has already been compared with Monte Carlo calculations (17) and is found to be in good agreement. But the differences in proton energies, in simulated site sizes and in the use of deuterons as primary ions in this work restrict the comparisons that might be made with either Glass and Roesch (7) or Gross and Rodgers (6).

The data presented here supports the conclusion that energy deposition within a volume is determined by the size and number of delta rays deposited in the site as a result of the ionization of the gas by the primary ion. Both the size and the number of events occurring in the site are shown generally to decrease as the impact parameter is enlarged. Variations and possible explanations for these observations are discussed in sections A and B of chapter IV.
For impact parameters greater than the radius of the site, the data show that for different energies of the same primary ion, the total energy deposited in the site is greater for the lower than for the higher energy primary ions up to a certain impact parameter. This is expected because the stopping power is greater for the lower than for the higher energy primary ions and therefore more energy is deposited in the vicinity of the site. However, after a certain impact parameter, the higher energy primary ion deposits more energy than the lower energy primary ion because many of the delta rays induced by the lower energy primary ions have insufficient energy to reach the site.

The observations made for the comparisons of the dose distributions for different primary ions suggest that the delta rays induced by the deuterons differ in some way from those induced by protons. In the comparison, the expectation was that the deuterons, by virtue of their higher stopping power, should, at most of the impact parameters, deposit more total energy in the site than the protons of lower stopping power. The observations show, however, that fewer events occur for the deuterons than for the protons. Two possibilities could cause this to happen:

1. Fewer delta rays are induced by the deuterons than by the protons.
2. The deuterons induce many more delta rays that have insufficient energy to reach the site than do the protons.

Rejection of the first possibility can be argued on the basis of the stopping power of the deuteron and evidence provided in the graphs. By
proposing that the deuterons induce fewer delta rays than the protons, the energy of those delta rays induced by the deuterons must be larger than that of those induced by the protons in order to have the same, and in some cases, larger stopping power than that of the proton. In the case of the 1.0 MeV deuteron and the 1.0 MeV proton with the 1.0 μm site diameter, figures 16b through 20b show no evidence that the deuterons produced higher linear energy events than the protons did. Evidence for the acceptance of the second possibility comes from the consideration of the 0.5 MeV proton and the 1.0 MeV deuteron spectra at the 0.30 and 0.35 μm impact parameters (figures 16a and 17a, respectively). From the raw data for the 0.30 μm impact parameter, it is observed that the number of events for the two spectra is nearly the same for the same number of gate signals. The shift in the distributions (figure 16a) implies that the mean energy of the delta rays induced by the deuterons is less compared to that of those induced by the protons. At the 0.35 μm impact parameter, the raw data shows a 17% reduction in the number of events induced by the deuterons from that at the 0.30 μm impact parameter. The raw data also shows an 8% increase in the number of events induced by the protons for the same impact parameter interval. While the mean energy of the proton distribution remained roughly the same, the mean energy for the deuteron distribution actually increased for the 0.35 μm impact parameter (figure 17a). This reduction in the number of events and increase in the mean energy of the events suggests that a number of potential events were lost as the impact parameter was increased from 0.30 μm to 0.35 μm. The fact that the number of events increased for the proton distribution over the same impact parameter
range would rule out any argument that the number of events by the deuterons is reduced by a reduction in the solid angle subtended by the site with respect to the beam line. The conclusion is then drawn that the deuterons induce more low energy delta rays than do protons with the same stopping power. No suggestion as to the mechanism for this feature will be made here.

The remaining comparisons of deuteron and proton distributions in section D of chapter IV lend credibility to the conclusion just drawn, in that 0.5 MeV protons deposit more energy in the site than do 1.0 MeV protons up to the 0.5 \( \mu \text{m} \) impact parameter for the 0.5 \( \mu \text{m} \) diameter site. However, 1.0 MeV deuterons, with the same stopping power as the 0.5 MeV protons, deposit less energy in the site than the 1.0 MeV protons for impact parameters greater than 0.35 \( \mu \text{m} \) at both site sizes (figures 17a through 20a and figures 16b through 20b). Also, from previous observations of distributions for primary ions of different energies, one would expect 0.75 MeV protons to deposit more energy than 1.0 MeV protons up to a certain impact parameter. However, 1.5 MeV deuterons, which have the same stopping power as the 0.75 MeV protons, show less energy deposited in the site than the 1.0 MeV protons up to the 0.75 \( \mu \text{m} \) impact parameter (figures 16a through 20a).

Clearly this study has not been exhaustive. A definitive set of experiments investigating relationships among the parameters used, and application of this information to derive better understanding of basic energy deposition mechanisms, should certainly use the present study, and cited previous studies, as a base of departure.
BIBLIOGRAPHY


