Measurement of Energy Deposition Near High Energy, Heavy Ion Tracks

**Progress Report
December 1982 - April 1985**

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August 1986

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FOREWORD

This work was also submitted by N.F. Metting as a thesis in partial fulfillment of the requirements for the degree of Master of Science in Radiological Sciences from the University of Washington, 1986.

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SUMMARY

The microscopic spatial distribution of energy deposition in irradiated tissue plays a significant role in the final biological effect produced. Therefore, it is important to have accurate microdosimetric spectra of radiation fields used for radiobiology and radiotherapy. The experiments described here were designed to measure the distributions of energy deposition around high energy heavy ion tracks generated at Lawrence Berkeley Laboratory's Bevalac Biomedical Facility. A small proportional counter mounted in a large (0.6 by 2.5 m) vacuum chamber was used to measure energy deposition distributions as a function of the distance between detector and primary ion track. The microdosimetric distributions for a homogeneous radiation field were then calculated by integrating over radial distance. This thesis discusses the rationale of the experimental design and the analysis of measurements on 600 MeV/amu iron tracks.

TABLE OF CONTENTS

	Page
List of Figures	ix
CHAPTER 1: INTRODUCTION	1
1.1 Physical Parameters of a Radiation Field	1
1.2 Early Explanations of RBE Data	1
1.3 Track Structure Models	3
1.4 Reasons for Interest in HZE Particles	5
CHAPTER 2: BACKGROUND	8
2.1 Microdosimetry	8
2.2 Simulation of Micrometer-Sized Sites	9
2.3 Previous Measurements	13
CHAPTER 3: EXPERIMENTAL METHOD	14
3.1 Overview	14
3.2 The Position-Sensitive Detector	16
3.3 The Proportional Counter	18
3.4 Data Acquisition and Electronics	20
3.5 Beam Line	23
CHAPTER 4: RESULTS AND DISCUSSION	24
4.1 Primary Ion Energy	24
4.2 Primary Ion Equilibrium	27
4.3 Delta-Ray Energy	30
4.4 Single Event Frequency Distribution of y	32
4.5 Microdosimetric Spectra	34
4.6 Conclusions and Relevance	38
LIST OF REFERENCES	44
APPENDIX I Particle Energy Calculations	51
APPENDIX II Stopping Power Calculation	52

LIST OF FIGURES

Number	Page
1. Bragg Curves for Several HZE Particles	7
2. Four Types of Wall Effects	12
3. The Experimental Chamber	15
4. The Position-Sensitive Detector	17
5. The Proportional Counter	19
6. The Shape of the PC	21
7. Electronics and Pulse-Processing System	22
8. Primary Ion Energy	25
9. Event Size in the PC	26
10. Event Size in the PC, Rescaled	28
11. Integration to a Uniform Field	29
12. Delta-Ray Equilibrium	31
13. Probability Density of Lineal Energy	33
14. Probability Densities vs. Radial Distance	35
15. Expectation Values $\bar{y}_F$ vs. Radial Distance	36
16. Frequency of Events per Primary vs. Radial Distance	37
17. Probability Densities Normalized per Primary Ion	41
18. Frequency Distribution Spectrum for the Uniform Field	42
19. Dose Distribution Spectrum for the Uniform Field	43

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CHAPTER 1

INTRODUCTION

1.1 PHYSICAL PARAMETERS OF A RADIATION FIELD

Ionizing radiation deposits energy in matter in the form of ionizations and excitations. Biological effects from exposure to any type of ionizing radiation are determined in part by several physical characteristics of the radiation field itself. First and foremost is the integral quantity of energy absorbed per unit mass of tissue, i.e., the absorbed dose. Secondly, the temporal rate at which this energy is deposited is important, because of the existence in living systems of radiation damage repair mechanisms. The extent of repair capability has been shown to be a function of dose rate.

A third physical parameter of importance is the spatial distribution of the energy deposited, at the microscopic level. Ionizing radiation deposits energy in discrete packets, non-uniformly throughout an irradiated volume. The distribution of these depositions, although stochastic in nature, is a characteristic variable of the field. Different radiations show different patterns of energy deposition. This report will use the term particle "track" as defined in ICRU Report 36, page 1. To quote, "the term particle track applies to the inchoate distribution of transfer points resulting from the passage of a single charged particle, i.e., the aggregate of electrons, ions, and excited atoms and molecules, etc., immediately after the ending of all secondary electron interactions, and to the related aggregate of energy deposits which is the energy expended at an individual transfer point." Radiations which differ in track structure might be expected to cause different effects for the same absorbed dose. In biological systems this is observed, and is usually quantified in the term "relative biological effectiveness" (RBE) for a given radiation.

1.2 EARLY EXPLANATIONS OF RBE DATA

By RBE is meant the findings from radiobiological experiments that some types of radiation fields are more effective than others at

causing a biological effect, even though the dose delivered is the same. This relative biological effectiveness is caused by the physical qualities of the tracks produced. Early target theory looked at discrete energy deposits, termed "hits" but did not consider the spatial correlation of these events, and thus could not explain RBE data. Radiation quality was characterized by Jordan (1938) as "linear ionization density," and by Gray (1947) as "mean linear ion density." A simplified explanation of quality was introduced by Lea in 1946 who used the term "energy dissipation." Lea's characterization was renamed "linear energy transfer" (LET) by Zirkley, et al., in 1952. The present ICRU definition of LET or restricted linear collision stopping power (L_{Δ}) of charged particles in a medium is the quotient of dE_{Δ} by dl , where dE_{Δ} is the mean energy loss due to collisions, with energy transfers less than some specific value Δ , and dl is the distance traversed by the particle. The quantity L_{∞} is often used to express the quality of a radiation for radiobiological experiments. For radiation protection purposes, a "quality factor," Q , has been assigned for radiations of differing LET values, based on RBE studies. For L_{∞} of up to about 100 keV/ μ m, the average quality factor can be approximated by the relation $\bar{Q} = 0.8 + 0.16 \bar{L}_{\infty}$ (ICRU Report 16). Q is defined to be 20 for LET's of larger value.

However, for high energy heavy ions, LET does not adequately describe the differences in the energy distribution and frequency of delta rays and the associated spatial distribution of dose for different radiations. It doesn't consider the fluctuation of energy transfer, and it averages over large numbers of primary particle interactions. Furthermore, LET is not readily measurable and therefore has a limited applicability in experimental situations. In the early 1950's Rossi and coworkers began to develop concepts and experimental methods for the study of the microscopic spatial distribution of energy in matter by ionizing radiations (see, for example, Rossi and Rosenzweig, 1955a, 1955b; Rossi, 1959, 1960). Thirty years has seen much progress, and many researchers are using microdosimetric methods and have contributed to our understanding. In 1983, the ICRU published

their Report 36, entitled Microdosimetry, which summarizes this field of dosimetry. Details of the theory and methods used in microdosimetry as they relate to this project will be given in later sections of this manuscript.

1.3 TRACK STRUCTURE MODELS

Several models of the track structure of charged particles moving through matter have been proposed. Chatterjee, et al. (1973, 1976), developed a model which divides the track into two regions: an inner region of very dense ionization called the core, and an outer region which encompasses the range of delta rays produced along the track, called the penumbra. The radius of each region is found empirically by the following equations:

$$r_c = 0.0116\beta, \text{ and}$$

$$r_p = 0.768 E - 1.925 \sqrt{E} + 1.257,$$

where $\beta = v/c$ (the ion velocity divided by the speed of light), E is the kinetic energy of the particle in MeV/amu, and the radii are in units of micrometers. The model gives analytical expressions for the energy densities in core and penumbra as functions of LET_∞ , and radial distance variable b :

$$Q_c = \frac{LET_\infty/2}{\pi r_c^2} + \frac{LET_\infty/2}{2\pi r_c^2 \ln(\sqrt{e} r_p/r_c)}$$

$$Q_p = \frac{LET_\infty/2}{2\pi b^2 \ln(\sqrt{e} r_p/r_c)}$$

A similar model of track structure that has been proposed to explain radiation quality relates dose response with the quantity Z^2/β^2

of the incident ionizing particle (Butts & Katz, 1967, Katz, 1970). The Katz model postulates an inner region of a track with such high energy density that every biological cell which sustains a hit is killed (ion kill). It further states that the cells missed by the primary particle are irradiated by secondary particles as if by a homogeneous low LET field, and the radiation damage sustained is termed "gamma kill". Both the Chatterjee and the Katz models are examples of homogeneous track structure models. Although it is generally agreed that there is no clear demarcation between a core region and the remainder of a track, it is treated as such, and the energy deposition outside of a core region is also treated as if it were homogeneously distributed in space.

Another approach to track structure modeling, one that more realistically predicts the true stochastic nature of the energy deposition and gives atomic scale resolution of its spatial distribution, uses the Monte Carlo method (Berger, 1963; Hamm, et.al., 1976; Wilson & Paretzke, 1981). In this calculational method, a computer program simulates ion tracks by randomly selecting elastic and inelastic scattering processes from probability tables derived from experimental cross-sections measured for the primary interaction processes. The spatial distribution and energy value of each ionization or excitation is recorded, and the number and size of interactions produced within any test volume defined by the computer program can then be obtained. Thus, Monte Carlo simulations can be used to predict the probability of energy depositions of a given size in biologically relevant shapes such as cell nuclei or DNA molecules.

The simulation of ion tracks is limited, however, by the availability of experimentally measured interaction cross-sections, which are used as input in the computer program. The data currently available allow the simulation of proton tracks with an incident energy of from about .3 to 20 MeV/amu (Wilson, W.E., private communication).

1.4 REASONS FOR INTEREST IN HZE PARTICLES

The properties and effects of high energy heavy ion radiation is becoming of greater interest for several reasons. One reason is the increasing time that man is spending outside of earth's atmosphere. In addition to large fluxes of electrons, protons, and helium nuclei, the space environment is characterized by heavier solar and galactic species, called cosmic rays. These are naturally occurring HZE particles (for high atomic number, high energy) and are defined as having an atomic number $Z > 2$, and a minimum energy of about 10 MeV per nucleon. Some of the more abundant HZE particles in space are carbon, oxygen, boron, and nitrogen. Of the elements with $Z > 14$, iron is by far the largest component. Cosmic rays are responsible for the retinal "light flash" effect reported by astronauts, and are also the cause of random bit changes (soft error upset) in large scale integrated computer memory (McNulty, 1982).

Another reason for interest in HZE radiation is its applicability in the treatment of human cancer. Technical advances in particle accelerator design have made possible facilities for the routine generation of high energy ion beams of almost any mass. A perusal of the Bragg curve characteristics of these beams is indicative of their usefulness in tumor treatment. A Bragg curve is a graph of the relative dose deposited by radiation as a function of its penetration depth in absorber. Figure 1 shows Bragg curves for several HZE particles moving in water. In this figure, the relative dose delivered by an ion is graphed as a function of its penetration distance. The region of relatively low and constant dose beginning at zero depth is known as the "plateau" region of the Bragg curve. The abrupt rise in relative dose seen near the end of each curve is known as the Bragg peak. The large ratio of energy loss at peak to energy loss at entrance plateau means that the intervening normal tissue absorbs much less energy per unit mass than does the tumor on which the beam is focused. A depth-dose curve of X-ray irradiation, in contrast, would

show a higher dose rate near the surface with a gradual decrease to the depth of the tumor. Very precise treatment localization of heavy ion radiation within the tissues of a patient is possible by placing upstream the appropriate collimators, absorbers, and/or filters (Pirruccello & Tobias, 1980).

FIGURE 1. Bragg Curves for Several HZE Particles Moving in Water.

FIGURE 1. Graphs showing the percentage of particles remaining in water as a function of distance from the source for several different particle sizes.

CHAPTER 2

BACKGROUND

2.1 MICRODOSIMETRY

Experimental microdosimetry is the measurement of energy deposition via ionizations produced by radiation in volumes small enough that the stochastics become important. The volume is chosen so that it is relevant to biological structures of interest, such as the cell nucleus (1-10 μm in diameter), or the width of a metaphase chromosome (1 μm). The measured ionization is proportional to the quantity "lineal energy", y , defined in ICRU 36 as "the quotient of ϵ by $\bar{\ell}$ where ϵ is the energy imparted to the volume by a single energy deposition event and $\bar{\ell}$ is the mean chord length in that volume." Lineal energy, y , is a stochastic (random) quantity, and is usually expressed in the units $\text{keV}/\mu\text{m}$. By counting the numbers of events contained within energy bins of some defined value, and dividing each by the total number of events measured, a probability density, $f(y)$, in energy can be drawn. Also called a frequency distribution, $f(y)$ gives information about what a volume of tissue of equivalent size would experience when irradiated by the same radiation field.

Since y is defined for single energy deposition events only, the probability density $f(y)$ is independent of both the absorbed dose and the dose rate. The expectation value

$$\bar{y}_F = \int_0^{\infty} y f(y) dy$$

is called the frequency mean lineal energy, and is a unique nonstochastic value calculated for the particular spectrum in question. Lineal energy can also be considered in terms of its dose distribution. The dose mean lineal energy

$$\bar{y}_D = \int_0^{\infty} y^2 f(y) dy / \bar{y}_F = \int_0^{\infty} y d(y) dy$$

is also a unique nonstochastic average value for a particular radiation field and a particular volume of interest.

After an event spectrum is measured and the values $\bar{y}_F$ and $\bar{y}_D$ are calculated, it is also possible to determine dose, quality factor, and dose equivalent. For unit density material, the absorbed dose D (in Joules/kg or Gray) is

$$D = 0.1602 \bar{y}_F N / V$$

where $\bar{x}$ is the average chord length in micrometers, V is the volume in micrometers cubed, $\bar{y}_F$ is in keV/ μm , and N is the total number of events. Quality factor can also be determined by calculating the LET distribution from $f(y)$. This process is approximated (Kellerer, 1972) by

$$\bar{Q} = 0.8 + 0.14 \bar{y}_D$$

for $\bar{y}_D$ in keV/ μm , and less than about 100 keV/ μm . Dose equivalent, the important quantity in radiation protection, can then be calculated in the usual way: $H = Q D$.

2.2 Simulation of Micrometer-Sized Sites

Proportional counters are used to simulate directly micrometer diameter volumes of tissue, and to measure the charge deposited as ion pairs in the counter gas by traversing particles. A proportional counter is a gas-filled detector operated in pulse mode which uses the phenomenon of gas multiplication to amplify the original deposited charge in a proportional manner.

Because of gas multiplication, the proportional counter can see very much smaller energy depositions than can an ion chamber. Gas multiplication is the result of increasing the electric field within the counting gas to an appropriately high value. In an electric field, ion pairs created by incident radiation will drift to their respective electrodes, colliding along the way with gas molecules. Since the free electron is easily accelerated by the field, it may have kinetic energy greater than the ionization energy of a neutral gas molecule, and a

collision between them would create an additional ion pair. The newly liberated electron will also be significantly accelerated by the field, undergo collisions with other gas molecules, creating more ionizations on its way to the anode, and so on. This cascade of ionizations is known as a Townsend avalanche, and in the detector the avalanche continues until all of the free electrons are collected at the anode. Its (now amplified) output pulse is directly proportional to the magnitude of the original deposition; thus the event is detected and the size of the event determined.

In order to simulate directly a micrometer diameter volume of tissue, the detector is filled with gas at a very low density, so that the mean energy loss of a charged particle traversing the simulated site is the same as that in the tissue volume. This will be true if the ratio of the density of the gas (ρ_g) to the density of the tissue (ρ_t) is equal to the inverse of the ratio of congruent chord lengths, i.e., $\rho_g/\rho_t = d_t/d_g$. For example, to simulate a 1.3 μm diameter cylindrical volume of tissue, $\rho_t = 1 \text{ g/cm}^3$ is the density of tissue, $d_t = 1.3 \mu\text{m}$ is the diameter of the tissue volume to be simulated, and $d_g = 0.64 \text{ cm}$ is the physical diameter of the detector. Therefore, the density of gas needed to simulate the site is $\rho_g = .2 \text{ mg/cm}^3$. From the Ideal Gas Law, we know that at constant temperature the ratio of the pressure and the density of a gas is a constant, i.e., $P/\rho = P'/\rho'$, and $P = \rho P'/\rho'$. At a pressure $P' = 760 \text{ torr}$, pure propane gas has a reported density of $\rho' = 1.8798 \text{ mg/cm}^3$. Thus $P = 82 \text{ torr}$, is the appropriate gas pressure to simulate a 1.3 μm site in a .64 cm diameter detector with propane.

An important part of the correct simulation of a microscopic volume of tissue is the maintenance of charged particle equilibrium in the detector volume. By this is meant that the total fluence of both primary and secondary charged particles is the same in the detector as it would be in the tissue volume simulated. In real tissue, there is in general the same density throughout. The fact that proportional counters are often constructed as gas-filled cavities surrounded by solid-phase walls (to maintain the reduced gas pressure and define the

shape of the site) means that the boundary of the detector volume there is a material phase change. This density difference is the cause of "wall effects" first recognized by Rossi (1967), and classified into four types by Oldenburg and Booz (1970), and Kellerer (1971).

Figure 2 illustrates the four types of wall effects. Part a) shows the "delta ray effect", in which a charged particle enters the volume at the same instant as one of its delta rays. Part b) illustrates the "re-entry effect", in which an electron traverses the cavity and then re-enters it due to its curled track. Part c) shows the "V-effect", in which two nuclear fragments originating outside the cavity both traverse it. Part d) shows the "scattering effect", in which an uncharged primary particle (photon or neutron) undergoes multiple scattering, producing charged particles close enough so that two or more enter the cavity. In all four of these cases the distance between the two entry points on the charged particles traversing the cavity may be large enough that only one of them could enter the actual microscopic volume in the real case. In other words, events which would normally occur in separate sites in the uniformly dense medium can occur simultaneously in the larger gas cavity. The simultaneous events are added together and detected as a single, larger event. Thus, the spectrum records fewer small events than would a site in tissue, and the large events are shifted to slightly higher values.

For this reason, wall-less proportional counters were designed. This type of detector still has an external solid wall to maintain the appropriate low gas pressure, but it is located far enough away from the sensitive volume to avoid wall effects. It is the sensitive volume which is (nearly) wall-less, its volume defined either by electric field lines or by a very fine metal or plastic grid which is usually over 90% transparent to the incoming radiation. For most applications the more rugged grid-wall type is used.

FIGURE 2. The Four Types of Wall Effects.

2.3 PREVIOUS MEASUREMENTS

Very few microdosimetric spectra for HZE particles have been published, and none are differential in radial distance. Table F.7 in ICRU Report 36 lists most of the measurements that have been done, in terms of the expectation value, $\bar{y}_D$. Most of these used walled proportional counters, and their interpretation is thus limited by wall effects. Measurements taken of 280 MeV/amu nitrogen beams using both walled and wall-less counters enabled Rodgers, et al., (1973), to show that the resulting values of $\bar{y}_D$ are about 25% higher for the walled counter in the plateau region, with much smaller differences near the Bragg peak. However, the wall effect is probably even larger than this since the counter, which was housed in a 10 cm diameter chamber, was not truly wall-less for ions of such high energy.

Preliminary work on the experiment reported in this thesis was conducted by the Radiological Research Laboratory at Columbia University in New York City, headed by Prof. Harald Rossi, and they continued in close collaboration. Early experiments using a wall-less proportional counter mounted in an eight-inch diameter tissue equivalent chamber were inconclusive on the question of wall effects (Kliuga, et al., 1978). Therefore it was decided to put the proportional counter into a larger chamber, and take differential spectra; i.e., to take a series of measurements with the counter at specified radial distances from the primary ions. These differential measurements would then be integrated over radial distance to construct lineal energy spectra for the uniform field.

CHAPTER 3

EXPERIMENTAL METHOD

3.1 OVERVIEW

Microdosimetric methods were used to measure energy deposition radially outward from the center of charged particle tracks. Experiments took place at the Bevalac Biomedical facility at Lawrence Berkeley Laboratory in various segments from December 1983 to April of 1985.

Figure 3 shows the experimental design. The chamber consists of a large aluminum tank, 2.5 m long by 0.6 m in diameter, with a forward window of mylar and sailcloth. Two detectors are mounted inside; a position sensitive detector (PSD) measured the position of each primary ion, and a wall-less proportional counter (PC) measured energy deposition in its sensitive volume in coincidence with the passage of a primary in the PSD. The chamber was filled with propane gas at a pressure such that the PC simulated a 1.3 μm diameter site. To measure energy deposition as a function of radial distance, the two detectors could be separated laterally in the chamber by a distance of up to 40 times the PC diameter by means of a selsyn-powered transverse carriage. In the experiment, the PSD was moved relative to the stationary PC, and the ion beam was steered after each move so that it centered on the PSD.

To determine how secondary charged particle fluence changes as a function of distance from the forward window, a tissue equivalent plastic plate was placed in the chamber upbeam from the detectors. The plate was moved longitudinally so that energy spectra could be recorded and compared for several intervening distances.

The chamber itself was positioned directly in the beam line of Cave 2 of the Bevalac Biomedical facility. The electronics and power supplies were located in both Cave 2 and in the outer electronics room.

Experimental Design

FIGURE 3. The Experimental Chamber, to scale.

3.2 THE POSITION-SENSITIVE DETECTOR

A solid-state, position-sensitive detector (PSD) was used to establish the position of each primary ion. Figure 4 shows a schematic diagram of the PSD, which is a 0.1 cm thick by 5 cm long by 1 cm wide silicon surface barrier detector. One side is resistive and grounded at one end. The amplitude of its output pulse (P) is proportional to the product of the ion energy and the position the ion traverses the PSD relative to the grounded end. The other side of the PSD is covered by a thin layer of gold for electrical contact (and to form the surface barrier characteristics), and is biased at +200 volts. It produces an output pulse amplitude (E) that is proportional only to the energy of the incident ion. In addition, this side of the PSD is cut by longitudinal grooves, so that it can be used as either of two widths: .1 cm or 1.0 cm. The narrower width was used for small radial distances, so that the measured position of the primary ion more adequately represented the simulated radial distance. The larger width was used at larger radial distances so that ten times the number of primaries could be inspected for the far fewer energy depositions expected. Amplifier gains for the two sides were adjusted such that P was equal to one half E (i.e., $P = E/2$) for tracks passing through the lengthwise center of the PSD. By taking the ratio of the two amplitudes, P/E, the position of the primary along the PSD was determined. The linearity of the PSD response was measured by irradiating it with a collimated alpha source at specified distances along its length. The output amplitude E of the energy side should have the same mean value all along its length, while the position amplitude, P, should vary linearly from zero at the grounded end to the value of E at the other end. We found slight deviations from linearity near the ends of the PSD, and data from particles traversing these areas weren't used.

FIGURE 4. The Position-Sensitive Detector.

3.3 THE PROPORTIONAL COUNTER

The proportional counter (PC) was a cylindrical, wall-less detector 0.64 cm in diameter by 0.64 cm high. Figure 5 shows a sketch of the detector. Its diameter is defined by a wire helix constructed with 0.0635 mm thick wire at a pitch of .20, making the detector 96% transparent to incoming radiation. The height of the sensitive volume is defined by electric field tubes. In order to keep the electric field uniform at the ends of the PC, the field tubes were held at a voltage 6/10th that of the helix by means of a voltage divider circuit, so that for a helix bias of -900 volts, the tubes were at -540 volts. The center anode wire was kept at ground potential. Since the tank is also at ground potential, there is an electric field of a few volts/cm just outside the helix. Thus, thermal electrons from ionizations produced outside the PC are repelled away from the detector, while those originating inside are collected on the relatively positive anode.

The counting gas used for the PC was pure propane, C_3H_8 . A static volume of gas was utilized: First the entire chamber was evacuated to a pressure of less than 1 torr, using a rotary vane fore pump. It was then flushed twice, each time filling the chamber with propane to a pressure of about 500 torr and then pumping down to less than 1 torr. The chamber was then filled to the appropriate pressure needed to simulate the chosen microscopic site size in the PC (see section 2.2 this paper). After filling, the gas inlet was sealed, and that filling was used for the duration of the measurement. Energy calibration of the PC was performed at the beginning and end of each measurement in order to quantitate any changes in the gas gain. This was accomplished by irradiating the PC with an aluminum k_α X-ray source located inside the chamber. The range of the secondary electron produced via the photoelectric effect by each of these monoenergetic 1.487 keV photons is 0.032 μm (Cole, 1969), considerably less than the simulated site diameter. Therefore, the mean value of the calibration peak must represent 1.487 keV, and calibration of the spectrum follows. Also, any shift

PROPORTIONAL COUNTER (PC)

FIGURE 5. The Proportional Counter.

in the position of this X-ray peak would mean that changes were occurring in the system, perhaps from contamination of the counting gas. No problems of this sort were found, however.

The shape of the PC boundary was measured using the collimated alpha source. Figure 6 shows the relative amount of charge detected at the anode for various positions of the alpha beam. The sets of events graphed as a function of the x-axis show a series of measurements across the cylinder in planes perpendicular to the anode at three different heights, normalized to show the expected half-circle shape. The set of events (asterisks) graphed as a function of the y-axis shows a series of measurements parallel to the PC's cylindrical axis and very near an outside edge. A variation of $\pm 12.6\%$ was measured around the value of the expected chord length along this vertical. It is also evident that the shape of the electric field varies in relation to the position of the helix coils. But, since the outside chord length variation introduced an overall volume error of only about 2%, the PC was judged to be working well.

3.4 DATA ACQUISITION AND ELECTRONICS

Figure 7 shows a block diagram of the electronics and pulse processing system. Data acquisition, storage, and on-line sampling were controlled by the Biomed PDP-11/45 computer, using software developed originally at Fermilab and modified at LBL (Schimmerling, et al., 1983). Program QDA took care of data acquisition via CAMAC electronics, with storage on magnetic tape for later analysis. Program MULTI, run simultaneously from another terminal, was able to sample a percentage of the data as it was being acquired and show it graphically, thus giving a real-time check on the progress of the measurement.

For each primary ion detected by the PSD, four separate measurements were taken in coincidence: PC low gain (LG), PC high gain (HG), PSD position (P), and PSD energy (E). The two low noise, charge-sensitive preamplifiers for the PSD were housed in a single

FIGURE 6. Measurement of the Shape of the Proportional Counter.

FIGURE 7. Block Diagram of the Electronics and Pulse-Processing System.

box located within the chamber and connected to the detector by short (8 cm) RG 174 coaxial cables. The single preamplifier used for the PC was also located in the tank as near as possible to the detector. Vacuum feedthroughs connected the preamplifiers to the remainder of the electronics located outside the chamber. Separate vacuum feedthroughs were used to accommodate the high voltage bias supply for each detector, and test input to the preamplifiers was provided by a precision pulser.

Pulses from each of the PSD preamplifiers are each routed to a linear shaping amplifier. The output from the proportional counter preamplifier is split into two linear shaping amplifiers, one of which is set at a gain of 24 times the other, so that both the larger (primary ion passage) and the smaller (delta ray passage) events could be detected. The shaped output pulses from each of the four amplifiers are then input into separate CAMAC analog-to-digital converters (ADC's) housed in a single CAMAC unit.

Pulses from the energy side (E) of the PSD were also each used to generate an enabling strobe for the four ADC's, so that all four inputs were stored as temporally coincided information. Strobe timing relative to the analog pulses was checked using a dual trace oscilloscope. The timing electronics are also shown in the figure.

3.5 BEAM LINE

The experiments were performed in Cave 2 of Lawrence Berkeley Laboratory's Biomedical Facility at the Bevatron. The high energy heavy ion beams were obtained by operating the Super Hilac and the Bevatron together in the Bevalac mode (Bevatron/Bevalac User's Handbook). Beam was delivered to the cave at 15 spills per minute, each spill of about 1 second duration. The average beam intensity was reduced to about 20,000 particles per spill, to prevent pulse pile up and dead time losses in the detector electronics. The beam was focused into a vertical ellipse about 5-7 cm high and about 4 cm wide. Minimal extra absorber (lead, water, etc.) was inserted upstream in order that the measurements be done in the plateau region, well in front of the Bragg peak.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 PRIMARY ION ENERGY

The incident primary ion beam consisted of 600 MeV/amu iron nuclei. Figure 8 shows a plot of the relative energy deposited in the PSD by the primary ions. In the figure, over 70% of the events are found in the major peak, which corresponds to 600 MeV/amu iron. The events depositing lesser amounts of energy are produced by spallation products and projectile fragments caused by the interaction of particles with the walls and windows of the beam line. The remainder of the analysis will use only those events which lie in the major peak of this distribution.

Figure 9 shows a scatter plot of event size in the PC as a function of position (the PSD ratio P/E). For this measurement, the PSD was positioned behind the proportional counter, and the beam was directly traversing the proportional counter much of the time. Notice in this figure that the PC diameter as detected by the PSD (see abscissal axis) is about one eighth the length of the PSD. This is in the same relation as that of the real physical PC diameter (.64 cm) to the real physical PSD length (5 cm), and confirms the gain settings chosen for the PSD amplifiers.

Note several other observations from figure 9: 1) The position of the PC relative to the PSD can be easily determined, allowing fairly precise determination of radial distance. 2) The direct ion traversals of the proportional counter show a variation in energy deposition covering a range of over 500 channels. Some of the smaller events may be due to pulse pile up effects in the electronics. The amplifier used for the PC looks at the amplitude of an incoming pulse from the charge sensitive preamplifier as the difference between its starting value and its peak. A pulse that occurs before the preceding pulse has finished starts at a higher value, and may reach the amplifier saturation value before it peaks. It would therefore be recorded as a lower value. 3) Some direct ion

FIGURE 8. Primary Ion Energy.

FIGURE 9. Scatter Plot of the Event Size in the Proportional Counter as a Function of Position.

traversals of the proportional counter show little or no energy deposition. These events may be from ions passing above or below the PC due to a possible failure of the switch which was designed to give the 0.1 cm active width on the PSD.

Figure 10 is the same data as figure 9, but with the scales adjusted to emphasize the similarity to the collimated alpha beam data plotted earlier in figure 6. Because the iron ions have a constant stopping power and traverse the PC normally to its cylindrical axis, we see the same fairly well-defined half circle shape.

4.2 PRIMARY ION EQUILIBRIUM

Since the Bevalac beam diameter cannot be made large enough in real cross section to provide uniform fluence over the entire entrance window, energy deposition in the PC was measured as a function of the radial distance between each primary ion track and PC detector. In order to construct (or simulate) a larger uniform field from these measurements, it is important to understand what has been measured. Figure 11 shows a visualization of the weighted summation to a uniform field. The proportional counter is the center of the system, with primary ions at varying distances, and annuli defined by PSD positions. Several radial distances are shown as arrows.

In the analysis of the taped data, pulse heights were sorted and binned by radial distance from the geometric center of the PC. Variable bin lengths were chosen, longer bins being used at large radial distances where y is expected to change slowly, and which had fewer counts. At this point, lineal energy spectra were constructed separately for each radial distance, and expectation values were also calculated.

The area of each radial distance bin is the area of a rectangle:

$$A_g = (\text{width of PSD}) (r_2 - r_1)$$

FIGURE 10. Event Size in the Proportional Counter as a Function of Position, rescaled.

FIGURE 11. Integration to a Uniform Field.

where $(r_2 - r_1)$ is the length of a radial distance bin. The total area of the annulus that the bin approximates is

$$A_T = (\pi) (r_2^2 - r_1^2).$$

To normalize for area around a track, therefore, the number of counts for each energy of a particular radial distance bin were multiplied by the applicable area ratio, $A = A_T/A_B$. The counts for each annulus were then normalized to unit number of primary ions, and the resulting numbers of counts for each energy at each radial distance were added together so that microdosimetric spectra were constructed for a uniform field out to the largest radial distance measured. For the remainder of this manuscript, the term "uniform field" will refer to the fully constructed field of the iron 600 MeV/amu beam, out to the maximum radial distance of 21.5 μm .

4.3 DELTA-RAY EQUILIBRIUM

The maximum energy secondary electron produced by 600 MeV/amu iron ions is 1.74 MeV (see Appendix I), and its range is over 8000 μm in tissue equivalent matter (ICRU Report 37). Since only about 300 μm of TE matter were simulated between the forward wall and the PC, complete delta-ray equilibrium was not achieved, and it is necessary to estimate the effect of this on our data.

The relative numbers of delta-rays per primary ion as a function of the distance from the TE plate was measured for a neon ion beam 670 MeV/amu, and for an argon ion beam, 570 MeV/amu. There were several problems in the electronic gain settings during the acquisition of these measurements which precluded the construction of dependable lineal energy spectra for the ions, but it is felt that the ratios of secondaries to primaries are reliable. Figure 12 shows these data for the various radial distances measured. Each of the curves in the figure can be approximated by a flat line. Since the number of delta rays per primary is expected to be high near the wall

FIGURE 12. Delta-Ray Equilibrium.

and then decrease to a constant level as effective equilibrium is reached, we conclude that delta-ray equilibrium has been effectively achieved, and probably at a closer distance from the plate than was measured.

This result is consistent with recent calculations (Kellerer, et al., 1985) on the dependence of absorbed dose on the distance from the entrance wall as a function of electron energy and emission angle, for secondaries created in the gas. Their conclusion is that effective delta-ray equilibrium is attained whenever the distance from the wall exceeds the radial distance, implying that equilibrium is achieved within a cone of 45 degrees centered at the entrance point of the beam. The reasoning they used can be extended to include the lower energy delta-rays originating in the wall. The far fewer higher energy wall secondaries cannot be expected to be perturbing the relative numbers, and this is born out by the data as shown in figure 12.

4.4 SINGLE EVENT FREQUENCY DISTRIBUTION OF Y

Kellerer (1984) has shown that the theoretical chord length distribution of a circle is

$$f_{\mu}(x) = \frac{x}{d^2} \sqrt{1-(x/d)^2}, \quad x \leq d$$

$$= 0, \quad x > d$$

where x is the chord length, and d is the diameter. Because our proportional counter detector is a right cylinder with its axis normal to a parallel beam of high energy monoenergetic ions, the lineal energy measured for the traversal of a particle is proportional to the chord length of a circle, and the frequency distribution $f(y)$ will follow the same shape curve. The dashed line drawn in on figure 13 shows the shape of this function for $d = 1.3 \mu\text{m}$. The points shown in this figure are the frequency distribution of lineal energy, $f(y)$, as a function of y , measured for primary ions passing through the PC, and these give a fairly good approximation to the theoretical curve.

FIGURE 13. Probability Density, $f(y)$, of Lineal Energy.

4.5 MICRODOSIMETRIC SPECTRA

Figure 14 shows frequency distributions for some of the radial distances. In each spectrum, $f(y)$ is multiplied by y , and then plotted as a function of y on a logarithmic scale, so that equal areas under the resulting curve represent equal probabilities of those events occurring. The first spectrum, graphed at a radial distance of $.65 \mu\text{m}$, includes all of the primary ion traversals, and therefore has the high energy peak, located at a lineal energy of $200 \text{ keV}/\mu\text{m}$. The outer radial distances show only secondary event probabilities, as expected. Each spectrum is normalized to unit area, with zero events not included. The expectation value of each distribution, $\bar{y}_F$, is marked with a vertical line; $\bar{y}_F$ is also plotted in figure 15 as a function of b . There is a steady decrease in $\bar{y}_F$ for about $5 \mu\text{m}$ radially outward, after which it remains fairly constant for the distance measured. It is assumed that $\bar{y}_F$ will eventually decrease to zero near the end of the range of secondaries. The initial decrease in $\bar{y}_F$ reflects the decreasing probability of encountering multiple numbers of secondary electrons crossing the detector. At distances over $5 \mu\text{m}$, there are either one or none crossing the site, and those that do cross deposit roughly the same energy.

Figure 16 shows the frequency of events per primary as a function of radial distance. If the spectra shown in figure 14 are normalized to unit number of primaries with these factors (see section 4.3) the result is figure 17, for each radial distance. Now they are in the form necessary for summation to the uniform field.

The frequency distribution spectrum for the uniform field is shown in figure 18. In this type of graphical representation, it is easy to visually separate the lower energy delta-ray peak from the higher energy peak produced by primary ion traversals. Inspection of the two peaks shows that for those $1.3 \mu\text{m}$ diameter sites into which energy is imparted by this radiation beam, 62% will have been traversed by a secondary electron, and only 38% will have been traversed by a primary. A calculation of the absorbed dose per event

FIGURE 14. Probability Densities as a Function of Radial Distance.

FIGURE 15. Expectation Values, $\bar{y}_F$ as a Function of Radial Distance.

FIGURE 16. Frequency of Events per Primary as a Function of Radial Distance.

FIGURE 17. Probability Densities Normalized per Primary Ion.

FIGURE 18. The Frequency Distribution Spectrum for the Uniform Field.

shows that the site that is traversed by the primary receives a dose of 8.4 Gray. The site that is located 21 μm away receives a dose of about .3 Gy.

Figure 19 shows the probability density of absorbed dose in y , multiplied by y , and then plotted as a function of the logarithm of y , for the uniform field. When plotted in this way, equal areas under the curve represent equal contributions to the absorbed dose. It is evident from this figure that energy deposition from primary ion traversal accounts for most, i.e., 96% of the absorbed dose. This means that although 62% of the energy deposition events were delta-ray traversals, they were responsible for only 4% of the dose delivered.

4.6 Conclusions and Relevance

In this experiment, energy deposition was measured in a 1.3 μm diameter simulated site, as a function of radial distance, to a distance of about 22 μm . The parameters of this experiment were chosen to obtain the maximum interesting data while designing and testing new experimental apparatus. High energy iron was chosen because it was relatively easy to produce at the Bevalac, and its high velocity results in a relatively high probability of delta-rays at large radial distances. These low energy events were found, and in the very low probability that is expected and was predicted by Chatterjee and others. The small simulated site size was chosen because of recent work which implies that the sensitive site (or sites) in a cell, although located within the nucleus, are smaller than the nucleus itself (Goodhead, et al., 1980). The $\bar{y}_F$ values shown in figure 15 are a measure of the energy deposited in a 1.3 μm site that is actually hit, instead of a macroscopic absorbed dose value. The microscopic values may ultimately be the important numbers in efforts to correlate the physical energy deposition with the chemical mechanisms, which eventually lead to biological end points of irradiation.

The $\bar{y}_F$ value for direct ion traversals of the PC is 135 KeV/ μm . In the discussion of figure 9, it was suggested that the very low

energy events recorded for direct traversals were probably not real. For this reason, the expectation value $\bar{y}_F$ was recalculated for direct traversals which produced at least 25 ionizations in the counter. The value for $\bar{y}_F$ is then 147 keV/ μm . The LET value predicted for this ion traveling in propane is $L_\infty = 191 \text{ keV}/\mu\text{m}$ (see Appendix II). There remains a 23% difference in the two values. The reason for part of the discrepancy is that the concept of LET fails to take into account the transport of energy out of the site by high energy delta rays, which is especially important for HZE particles. There is also the possibility that for particles of such high LET, the proportional counter itself was responding in a non-linear manner for direct ion traversals. This possibility will have to be investigated, and if needed appropriate changes made in the detector, before further measurements are attempted.

Chatterjee's track structure model predicts a penumbra radius of 415 μm for 600 MeV/nucleon iron ions. Our data has shown a good approximation to his energy density predictions. It is possible to extend the simulated radial distance out to 415 μm by raising the pressure of the counting gas so that the proportional counter simulates a 9 μm diameter site and using the entire extent of the chamber diameter. This measurement would also more closely simulate the size of a cell nucleus and would be of special interest to some researchers in that respect, as well as testing Chatterjee's prediction of 415 μm as the maximum radial extent. However, such measurements would require much more beam time since the probability of an event per primary continues to decrease, and would be approximately one in 10^4 at 200 μm .

In order to completely characterize the microdosimetry of one ion, the measurements should be made for several site sizes, several primary ion energies, and many radial distances. From there, it would be very interesting to repeat all of the measurements for several different ion species, so that general conclusions can be

drawn about the track structure of high energy heavy ions. As more scientific resources are made available for this study (especially in the form of ion beam machine time), questions may then be answered which will eventually aid in the analysis of radiobiological effect.

FIGURE 19. The Dose Distribution Spectrum for the Uniform Field.

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APPENDIX I

PARTICLE ENERGY CALCULATIONS

1. Velocity of the Primary Ion, 600 MeV/amu iron

$$\beta = (1 - (1 + T/m_0c^2)^{-2})^{1/2} \quad \text{where } T = 600 \text{ MeV/amu}$$
$$m_0c^2 = 931 \text{ MeV/amu}$$

$$\beta = .794 = v/c \quad c = \text{speed of light} = 2.99 \times 10^8 \text{ m/sec}$$
$$v = .794 c$$
$$v = 2.38 \times 10^8 \text{ m/sec}$$

2. Maximum Transferable Energy

$$E'_{\text{max}} = 2 m_e c^2 \frac{\beta^2}{1 - \beta^2}$$
$$m_e = \text{electron rest mass} = 9.11 \times 10^{-31} \text{ kg}$$
$$c = \text{speed of light}$$
$$\beta = .794 \text{ (see above)}$$

$$= 2.79 \times 10^{-13} \text{ kgm}^2/\text{sec}^2$$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ joules}$$

$$= 1.74 \text{ MeV}$$

APPENDIX II

STOPPING POWER CALCULATION

Stopping Power of Propane

Method using Ziegler's tables and Bragg Additivity.

<u>Target</u>	<u>Ion</u>	<u>S (MeV/(mg/cm²))</u>
H	Fe, 600 MeV/amu	3.55
C	Fe, 600 MeV/amu	1.55

$$S_{C_3H_8} = 36/44 (1.55) + 8/44 (3.55)$$

$$= 1.91 \text{ MeV}/(\text{mg}/\text{cm}^2) (10^3 \text{ keV}/\text{MeV}) (1000 \text{ mg}/\text{cm}^3) (\text{cm}/10^4 \mu\text{m})$$

$$= 191 \text{ KeV}/\mu\text{m}$$

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