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MEASUREMENT OF THE OPTICAL
PERFORMANCE OF LIQUID
SCINTILLATOR FILLED TEFLON-FIBER TUBES

by

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MAY 1990

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ABSTRACT

Measurement of the Optical Performance of Liquid
Scintillator Filled Teflon-Fiber Tubes. (May 1990)

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Chair of Advisory Committee: Dr. Robert C. Webb

A study of the optical performance of a liquid scintillator (BC 517L) filled Teflon tube of inner diameter 0.06 cm, was carried out using a rectangular array of those tubes. Two experimental methods, the cosmic ray telescope and the direct source method, were used in measuring the light output (in photoelectrons) and the light attenuation length through the scintillator.

Results showed the light output from this array for minimum ionizing charged particles to be a fraction of a photoelectron (about 10^{-2}) and the attenuation length to be about 20.0 cm, for high energy particles, suggesting a limiting value for the tube diameter of the Teflon that can be used in scintillating fiber calorimeters for high energy physics experiments.

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CHAPTER I

INTRODUCTION

Elementary particle physics owes many of its discoveries to the continuing refinement of techniques for measuring the trajectories and energies of individual particles. In the recent years large calorimeters have been widely employed and have been shown to offer many attractive capabilities. They are not only sensitive to charged particles but also to neutral ones, and their response to different particles such as electrons, muons, and hadrons allows particle identification. Notable among other attractive capabilities, is their fast time response which allows operation at high particle rates.

A considerable effort has been devoted to signal readout techniques for calorimeters during the past decade, to move towards optimally matching with experimental applications, the goal being to minimize instrumental effects in these experiments. The instrumentation used can be categorized into 'light collecting' and 'charge collecting' devices. Light collecting devices are used to measure scintillator or Cherenkov light, while charge collecting devices are employed in ion chambers, or saturated Geigers tubes, etc.

Most active readout materials have a high enough density for them to be used as homogeneously sensitive calorimeters. Some of them such as NaI, CsI, and BaF₂ whose detection mechanism is by scintillation, have a good energy resolution, a fast time response (about 300 ns), are mechanically stable, and are not susceptible to early radiation damage.^{1,2,3}

The scintillation detector is one of the most widely used particle detection device in particle physics today. It makes use of the fact that certain materials when struck by an ionizing particle or other radiation, emit a small flash of light,

The citations in this thesis follow the style of Physical Review D

i.e. a scintillation. When coupled to an amplifying device such as a photomultiplier, these scintillations can be converted into electrical pulses which can be analyzed and counted electronically to give a variety of information, among them; energy deposition, time of transit, and pulse shape discrimination.

Early light-collecting sampling calorimeters used scintillator plates individually coupled to lightguides⁴ but the introduction of cheap and durable plastic scintillators, using wavelength shifters (WLSs) has brought about their obsolescence.⁵ The principle of the WSL is that scintillator light is absorbed and re-emitted at longer wavelengths that are compatible to the light detectors (photomultipliers). This avoids the complicated and costly optical contacts that have to be used instead, and minimizes dead spaces.

Liquid scintillators are liquid solutions of one or more scintillators in a solvent. During the last ten years a large number of liquid scintillation detectors have been tested and used in various experiments. The efficacy of these detectors with regard to various shapes and volumes has also been studied.

Long liquid scintillation detectors⁶ have been found to be efficient in fast-neutron registration and pulse shape discrimination in neutron spectrometry⁷, and have been employed in the efficient calibration of time-of-flight spectra in neutron experiments. Small liquid-scintillation counters have produced good results in low energy (γ, p) experiments, particularly in p/γ discrimination techniques⁸. Also, absorber-scintillation calorimeters such as lead-liquid scintillation electromagnetic calorimeters, which have long term stability and multishower reconstruction capabilities have been used for fixed target experiments with high intensity hadron beams.⁹ An innovative technique using very long, narrow, Teflon tubes (inner diameter 4.6 mm) filled with liquid scintillator has also been studied in large photon calorimeters.¹⁰ The Teflon tubes define the spatial granularity of the active element and guide the light through the tubes by total internal reflection to photomultipliers. A refinement of this technique is the use of scintillating optical fibers¹¹ embedded in a metal matrix.

In this thesis a test cell has been constructed to study the optical performance of liquid-scintillator filled Teflon-fiber tubes of inner diameter 0.6 mm. The performance of the tubes is given by studying the absolute light yield and the attenuation length, using cosmic rays and radioactive sources. The principle of light output readings from the scintillator in the Teflon tubes is by total internal reflection of light in the tubes due to differences in their refractive indices, as in optical fibers. This information will help in the development of a prototype of a liquid-scintillator Spaghetti calorimeter that will augment interest in investigating such calorimeter design for use in the proposed Superconducting Super Collider (SSC).

Chapter I introduces the test cell and its design specifications, provides information about the properties of the liquid scintillator, and photomultipliers used in the study.

Chapter II describes some of the main apparatus and provides a list of the electronic devices used in the experiments. The electronic devices (NIM modules) used are also listed.

Chapter III describes some important principles relevant to the experiments.

Chapter IV describes the two experimental methods used in the measurement of the optical performance of the Teflon tubes.

Chapter V explains how the mean path length and the geometrical efficiency of the test cell were calculated using two Monte Carlo simulations of cosmic rays and radiation from a radioactive source impinging on the scintillator in the Teflon tubes.

Chapter VI gives the conclusion of the study.

Appendix A gives the Monte Carlo program used in the simulation of cosmic rays to evaluate the mean free path and the geometrical efficiency of the test cell.

Appendix B gives the Monte Carlo program used in the simulation of a radioactive source to evaluate the mean free path.

CHAPTER II

EXPERIMENTAL APPARATUS

The Test Cell

The test cell consisted of 60 quartz glass tubes 1 m long, 2 mm outer diameter and 1.0 mm inner diameter. Long Teflon (Polytetrafluoroethylene) tubes (AWG 24) of approximately 0.6 mm inner diameter, were inserted through these glass tubes protruding about 2.0 mm from each end. Table 1 lists some relevant physical constants of Teflon.¹² Sixty such tubes were used, closely packed in rows of six and arranged in a 6×10 rectangular array (Figure 1). The quartz tubes were held in place with RTV by two 2 inch diameter acrylic disks, 0.25 inches in thickness, with holes drilled in accordance with the rectangular array. A third disk also drilled in the same manner was placed in the center of the arrangement for support (Figure 2). The RTV used was a custom formulated thixotropic flexible epoxy called 310T, consisting of two parts, the Epoxy resin and the hardener, and was mixed by using 10 parts resin and 6 parts hardner by weight.

The outer ends of the epoxied disks were machined (1.25 in diameter, 0.125 in thickness) so that they may also serve as chambers for the flow of liquid scintillator, via a tube, when filling the length of the tubes. A dark black delrin disk of 1.0 mm thickness, fit into the machined area, and held the protruding portion of the Teflon tubes in place at both ends. Two ultraviolet (UV) transmitting acrylic disks, of the same dimensions as the other disks were placed at the ends, to form a window for light detection, as well as a lid for the oil chambers, sealed with O rings and secured with steel screws (Figure 3). The luminous transmittance of the UV transmitting disks was about 92%, and UV transmission wavelengths was between 280 and 360 nanometers. Light detection was accomplished by using two linear focused, end

Figure 1. The completed test cell with photomultipliers. (Inset) Cross-section of the 6×10 rectangular array.

against the UV disks, using an optical coupler (MP - 400, viscosity 1 m c/St). Finally the photomultipliers were shielded with Mu-metal, so as not to be affected by stray magnetic fields.

The Photomultiplier

Photomultipliers (PM) are electron tube devices which convert light into measurable electric current. It consists of an evacuated glass tube housing containing a cathode made of photosensitive material with an electron collection system, a dynode string or electron multiplier section, and an anode from which the final signals are taken. During operation, a constant voltage is applied to the length of the cathode-dynode-anode structure creating a 'ladder' potential.

Figure 2. Components of the test cell.

When an incident photon, from a light source (scintillator) impinges on the window (glass or quartz) of the photomultiplier, containing the photocathode, an electron is emitted via the photoelectric effect, whose energies is given by Einstein's formula,

$$E = h\nu - \phi \quad (1)$$

where E is the kinetic energy of the emitted electron, ν is the frequency of the incident light and ϕ is the work function. However, above the minimum frequency or threshold, the efficiency of the photoelectric conversion varies strongly with the frequency of the incident light and the material of the photocathode. This spectral response is expressed by the quantum efficiency, $\eta(\lambda)$

$$\eta(\lambda) = \frac{\text{number of photoelectrons released}}{\text{number of incident photons on cathode } (\lambda)} \quad (2)$$

Figure 3. One end of the test cell.

Table 1. Some physical constants of Teflon.

Density : Completely Amorphous	2.0 at 23°
[D] Crystalline	2.302 at 23°
After melting & Crystallization	1.525
Dielectric Constant $[\epsilon]$	$1 + 0.238 D$
Lamellar Thickness $[\mu m]$	9.2 (%C)
Molecular Weight $\log M_w$	22.524-9.967 gm/cm ⁻³
Radiation Degradation in Air Radicals/10 ⁶ C Atoms	$3.7 \times 10^{-5} D^{0.89}$ $D = \text{rad}$
Refractive Index $[n_D]$	1.376
Weatherability	No change observed

where λ is the wavelength of the incident light.

The electron released from the photocathode (photoelectron) is then accelerated due to the high voltage, towards the first dynode, where upon striking, it transfers some of its energy to the electrons in the dynode. This causes secondary electrons to be emitted, which are then accelerated towards the next dynode where more electrons are released and further accelerated. This electron cascade continues down the dynode string, until it reaches the anode, where it collects to give a current, which can be amplified or analyzed.

In the case of scintillation counting, photomultipliers are operated in pulsed mode, and since the cathode and dynode systems are assumed linear, the current of the output will be directly proportional to the number of incident photons. Thus, a detector coupled to a photomultiplier is capable of providing not only information on the particle's presence but also the energy it has left in the scintillator.

The photomultiplier used to evaluate the light performance of the test cell was the EMI type 9839B. This is a fast linear focused, end window PM, approximately 51.0 mm (2.0 in) in diameter and 150 mm (5.91 in) in length. Figure 4(a) gives an outline of the PMT and its relevant dimensions, Figure 5(b) gives a graph of the quantum efficiency of the photocathode, and Figure 6 shows the relationship between gain and supply voltage for this PM. The overall electrical characteristics and ratings of the PMT are provided in Table 2.¹³

The Liquid Scintillator

Scintillators are materials that exhibit the property known as luminescence. These materials when exposed to certain forms of energy, e.g. radiation, absorb and reemit the energy in the form of visible light. As a first approximation, the time evolution of the reemission process may be described as an exponential decay given by,

$$N = \frac{N_0}{\tau_d} \exp\left(\frac{-t}{\tau_d}\right), \quad (3)$$

Table 2. Electrical Characteristics of PM EMI 9839B.

Spectral Response & Window	Bialkali/B
No., Type & Material of Dinodes	12, Linear Focused, BeCu
Effective Cathode Dia., (mm)	45.0
Quantum Efficiency (%) at Peak	27
Anode Sensitivity, A/lm at V_{k-a}	500 at 1900
Gain	6.7×10^6
Dark Emission, I_a (dark) nA	2.0
Rise Time, ns	3.0

where N is the number of photons emitted at time t , N_0 the total number of photons emitted, and τ_d the decay constant. The finite risetime from zero to the maximum in most materials is usually much more rapid than the decay time.

A good scintillator should satisfy the following requirements:¹⁴

1. a high efficiency for conversion of the exciting energy to fluorescent radiation
2. transparency to its fluorescent radiation, to allow transmission of light
3. emission in a spectral range consistent with the spectral response of the photomultipliers used
4. a short decay constant, τ

Liquid scintillators contain materials of liquid solutions of one or more organic scintillators in an organic solvent. When a particle passes through the liquid, the ionization energy is absorbed mainly by the solvent and then passes it on to the scintillation solute, the process occurring very quickly and efficiently.

(a)

(b)

Figure 4. (a) Outline & (b) Spectral response of the EMI 9839B.

Gain Versus Supply Voltage.

Figure 6. Gain versus supply voltage on PM of the EMI 9839B.

Table 3. Physical constants of liquid scintillator BC-517L.

Light Output % Anthracene	30% in Air
Decay Time, ns	2.0
Density, gm/cm ³	0.86
Index of Refraction at 425 nm	1.47
Wavelength of Max. Emission, nm	425
Flash Point, °F	215(101.8°C)
No. of C Atoms per cm ³	3.68×10^{22}
No. of H Atoms per cm ³	7.40×10^{22}
Ratio H:C Atoms	2.01
No. of Electrons cm ³	2.95×10^{23}

The response of liquid scintillators is generally quite fast with decay times on the order of 3 to 4 ns. In most cases, wavelength shifters, materials which absorb light of one frequency and reemit it at another, are added to the liquid to make the spectrum of emitted light more compatible with a photocathode of a PM. Usually the light output of scintillators is given as a relative measure of the compound to a scintillation standard; anthracene.

The liquid scintillator used in the experiments was the BC-517L. The solvent is a mixture of pseudocumene (PC) and mineral oil (MO), with the oil comprising over 75%. The primary scintillation light is given out at 370 nm, but due to use of wavelength shifters, the maximum emission wavelength is 425 nm. Figure 3 gives some of the important physical constants of BC-517L.

Electronic Devices

With the exception of the attenuator, all the electronic devices, for example, amplifier, discriminators, multichannel analyzer, etc., were in the form of modules.

Table 4. List of Electronic Devices & Make.

Amplifier	LeCroy NIM Model 612AM, Six channel variable
Discriminator	LeCroy NIM Model 821, Quad Discriminator
Coincidence	LRS NIM Model 365AL, 4-Fold Logic unit
Multichannel Analyzer	LeCroy NIM Model 3001, qVt
Interface (Printer)	LeCroy NIM Model 3157
Printer	DATEL Systems Model DPP-Q7
Scaler	Jorway NIM Model 1880B, Dual Channel BCD
LED Pulser	Six Channel Pulser
Attenuator	Kay Electronics Model 20-0

employing the standardized modular system, NIM (Nuclear Instrument Module). The cables used for connections were the standard RG-58C/U (50Ω) with BNC and SHV connectors. A list of these electronics devices is listed in Table 4.

CHAPTER III

EXPERIMENTAL PRINCIPLES

Total Internal Reflection in the Teflon tubes.

Total internal reflection of light can occur when it traverses at an angle the boundary between two media, one of which has a refractive index greater than the other. The angle at which refraction ceases and total reflection begins is called the critical angle, and is specified by θ_c , where

$$\theta_c = \sin^{-1} \left(\frac{n_{med}}{n_{scint}} \right) \quad (4)$$

with n_{scint} being the greater index of refraction of the scintillator and n_{med} that of the surrounding medium, in this case the Teflon tube. This effect is illustrated in Figure 7.

For the liquid scintillator BG-517L used, the index of refraction at 425 nm, which is the wavelength of maximum emission, is $n_{scint} = 1.47$, and the index of refraction of Teflon is $n_{med} = 1.376$, the critical angle is

$$\theta_c = 69.5^\circ \quad (5)$$

With reference to the longitudinal dimension of the Teflon tubes, all angles of light less than about 20° from the Teflon surface will be totally reflected.

Single Electron Spectrum

This is the spectrum of photomultiplier output pulses resulting from the entry of only single electrons into the multiplier system. Ideally this multiplication process produces a Poisson distribution of output charges, since single electrons entering the

Figure 7. Diagram of a scintillator filled Teflon tube.

system will produce different numbers of secondary electrons. Thus the probability of observing a yield of n secondary electrons per primary is

$$p(n) = \frac{(\mu)^n e^{-\mu}}{n!} \quad (6)$$

where μ is the average number of photoelectrons in the sample.¹⁶ The form of this spectrum is usually defined by the multiplication statistics of the first few stages, particularly the first.

The distribution of this spectrum can be measured by illuminating the PM with a very weak light source such that the probability of more than one single electron entering the multiplier at the same time is small.

The single electron spectrum of the PM, EMI 9839B used in the experiment is shown in Figure 8(a) and (b), where two radioactive sources, ^{90}Sr and ^{137}Cs , have

been used to produce scintillation light pulses.

Light Collection

The loss of light from the scintillator filled Teflon tubes occurs basically in two ways: one is by escaping through the surface of the Teflon, when the angle is greater than the critical angle, and the other is by absorption of the light by the scintillator. This absorption is characterized by the attenuation length, and is defined by the total path length travelled by the photons through the scintillation after which the light intensity is reduced by a factor of e^{-1} . The light intensity as a function of length is then,

$$L(x) = L_0 \exp\left(\frac{-x}{l}\right) \quad (7)$$

where l is the attenuation length, x the path length travelled by the light, and L_0 is the initial light intensity.

The method used to measure light intensity or light yield is to analyze the charge spectrum from the anode of the photomultiplier. This is characterized by a very sharp initial peak, the pedestal, which is the result of a trigger when no charge is present at the anode, and a broad peak at the mean number of photoelectrons times the gain of the photomultiplier. The position of the broad peak relative to the pedestal is a measure of the total charge delivered by the anode of the PM, which is a measure of the number of photoelectrons produced at the cathode. As the light intensity increases, the mean number of photoelectrons increases. Thus, the light yield can be given in photoelectrons, and is accomplished by calibrating the analyzer (multichannel analyzer) in terms of channels per photoelectron. This calibration is done by illuminating the PM with a very weak light source to get a single photon response, and then measuring the absolute position of the single photoelectron spectrum. This measurement is independent of the operating voltage of the PM or the gain due to the associated electronics.

Vertical Scale: 50 mV/cm

Horizontal Scale: 0.1 μ m/cm

Source: 100 μ Ci, ^{90}Sr .

Vertical Scale: 0.1 V/cm

Horizontal Scale: 0.1 μ s/cm

Source: 5 mCi, ^{137}Cs .

Figure 8. Anode signals from liquid scintillator BC 517L.

Figure 9. Set-up for LED single photoelectron calibration of spectra.

One way of getting the single photoelectron response is to adjust the light output of the cell to give single photoelectrons an occupancy of a few percent and gate the corresponding output signals of the PM with that of a pulsed, light-emitting diode (LED) triggering it. This method allows for the periodic check of any gain fluctuations, during the experiment (Figure 9).

Response Resolution

The energy resolution obtained using a particular photomultiplier-scintillator combination depends on the matching of the scintillator emission spectrum, $F(\lambda)$ and on the absolute spectral sensitivity of the PM cathode. This is given by the photocathode response factor η of the combination.

$$\eta = \frac{\int \phi(\lambda) F(\lambda) d\lambda}{\int F(\lambda) d\lambda},$$

where the integrations are taken over the spectrum $F(\lambda)$.¹⁷

A numerical calculation done with the PM-scintillator combination, EMI 9839B-BC 517L, gave the value of $\eta \approx 25\%$.

CHAPTER IV

THE EXPERIMENTS

Two experimental setups were used to measure the light output of the liquid scintillator filled Teflon-fiber tubes, viz.

1. The Cosmic Ray Telescope.
2. Direct Source Measurement.

The Cosmic Ray Telescope

Method

In this arrangement, the test cell was irradiated with cosmic rays and the resulting pulse height spectrum (mostly due to muons), were analyzed by a multichannel analyzer gated with a coincidence pulse from two plastic 'paddle' scintillation counters and a plastic 'chip' counter. The paddle counters were arranged to sandwich the chip counter and the test cell, with the later below, so as to define the trajectory of the ionizing cosmic ray particles, that have a high probability of intersecting the Teflon-fiber tubes in the test cell.

Using this method, the inefficiency, $P(0)$ can be measured by putting $n = 0$, in Eq. (6), to give

$$P(0) = \exp(-\mu) \quad (8)$$

or, $\ln P(0) = -\mu$, a measure of the average number of photoelectrons. Referring to the pulse to be analyzed as D (or E) depending on the PM used, and the paddle chip-paddle counters as A , B , and C respectively, the efficiency will be defined by the coincidence ratio,

$$efficiency = \frac{(A \cdot B \cdot C \cdot D)}{(A \cdot B \cdot C)}, \quad (9)$$

and thus,

$$inefficiency = (1 - efficiency)$$

The discriminator for D was set below the threshold for single photoelectrons. By scanning this 'telescope' arrangement over the length of the test cell, a measurement of the light output versus position can be obtained. Figure 10 gives a schematic diagram of this arrangement.

Results

The measurements were made, without the optical coupler, and using one photomultiplier at a time (either D or E) throughout the length of the test cell, marking the center of the length as 0.0 cm. Readings were taken every 10 cm from the center of the cell for 50 cm on both sides, thus utilizing a total length of 100 cm. The assignment of negative and positive values to the length was arbitrary.

A fit with a single exponential in the range from +50 cm to -10 cm and -50 cm to +10 cm with photomultipliers D & E respectively, gave a measured attenuation length of 21.0 ± 6.4 cm with D and 19.0 ± 5.7 cm with E .

The results of the inefficiency measurements for the PMs labelled D and E , as a function of length are plotted in Figure 11. The measurements were taken with the test cell hermetically sealed from light by enclosing it with a Polyvinylchloride (PVC) tube, 4.0 mm in thickness.

The reproducibility of the attenuation length measurement was tested by draining the old liquid scintillator and filling it again, and enclosing it with a thin aluminized vinyl, 0.5 mm in thickness, wrapped around the test cell, and using an optical coupler on the face of the photomultiplier. Only one of photomultipliers was used in this test, with the position of the disk facing the photomultiplier taken as the -60.0 cm mark. The fitted values were from -50.0 cm to -20.0 cm. for this measurement.

Figure 10. Set-up for inefficiency measurement.

Figure 11. Attenuation length of test cell using PMs at each end.

The pulse shape of these measurements was a single photoelectron spectrum. The results of the measurements are plotted in Figure 12. The attenuation length measured was 18.0 ± 6.73 cm. Thus no appreciable change in the attenuation length was noted.

Direct Source Measurements

Method

In this method a collimated radioactive source was kept at a fixed height above the test cell and measurements at various points along the length of the test cell were made. The resulting spectra was calibrated in terms of the number of photoelectrons observed.

However, the light yield per detected gamma ray was of the order of a fraction of a photoelectron and thus only the single photoelectron peak was observed in these measurements (the figure on p.28). The change as a function of distance, will be in the height (frequency) of the peaks. However, the ratios of the heights of the peaks can also be used as a measure of the average number of photoelectrons. This was measured as follows: expressing the total counts of the peak for a given time by,

$$Rate_x = R_T(1 - P_x(0)) \quad (10)$$

where $P_x(0)$ is the inefficiency as a function of distance, given by Eq. (8). The ratio of the heights of the peaks at distances x_1 and x_2 is then,

$$\frac{R_{x_1}}{R_{x_2}} = \frac{R_T(1 - P_{x_1}(0))}{R_T(1 - P_{x_2}(0))} = \frac{1 - e^{-\lambda_{x_1}}}{1 - e^{-\lambda_{x_2}}} \quad (11)$$

since $\lambda \ll 1$, the ratio can be written as

$$\frac{R_{x_1}}{R_{x_2}} = \frac{1 - (1 - \lambda_{x_1} + \lambda_{x_1}^2/2! - \dots)}{1 - (1 - \lambda_{x_2} + \lambda_{x_2}^2/2! - \dots)} \simeq \frac{\lambda_{x_1}}{\lambda_{x_2}} \quad (12)$$

where λ_{x_1} and λ_{x_2} are the average number of photoelectrons at position x_1 and x_2 . Measuring the light output as a function of distance gave the attenuation length of

Attenuation length using cosmic rays

Figure 12. Attenuation length of test cell using one photomultiplier (*D*) (with optical coupler).

the scintillator filled test cell. The radioactive source measurements were made with a 5.0 mCi ^{137}Cs , surrounded with 4.0 inches of lead, with a collimation width of approximately 2.0 cm. Source measurements were also taken with a 100 μCi ^{90}Sr .

Figure 13 gives a diagram of the set-up for the direct source measurements. Figure 14 gives an example of the spectra using the radioactive source ^{90}Sr .

Results

Using the source ^{90}Sr , the ratio of different positions from the face of the photomultiplier was calculated using Eq. (11), where λ_{x_2} was the average number of photoelectrons at the position where no significant change in the height of the peak was observed, about 55.0 cm. The ratio was about 1.2 at the 15.0 cm position. The fitted values were from 15 cm to 32 cm. The value of the attenuation length measured was 21.0 ± 6.1 cm. Figure 15 gives the attenuation curve for the scintillator (BC 517L) filled Teflon tube arrangement, where the vertical scale is the ratio of the average photoelectrons for different peaks as a function of distance.

The ^{137}Cs source gave a ratio of 1.6 at 15.0 cm from the photomultiplier. The fitted values were from 15 cm to 35 cm. The attenuation length measured was 20.5 ± 4.0 cm. These results are given in Figure 16.

Figure 13. Set-up for direct source measurements.

^{90}Sr Signal Spectrum

at 20.0 cm from PM.

Same Signal Amplified ($\times 10$)

Clearly showing a 1st

Photoelectron Spectrum.

Figure 14. Spectra of signal output using ^{90}Sr .

Attenuation curve for BC-517L with Sr-90

Figure 15. Attenuation curve for 0.6 mm diameter of scintillator filled Teflon fiber using ^{90}Sr .

Attenuation curve for BC-517L with Cs-137

Figure 16. Attenuation curve for 0.6 mm diameter of fiber using ^{137}Cs .

CHAPTER V

MONTE CARLO SIMULATIONS

Two Monte Carlo simulations were used to find the mean path length and the geometrical efficiency of the test cell.

The first simulation for cosmic rays was done by enclosing the whole length of the test cell in a sphere with the x, y, & z axes along the width, height, & length respectively, and choosing a random direction vector with origin at the center of the cell. A plane was then chosen perpendicular to this vector. The vector was then translated to a random point on this plane and checked to see if it had passed through the specified volume of the array of the scintillator material (inside the Teflon tubes), by satisfying certain conditions. If these conditions were met, the path length through the scintillator was recorded, and the next direction vector was randomly generated and the process was repeated. Due to the arrangement of the cosmic telescope, most of the cosmic rays are at an angle of 45° and hence the direction vector was fixed so as not to vary more than this angle from the normal; i.e. the y axis. At the end of a specified number of times, the mean of all the path lengths was calculated to give the *mean path length*, through the test cell.

The mean path length for this simulation was 1.10 mm.

The geometrical efficiency of the test cell was $\approx 69\%$, and was evaluated by the ratio,

$$\text{geom. eff} = \frac{\text{no. of passes through the test cell}}{\text{no. of events recorded above min. value}}$$

where the minimum value of the path length was set at 0.05 cm, so as to neglect any glancing events.

Assuming a linear relationship between the mean path length and the average number of photoelectrons¹⁸ we can conclude that,

$$1.0 \text{ mm path length} = (63.0 \pm 8.0) \times 10^{-3} \text{ photoelectrons.}$$

The second simulation for radiation from a radioactive source impinging on the of the test cell, was done by assuming a point source, located at a distance of a few centimeters from the top (width) of the cell, permeating its dimensions. First a random direction vector was chosen confined within a given angle (θ) and a randomly chosen azimuthal angle (ϕ), with origin at the center of the cell. The origin was then translated to a specified point above the cell, 'h-source'. The vector was then checked, as in the first simulation, for passage through scintillator material and path length duly recorded for a specified number of events.

Since the path length and the efficiency of the cell would depend on the height of the source (h-source) and confining angle (θ) chosen for this simulated radiation, these were chosen by using the relation

$$\theta = \tan^{-1} \left(\frac{0.95}{h - \text{source}} \right)$$

with h-source = 3.0 cm and $\theta = 36^\circ$ (in radians).

The mean path length calculated for this simulation was 1.20 mm.

CHAPTER VI

CONCLUSION

We can conclude from the methods used, that the light output for the scintillator filled Teflon tube is $(63.0 \pm 8.0) \times 10^{-3}$ photoelectrons; i.e. a fraction of a photoelectron. when working at tube diameters of 0.6 mm. The mean attenuation length is 19.3 ± 0.31 cm for the cosmic telescope method and 20.8 ± 1.1 cm for the direct source method.

The difficulty with working with tubes of such small diameters, is the uncertainty of microscopic air bubbles trapped in the Teflon tubes. These bubbles tend to retard the performance of the test cell as well as the scintillator. Preliminary readings with observed bubbles trapped inside the tube arrangement produced erratic outputs, throughout the length of the cell.

The optical performance of the photomultiplier was also dependent on the coupling of the PM to the window of the test cell. Initial observations without any coupling medium, except air, showed the light output to be much below the 1st photoelectron level. The subsequent use of an optical coupler (MP-400) showed an increase in performance of the test cell.

Studies done with different widths of the scintillator, totally internally reflecting from a sheet of Teflon, showed that the light output was reduced linearly as a function of the width (level) of the scintillation. The measurements were taken at widths 4.0 mm, 2.0 mm, and 1.0 mm.¹⁸ Thus it can be concluded, that the performance of the test cell 0.6 mm in diameter, has helped to define a limiting value for the width of the scintillator filled Teflon tubes. This information should prove helpful in the building of a prototype calorimeter for use at the SSC.

Using Monte Carlo simulations of cosmic rays and radiation from a radioactive source impinging on the cell (Appendix A & B), the mean path length of the test

cell was calculated to be 1.10 mm and 1.20 mm respectively, and the geometrical efficiency of the test cell was approximately 69%. Hence a 1 mm path length gives a light output of $(63.0 \pm 8.0) \times 10^{-3}$ photoelectrons from the test cell.

The stability of the light output and the attenuation length was observed for a period of 6 months. No noticeable degradation was observed in the performance of the test cell. Also, irradiation of the Teflon to 2.2×10^4 rad revealed no observed damage to it. However, it is known that on irradiating Teflon to 4×10^6 rad, it becomes brittle.¹⁰ A detector operating at SSC energies and utilizing the same principles as the test cell, would therefore require another medium for the total internal reflection. Whether the limit established here is valid for other mediums is a concern for future thought.

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APPENDIX A

MONTE CARLO PROGRAM FOR SIMULATION OF COSMIC RAYS

```

*
* Monte Carlo simulation of cosmic rays to determine path length
* within a Test Cell
*
* No implicit data types:
*   Implicit None
*
* Included files
*   Include '($SMGDEF)'
*
* Internal Variable Declarations:
*
* in order  PARAMETER, CHARACTER, LOGICAL, BYTE, INTEGER*2, INTEGER*4,
* REAL, other {with alphabetical ordering}
*
      Parameter      pi = 3.1415927

      Character      line*(78), yn*(3), line2*(24)

      Logical        flag_good, flag_wait, flag_maybe_good, flag_display,
&                  flag_fired(100)

      Integer*4
&                  ch_inp,          !dummy key input variable (SMG use)
&                  disp_1,          !display id (SMG use)
&                  i_fiber,         !loop var. for fiber counting
&                  i_site,          !loop var. for fiber counting (2)
&                  i_stat,          !status storage for calling routines
&                  i_try,           !loop var. for # tries
&                  i_use1,          !loop var. for disp. vector 1 use
&                  i_use2,          !loop var. for disp. vector 2 use
&                  idum,            !seed for random number generator
&                  key_bd,          !keyboard id (SMG use)
&                  n_fiber,         !total # of fibers
&                  n_good,          !# of good events (particle triggered
&                                  !   a fiber
&                  n_pass_events,   !# of events where particle passed
&                                  !   the cell
&                  n_too_low,       !# of events where r_intersect < r_min
&                  N_tries,         !# of monte carlo tries
&                  n_use1,          !# of uses for disp. vector 1
&                  n_use2,          !# of uses for disp. vector 2
&                  paste_bd,        !pasteboard id (SMG use)
&                  x_pos,           !x and y positions on screen
&                  y_pos,           !   for fiber (SMG use)

      Real*8
&                  a,b,c,           !dummy co-efficients
&                  d0,d1,           !distance from end points of
&                                  !   the path to fiber center
&                  Mean,            !mean path length
&                  phi,             !normal vector angle from origin
&                  radp,            !radius of random point on plane
&                  Rand,            !random variable
&                  r_fiber_intersect, !path distance through fibers
&                                  !radius for inside fiber case
&                  rho,             !radius of normal vector
&                  rho1,            !projection on x-z plane

```

```

&          rho_m,          lpath distance inside fiber case
&          r_intersect,    lpath distance
&          r_tot,          ltotal path distance measured

&          S_rad,          lmaximum boundary point
&          sq_two,         linverse of square root two
&          t,t0,t1,        lparticle path parameterization
&                          l variable
&          theta,          lazimuthal angle on circular plane
&          x0,y0,z0,        lorigin of normal vector
&          x1,y1,z1,        lcoordinate of normal vector
&          xi0,yi0,zi0,     lparticle path starting point
&                          l (on the sphere)
&          xi1,yi1,zi1,     lparticle path final point
&                          l (on the sphere)
&          xi2,yi2,zi2,     lparticle path arbitrary point
&                          l (in general, not on sphere)
&          xm,ym,          lclosest point to fiber
&          xp,yp,          lcoordinate on circular plane
&                          l perpendicular to normal vector
& Height, Length, r_min, Width, x_comp1, y_comp1, x_comp2, y_comp2,
& rad_fiber, x_fiber(100), y_fiber(100), x_max, y_max, z_max
*
* Function definitions: rand(seed)
*
*      Integer      SMG$Create_Pasteboard,
&                  SMG$Create_Virtual_Display,
&                  SMG$Create_Virtual_Keyboard,
&                  SMG$Paste_Virtual_Display,
&                  SMG$Put_Chars,
&                  SMG$Read_Keystroke,
&                  SMG$Label_Border
*
*****
* Program parameters.
*
*      * dimension of the cell
LENGTH = 100.0
WIDTH = 1.953
HEIGHT = 1.4211
*
*      * radius of each fiber
RAD_FIBER = 0.03
*
*      * minimum path length for the event to register
r_min = 0.05
*
*      * position of the first fiber
X_FIBER(1) = 0.879
Y_FIBER(1) = 0.507
*
*      * the two disp. vectors to generate the fiber array
X_COMP1 = 0.0
Y_COMP1 = -0.225
X_COMP2 = -0.195
Y_COMP2 = 0.113
*
*      * # of times these disp. vectors are to be used to generate array.
N_USE1 = 5
N_USE2 = 10

```

```

*      * the boundary of the cell
      z_max = Length/2
      y_max = height/2
      x_max = width/2
*      *****

*      *****
* Dimensions of the cylindrical fibers in test cell.
      n_fiber = (n_use1+1) * (n_use2)
      Write (*, '( " total # sites is : ', I5, ') ' ) n_fiber
      Write (*, '( " ' ' ) ' )
*      *****

*****
* Array of sites in the cross section where the fiber centers are.
      i_site = 2
      Do i_use2 = 1, n_use2
        Do i_use1 = 1, n_use1
          x_fiber(i_site) = x_fiber(i_site-1) + x_comp1
          y_fiber(i_site) = y_fiber(i_site-1) + y_comp1
          i_site = i_site+1
        EndDo
        x_fiber(i_site) = x_fiber(i_site-1) + x_comp2
        y_fiber(i_site) = y_fiber(i_site-1) + y_comp2
        i_site = i_site+1
        y_comp1 = -y_comp1
        y_comp2 = -y_comp2

      EndDo
*****

*****
* Output the array.
      Write (*, '( " : (x-comp, y-comp) ' ' ) ' )
      Do i_site = 1, n_fiber
        Write (*, '( " fiber # ', I2, ' : ( ', F6.4, ' ', ' ', F6.4, ' ' ) ' ' )
        i_site, x_fiber(i_site), y_fiber(i_site)
      &
      End Do
*****

*****
* Do a few calculations outside the Monte Carlo loop.
      S_rad = Sqrt(z_max*z_max + y_max*y_max + x_max*x_max)
*****

*****
* Get Monte Carlo parameters.
      Write (*, '( " ' ' ) ' )
      Write (*, '( " Enter # of trial particles: ', I5, ') ' )
      Read (*, '( I ) ' ) N_tries
      Write (*, '( " ' ' ) ' )
*****

*****
* Display the events on the screen?
      Write (*, '( " ' ' ) ' )
      Write (*, '( " Do you want each event to be displayed? ', I5, ') ' )
      Read (*, '( A ) ' ) yn
      Write (*, '( " ' ' ) ' )

```

```

      flag_display = ( (yn.EQ.'y').or.(yn.EQ.'Y').or.(yn.EQ.'yes').or.
&                      (yn.EQ.'Yes').or.(yn.EQ.'YES') )
*****

* Wait for a keypress every path?
  If (flag_display) then
    Write (*,'('' ''')')
    Write (*,
&          ' ('' Wait for keypress for every particle path try? ''',$')
    Read (*,'(A)') yn
    Write (*,'('' ''')')
    flag_wait = ( (yn.EQ.'y').or.(yn.EQ.'Y').or.(yn.EQ.'yes').or.
&                  (yn.EQ.'Yes').or.(yn.EQ.'YES') )
    Else
      flag_wait = .false.
    End If
  *****

* Set up display.
  If (flag_display) then
    i_stat = SMG$Create_Pasteboard (paste_bd)
    i_stat = SMG$Create_Virtual_Keyboard (key_bd)
    i_stat = SMG$Create_Virtual_Display (22,78,disp_1,SMG$M_Border)
    i_stat = SMG$Paste_Virtual_Display (disp_1, paste_bd, 2,2)
    Do i_site = 1, n_fiber
      x_pos = x_fiber(i_site)/x_max * 38 + 39
      y_pos = - y_fiber(i_site)/y_max * 10 + 11
      i_stat = SMG$Put_Chars (disp_1,'.',y_pos,x_pos)
    End Do
  End If
  *****

* Do Monte Carlo.
  r_tot = 0.
  sq_two = 1./sqrt(2.)
  Idum = -3
  n_good = 0
  n_too_low = 0
  n_pass_events = 0
  Do i_try = 1, N_tries

  * *****
  * ** Generate a random particle path.
  * ** First, pick a random direction, i.e. a random spot on a sphere.
  * y1 = ( Rand(idum) * (1.-sq_two) + sq_two )
  * rho1 = sqrt(1.-y1*y1)
  * phi = Rand(idum) * 2.*pi
  * z1 = rho1 * cos(phi)
  * x1 = rho1 * sin(phi)
  * ** Now, pick a random point on a circle on a plane that is
  * ** perpendicular to this direction.
  * theta = Rand(idum) * 2.*pi
  * radp = sqrt ( Rand(idum) * (S_rad)**2. )
  * xp = radp * cos(theta)
  * yp = radp * sin(theta)
  * x0 = -xp*z1/rho1 - yp*y1*x1/rho1
  * y0 = yp*rho1

```



```

z0 = xp*x1/rho1 - yp*y1*z1/rho1
** Determine the intersection of this particle path the cell.
a = x1*x1 + y1*y1 + z1*z1
b = 2* ( x0*x1 + y0*y1 + z0*z1 )
c = x0*x0 + y0*y0 + z0*z0 - S_rad**2.
t0 = (-b+sqrt(b*b-4*a*c)) / (2*a)
t1 = (-b-sqrt(b*b-4*a*c)) / (2*a)
xi0 = x0 + x1*t0
yi0 = y0 + y1*t0
zi0 = z0 + z1*t0
xi1 = x0 + x1*t1
yi1 = y0 + y1*t1
zi1 = z0 + z1*t1
*****

** Check to see if it's worth looping through n_fiber pts.
flag_maybe_good = .true.
If ( (xi0.GT.x_max) .and. (xi1.GT.x_max) ) flag_maybe_good = .false.
If ( (xi0.LT.-x_max) .and. (xi1.LT.-x_max) ) flag_maybe_good = .false.
If ( (yi0.GT.y_max) .and. (yi1.GT.y_max) ) flag_maybe_good = .false.
If ( (yi0.LT.-y_max) .and. (yi1.LT.-y_max) ) flag_maybe_good = .false.
If ( (zi0.GT.z_max) .and. (zi1.GT.z_max) ) flag_maybe_good = .false.
If ( (zi0.LT.-z_max) .and. (zi1.LT.-z_max) ) flag_maybe_good = .false.
*****

** Check to see if the path cuts through test cell at all.
If (flag_maybe_good) then
    flag_maybe_good = .false.
    t = (x_max-xi0)/x1
    & If ( (abs(yi0+t*y1).LT.y_max) .and.
        (abs(zi0+t*z1).LT.z_max) ) then
        flag_maybe_good = .true.
    End If
    t = (-x_max-xi0)/x1
    & If ( (abs(yi0+t*y1).LT.y_max) .and.
        (abs(zi0+t*z1).LT.z_max) ) then
        flag_maybe_good = .true.
    End If
    t = (y_max-yi0)/y1
    & If ( (abs(xi0+t*x1).LT.x_max) .and.
        (abs(zi0+t*z1).LT.z_max) ) then
        flag_maybe_good = .true.
    End If
    t = (-y_max-yi0)/y1
    & If ( (abs(xi0+t*x1).LT.x_max) .and.
        (abs(zi0+t*z1).LT.z_max) ) then
        flag_maybe_good = .true.
    End If
    t = (z_max-zi0)/z1
    & If ( (abs(yi0+t*y1).LT.y_max) .and.
        (abs(xi0+t*x1).LT.x_max) ) then
        flag_maybe_good = .true.
    End If
    t = (-z_max-zi0)/z1
    & If ( (abs(yi0+t*y1).LT.y_max) .and.
        (abs(xi0+t*x1).LT.x_max) ) then
        flag_maybe_good = .true.
    End If

```

```

                                If (flag_maybe_good) n_pass_events = n_pass_events + 1
End If
*****

** Now, loop through n_fibers to calculate total path length.
flag_good = .false.
r_intersect = 0.
If (flag_maybe_good) then
Do i_fiber = 1, n_fiber

    *****
    *** Figure out the path length.
    *** look at different cases.
    d0 = sqrt( (xi0-x_fiber(i_fiber))**2.
&          + (yi0-y_fiber(i_fiber))**2. )
    d1 = sqrt( (xi1-x_fiber(i_fiber))**2.
&          + (yi1-y_fiber(i_fiber))**2. )

    r_fiber_intersect = 0.
    flag_fired(i_fiber) = .false.
    If (d0.LE.rad_fiber) then

        *****
        *** The beginning of trajectory is inside a fiber.
        flag_good = .true.

        x_pos = x_fiber(i_fiber)/x_max * 38 + 39
        y_pos = - y_fiber(i_fiber)/y_max * 10 + 11
        l_stat = SMG$Put_Chars (disp_1,'*',y_pos,x_pos)
        flag_fired(i_fiber) = .true.

        a = (xi1-xi0)**2.+(yi1-yi0)**2.
        b = 2*( (xi0-x_fiber(i_fiber))*(xi1-xi0)
&          + (yi0-y_fiber(i_fiber))*(yi1-yi0) )
        c = (xi0-x_fiber(i_fiber))**2.
&          + (yi0-y_fiber(i_fiber))**2. - rad_fiber**2.
        t = ( -b+sqrt(b*b-4*a*c) )/ (2*a)

        If (t.GT.1.) then
&          r_fiber_intersect = sqrt( (xi1-xi0)**2.
&          + (yi1-yi0)**2.
&          + (zi1-zi0)**2. )
        Else
            xi2 = xi0 + (xi1-xi0)*t
            yi2 = yi0 + (yi1-yi0)*t
            zi2 = zi0 + (zi1-zi0)*t
            r_fiber_intersect = sqrt( (xi2-xi0)**2.
&          + (yi2-yi0)**2.
&          + (zi2-zi0)**2. )
        EndIf
    *****

Else If (d1.LE.rad_fiber) then

    *****
    *** The end of trajectory is inside a fiber.
    flag_good = .true.

    x_pos = x_fiber(i_fiber)/x_max * 38 + 39

```



```

*      *      *      *****
*      EndIf
*      *****

r_intersect = r_intersect + r_fiber_intersect
End Do
End If
** end of n_fibers loop.
*****

** Keep up the accounting.
If (flag_good) then
    n_good = n_good + 1
    If (r_intersect.LE.r_min) then
        n_too_low = n_too_low + 1
    Else
        r_tot = r_tot + r_intersect
    End If
End If
*****

** Dump info about particle path. Clean up screen.
If (flag_display.and.flag_good) then
    Write (line, '(' try #', I7, ':(' ,
    &      F7.3, ', ', F7.3, ', ', F7.3,
    &      ') ~ (' , F7.3, ', ', F7.3, ', ', F7.3, ') r=', F7.3)')
    &      i_try, xi0, yi0, zi0, xi1, yi1, zi1, r_intersect
    i_stat = SMG$Label_Border (disp_1, line)
    If (flag_wait) i_stat = SMG$Read_Keystroke (key_bd, ch_inp)
    Do i_site = 1, n_fiber
        If (flag_fired(i_site)) then
            x_pos = x_fiber(i_site)/x_max * 38 + 39
            y_pos = - y_fiber(i_site)/y_max * 10 + 11
            i_stat = SMG$Put_Chars (disp_1, '.', y_pos, x_pos)
        End If
    End Do
End If
*****

End Do
* end of monte carlo loop.
*****
Mean = r_tot/ ( N_good- n_too_low)

*****
* Write out the result
Write (*, '(' ')')
Write (*, '(' Out of ', I7, ' tries, ')') n_tries
Write (*, '(' ', I7, ' particles passed the chamber, ')')
    &      n_pass_events
Write (*, '(' and ', I7, ' events were counted, ')') n_good
Write (*, '(' and ', I7, ' events were too low. ')') n_too_low

Write (*, '(' So, total # of good events = ', I7)') n_good - n_too_low

Write (*, '(' The Mean Path Length is: ', F10.6)') Mean
*****

```

```

*****
* that's all, folks.
* End

```

```

*****
*****
Function rand(idum)
*
* Generate random numbers from 0 to 1
*
* Variable Declaration.
*
    Dimension      v(97)
    Data           iff /0/

* *****
* Initialize the function.
    If(idum.lt.0.OR.iff.eq.0) then
        iff=1
        Iseed = Abs(idum)
        idum = 1
        Do J = 1, 97
            Dum = Ran(Iseed)
        EndDo
        Do J = 1, 97
            V(J) = Ran(Iseed)
        EndDo
        Y = Ran(Iseed)
    EndIf
* *****
* *****
* Figure out the next random number.
    J = 1 + Int(97. * Y)
    If(J.gt.97.OR.J.lt.1) pause
    Y = V(J)
    Rand = Y
    V(J) = Ran(Iseed)
* *****
* The end.
    Return
End
* *****

```

APPENDIX B

MONTE CARLO PROGRAM FOR SIMULATION OF RADIATION FROM A SOURCE

```

*
* Monte Carlo simulation of radioactive source to determine path length
* within a Test Cell
*
* No implicit data types:
*   Implicit None
*
* Included files
*   Include '($SMGDEF)'
*
* Internal Variable Declarations:
*
* in order  PARAMETER, CHARACTER, LOGICAL, BYTE, INTEGER*2, INTEGER*4,
* REAL, other {with alphabetical ordering in each category}.
*
  Parameter      pi = 3.1415927

  Character      line*(78), yn*(3), line2*(24)

  Logical
&               flag_display, flag_fired(100), flag_good,
&               flag_maybe_good, flag_wait

  Integer*4
&               ch_inp,          !dummy key input variable (SMG use)
&               disp_1,          !display id (SMG use)
&               i_fiber,         !loop var. for fiber counting
&               i_site,          !loop var. for fiber counting (2)
&               i_stat,          !status storage for calling routines
&               i_try,           !loop var. for # tries
&               i_use1,          !loop var. for disp. vector 1 use
&               i_use2,          !loop var. for disp. vector 2 use
&               idum,            !seed for random number generator
&               key_bd,          !keyboard id (SMG use)
&               n_fiber,         !total # of fibers
&               n_good,          !# of good events (particle triggered
&                               !   a fiber
&               n_pass_events,   !# of events where particle passed
&                               !   the cell
&               n_too_low,       !# of events where r_intersect < r_min
&               N_tries,         !# of monte carlo tries
&               n_use1,          !# of uses for disp. vector 1
&               n_use2,          !# of uses for disp. vector 2
&               paste_bd,        !pasteboard id (SMG use)
&               x_pos,           !x and y positions on screen
&               y_pos,           !   for fiber (SMG use)

  Real*8
&               a,b,c,           !dummy co-efficients
&               d0,d1,           !distance from end points of
&                               !   the path to fiber center
&               Mean,            !mean path length
&               phi,             !azimuthal angle
&               radp,            !radius of random point on plane
&               Rand,            !random variable
&               r_fiber_intersect, !path distance through fibers
&               rho,             !radius for inside fiber case

```

```

&          rho1,          !radius of normal vector
&          rho_m,          ! projection on x-z plane
&          r_intersect,    ! path distance inside fiber case
&          r_tot,          ! path distance
&                          !total path distance measured

&          S_rad,          !maximum boundary point
&          t,t0,t1,        !particle path parameterization
&                          ! variable
&          theta,          !angle of individual paths
&          x0,y0,z0,        !origin of normal vector
&          x1,y1,z1,        !coordinate of normal vector
&          xi0,yi0,zi0,     !particle path starting point
&                          ! (on the sphere)
&          xi1,yi1,zi1,     !particle path final point
&                          ! (on the sphere)
&          xi2,yi2,zi2,     !particle path arbitrary point
&                          ! (in general, not on sphere)
&          xm,ym,          !closest point to fiber
&          xp,yp,          !coordinate on circular plane
&                          ! perpendicular to normal vector
& Height, h_source, Length, r_min, theta_m, Width, x_comp1,
& y_comp1, x_comp2, y_comp2, rad_fiber, x_fiber(100), y_fiber(100),
& x_max, y_max, z_max

```

```

*
* Function definitions: rand(seed)

```

```

*      Integer      SMG$Create_Pasteboard,
&                  SMG$Create_Virtual_Display,
&                  SMG$Create_Virtual_Keyboard,
&                  SMG$Paste_Virtual_Display,
&                  SMG$Put_Chars,
&                  SMG$Read_Keystroke,
&                  SMG$Label_Border

```

```

*****
* Program parameters.

```

```

*      * dimension of the cell
      LENGTH = 100.0
      WIDTH  = 1.953
      HEIGHT = 1.4211

*      * radius of each fiber
      RAD_FIBER = 0.03

*      * minimum path length for the event to register
      r_min = 0.05

*      * position of the first fiber
      X_FIBER(1) = 0.879
      Y_FIBER(1) = 0.507

*      * the two disp. vectors to generate the fiber array
      X_COMP1 = 0.0
      Y_COMP1 = -0.225
      X_COMP2 = -0.195
      Y_COMP2 = 0.113

```

```

*      * # of times these disp. vectors are to be used to generate array.
      N_USE1 = 5
      N_USE2 = 10

*      * interior angle of the cone (from the vertical) that encloses the
*      * paths from a source.
      theta_m = pi/9.

*      * the height of the source above the cell
      h_source = 2.0

*      * the boundary of the cell
      z_max = length/2
      y_max = height/2
      x_max = width/2
.....

* Dimensions of the cylindrical fibers inside.
      n_fiber = (n_use1+1) * (n_use2)
      Write (*, '( " total # sites is : ', I5)') n_fiber
      Write (*, '( " '))
.....

* Array of sites in the cross section where the fiber centers are.
      i_site = 2
      Do i_use2 = 1, n_use2
        Do i_use1 = 1, n_use1
          x_fiber(i_site) = x_fiber(i_site-1) + x_comp1
          y_fiber(i_site) = y_fiber(i_site-1) + y_comp1
          i_site = i_site+1
        EndDo
        x_fiber(i_site) = x_fiber(i_site-1) + x_comp2
        y_fiber(i_site) = y_fiber(i_site-1) + y_comp2
        i_site = i_site+1
        y_comp1 = -y_comp1
        y_comp2 = -y_comp2
      EndDo
.....

* Output the array.
      Write (*, '( " : (x-comp, y-comp)'))
      Do i_site = 1, n_fiber
        Write (*, '( " fiber # ', I2, ' : ( ', F6.4, ' ', ' ', F6.4, ' ')')
        & i_site, x_fiber(i_site), y_fiber(i_site)
      End Do
.....

* Do a few calculations inside the Monte Carlo loop.
      S_rad = Sqrt(z_max*z_max + y_max*y_max + x_max*x_max)
.....

* Get Monte Carlo parameters.
      Write (*, '( " '))
      Write (*, '( " Enter # of trial particles: ', I5)')

```



```

x1 = rho1 * sin(phi)

* .....
* ** the "source" is h_source above the cell.
* x0 = 0.
* y0 = y_max + h_source
* z0 = 0.

* .....
* ** Determine the intersection of this particle path with the cell.
* a = x1*x1 + y1*y1 + z1*z1
* b = 2* ( x0*x1 + y0*y1 + z0*z1 )
* c = x0*x0 + y0*y0 + z0*z0 - S_rad**2.
* t0 = (-b+sqrt(b*b-4*a*c)) / (2*a)
* t1 = (-b-sqrt(b*b-4*a*c)) / (2*a)
* xi0 = x0 + x1*t0
* yi0 = y0 + y1*t0
* zi0 = z0 + z1*t0
* xi1 = x0 + x1*t1
* yi1 = y0 + y1*t1
* zi1 = z0 + z1*t1
* .....

* .....
* ** Check to see if it's worth looping through n_fiber pts.
* flag_maybe_good = .true.
* If ( (xi0.GT.x_max) .and. (xi1.GT.x_max) ) flag_maybe_good = .false.
* If ( (xi0.LT.-x_max) .and. (xi1.LT.-x_max) ) flag_maybe_good = .false.
* If ( (yi0.GT.y_max) .and. (yi1.GT.y_max) ) flag_maybe_good = .false.
* If ( (yi0.LT.-y_max) .and. (yi1.LT.-y_max) ) flag_maybe_good = .false.
* If ( (zi0.GT.z_max) .and. (zi1.GT.z_max) ) flag_maybe_good = .false.
* If ( (zi0.LT.-z_max) .and. (zi1.LT.-z_max) ) flag_maybe_good = .false.
* .....

* .....
* ** Check to see if the path cuts through cell at all.
* If (flag_maybe_good) then
*   flag_maybe_good = .false.
*   t = (x_max-xi0)/x1
*   & If ( (abs(yi0+t*y1).LT.y_max) .and.
*   &   (abs(zi0+t*z1).LT.z_max) ) then
*     flag_maybe_good = .true.
*   End If
*   t = (-x_max-xi0)/x1
*   & If ( (abs(yi0+t*y1).LT.y_max) .and.
*   &   (abs(zi0+t*z1).LT.z_max) ) then
*     flag_maybe_good = .true.
*   End If
*   t = (y_max-yi0)/y1
*   & If ( (abs(xi0+t*x1).LT.x_max) .and.
*   &   (abs(zi0+t*z1).LT.z_max) ) then
*     flag_maybe_good = .true.
*   End If
*   t = (-y_max-yi0)/y1
*   & If ( (abs(xi0+t*x1).LT.x_max) .and.
*   &   (abs(zi0+t*z1).LT.z_max) ) then
*     flag_maybe_good = .true.
*   End If
*   t = (z_max-zi0)/z1
*   & If ( (abs(yi0+t*y1).LT.y_max) .and.

```

```

&          (abs(xi0+t*x1).LT.x_max) ) then
              flag_maybe_good = .true.
End If
t = (-z_max-z10)/z1
If ( (abs(yi0+t*y1).LT.y_max) .and.
&      (abs(xi0+t*x1).LT.x_max) ) then
              flag_maybe_good = .true.
End If
If (flag_maybe_good) n_pass_events = n_pass_events + 1
End If
*****

*
* *****
* ** Loop through n_fibers to calculate total path length.
* flag_good = .false.
* r_intersect = 0.
* If (flag_maybe_good) then
* Do i_fiber = 1, n_fiber
*
* * *****
* * *** Figure out the path length.
* * *** look at different cases.
* *
&      d0 = sqrt( (xi0-x_fiber(i_fiber))**2.
&      + (yi0-y_fiber(i_fiber))**2. )
&      d1 = sqrt( (xi1-x_fiber(i_fiber))**2.
&      + (yi1-y_fiber(i_fiber))**2. )

r_fiber_intersect = 0.
flag_fired(i_fiber) = .false.
If (d0.LE.rad_fiber) then

*
* * *****
* * **** The beginning of trajectory is inside a fiber.
* * flag_good = .true.

x_pos = x_fiber(i_fiber)/x_max * 38 + 39
y_pos = - y_fiber(i_fiber)/y_max * 10 + 11
i_stat = SMG$Put_Chars (disp_1,'*',y_pos,x_pos)
flag_fired(i_fiber) = .true.

a = (xi1-xi0)**2.+(yi1-yi0)**2.
b = 2*( (xi0-x_fiber(i_fiber))*(xi1-xi0)
&      + (yi0-y_fiber(i_fiber))*(yi1-yi0) )
&      c = (xi0-x_fiber(i_fiber))**2.
&      + (yi0-y_fiber(i_fiber))**2. - rad_fiber**2.
t = ( -b+sqrt(b*b-4*a*c) )/ (2*a)
If (t.GT.1.) then
&      r_fiber_intersect = sqrt( (xi1-xi0)**2.
&      + (yi1-yi0)**2.
&      + (zi1-zi0)**2. )
Else
xi2 = xi0 + (xi1-xi0)*t
yi2 = yi0 + (yi1-yi0)*t
zi2 = zi0 + (zi1-zi0)*t
&      r_fiber_intersect = sqrt( (xi2-xi0)**2.
&      + (yi2-yi0)**2.
&      + (zi2-zi0)**2. )
&
&
EndIf
*
* * *****

```

```

Else If (d1.LE.rad_fiber) then
*
*
*
*****
**** The end of trajectory is inside a fiber.
flag_good = .true.

x_pos = x_fiber(i_fiber)/x_max * 38 + 39
y_pos = - y_fiber(i_fiber)/y_max * 10 + 11
i_stat = SMG$Put_Chars (disp_1,'*',y_pos,x_pos)
flag_fired(i_fiber) = .true.

a = (xi1-xi0)**2.+(yi1-yi0)**2.
b = - 2.*( (xi0-x_fiber(i_fiber))*(xi1-xi0)
+ (yi0-y_fiber(i_fiber))*(yi1-yi0) )
c = (xi0-x_fiber(i_fiber))**2.
+ (yi0-y_fiber(i_fiber))**2. - rad_fiber**2.
t = ( -b+sqrt(b*b-4*a*c) )/ (2*a)
If (t.GT.1.) then
r_fiber_intersect = sqrt( (xi1-xi0)**2.
+ (yi1-yi0)**2.
+ (zi1-zi0)**2. )
Else
xi2 = xi1 - (xi1-xi0)*t
yi2 = yi1 - (yi1-yi0)*t
zi2 = zi1 - (zi1-zi0)*t
r_fiber_intersect = sqrt( (xi2-xi0)**2.
+ (yi2-yi0)**2.
+ (zi2-zi0)**2. )
EndIf
*****

Else
*
*
*
*****
**** The trajectory either goes through a fiber or
**** not at all.
t = ( (x_fiber(i_fiber)-xi0)*(xi1-xi0) +
(y_fiber(i_fiber)-yi0)*(yi1-yi0) )
/ ( (xi1-xi0)**2. + (yi1-yi0)**2. )
If ( (t.GE.0.) .AND. (t.LE.1.) ) then
*
*
*
***** trajectory might be inside this fiber
***** so figure out the intersection.
xm = xi0 + (xi1-xi0)*t
ym = yi0 + (yi1-yi0)*t
rho_m = sqrt( (x_fiber(i_fiber)-xm)**2.
+ (y_fiber(i_fiber)-ym)**2. )
If (rho_m.LE.rad_fiber) then
flag_good = .true.

x_pos = x_fiber(i_fiber)/x_max * 38 + 39
y_pos = - y_fiber(i_fiber)/y_max * 10 + 11
i_stat = SMG$Put_Chars (disp_1,'*',y_pos,x_pos)
flag_fired(i_fiber) = .true.

rho = 2.*sqrt
(rad_fiber**2.-rho_m**2.)
Else
rho = 0.

```

```

                                EndIf
                                *****

                                EndIf
                                r_fiber_intersect = rho * sqrt(1 + (zi1-zi0)**2./
                                &      ( (xi1-xi0)**2.+(yi1-yi0)**2. ) )
                                *****

                                EndIf
                                *****

                                r_intersect = r_intersect + r_fiber_intersect
                                End Do
                                End If
                                ** end of n_fibers loop.
                                *****

                                *****
                                * Keep up the accounting.
                                *
                                If (flag_good) then
                                    n_good = n_good + 1
                                    If (r_intersect.LE.r_min) then
                                        n_too_low = n_too_low + 1
                                    Else
                                        r_tot = r_tot + r_intersect
                                    End If
                                End If

                                *****

                                *****
                                ** Dump info about particle path. Clean up screen.
                                *
                                If (flag_display.and.flag_good) then
                                    Write (line,(' try #',I7,':('',
                                    &      F7.3,',',F7.3,',',F7.3,
                                    &      ') ~ ('',F7.3,',',F7.3,',',F7.3,') r=',F7.3,')
                                    &      i_try, xi0,yi0,zi0,xi1,yi1,zi1,r_intersect
                                    i_stat = SMG$Label_Border (disp_1,line)
                                    If (flag_wait) i_stat = SMG$Read_Keystroke (key_bd, ch_inp)
                                    Do i_site = 1, n_fiber
                                        If (flag_fired(i_site)) then
                                            x_pos = x_fiber(i_site)/x_max * 38 + 39
                                            y_pos = - y_fiber(i_site)/y_max * 10 + 11
                                            i_stat = SMG$Put_Chars (disp_1,.',',y_pos,x_pos)
                                        End If
                                    End Do
                                End If

                                *****

                                End Do
                                * end of monte carlo loop.
                                *****

                                Mean = r_tot/ ( N_good- n_too_low)

                                *****

                                * Write out the result
                                Write (*,(' '))
                                Write (*,(' Out of ',I7,' tries, ')') n_tries
                                Write (*,(' ',I7,' particles passed the cell,')')
                                &      n_pass_events
                                Write (*,(' and ',I7,' events were counted, ')') n_good

```

```

Write (*, '(' and ',17,' events were too low. ')') n_too_low
Write (*, '(' So, total # of good events = ',17)') n_good - n_too_low
Write (*, '(' The Mean Path Length is:',F10.6)') Mean
*****
* that's all, folks.
End

-----
Function rand(idum)
*
* Generate random numbers from 0 to 1
*
* Variable Declarations.
*

Dimension      v(97)
Data           iff /0/

*****
* Initialize the function.
If(idum.lt.0.OR.iff.eq.0) then
    iff=1
    iseed = Abs(idum)
    idum = 1
    Do J = 1, 97
        Dum = Ran(iseed)
    EndDo
    Do J = 1, 97
        V(J) = Ran(iseed)
    EndDo
    Y = Ran(iseed)
EndIf

*****

* Figure out the next random number.
J = 1 + Int(97. * Y)
If(J.gt.97.OR.J.lt.1) pause
Y = V(J)
Rand = Y
V(J) = Ran(iseed)

*****

* The end.
Return
End

```

END

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