Effects of a Hadron Irradiation on Scintillating Fibers*

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Abstract

Trackers based on scintillating-fiber technology are being considered by the Solenoidal Detector Collaboration at SSC and the DØ collaboration at Fermilab. An important issue is the effect of the radiation existing in the detector cores on fiber properties. Most studies of radiation damage in scintillators have irradiated small bulk samples rather than fibers, and have used X-rays, ^{60}Co gammas, or electron beams, often at accelerated rates.

We have irradiated some 600 fibers in the Fermilab Tevatron CØ area, thereby obtaining a hadronic irradiation at realistic rates. Four-meter-long samples of ten Bicron polystyrene-based fiber types, maintained in air, dry nitrogen, argon, and vacuum atmospheres within stainless-steel tubes, were irradiated for seven weeks at various distances from the accelerator beam pipes. Maximum doses, measured by thermoluminescence detectors, were about 80 Krad.

Fiber properties, particularly light yield and attenuation length, have been measured over a one-year period. A description of the work together with the results is presented. At the doses achieved, corresponding to a few years of actual fiber-tracking detector operation, little degradation is observed. In addition, recovery after several days' exposure to air has been noted. Properties of unirradiated samples kept in darkness show no changes after one year.

I. INTRODUCTION

Scintillating-fiber technology possesses great potential for use in charged-particle tracking systems in detectors at the new generation of accelerators. For example, a system employing 473 K fibers of 925-μm-dia. and 4.3 m maximum length is one of the central-tracking options for the Solenoidal Detector Collaboration (SDC) at the Superconducting Super Collider [1]. A smaller-scale system, using 10.3 K fibers of 870-μm-dia. with a maximum length of 1.8 m, is planned for the Fermilab DØ upgrade [2]. An important aspect of the development work is to insure that the fibers will operate satisfactorily in the radiation environment existing in the detector cores.

Considerable work has been done studying the effects of radiation on plastic scintillator [3]. Such studies are difficult, partly because of the many variables involved, and not all studies are directly applicable to scintillating fibers. For example, the surrounding atmosphere plays an important role, both in the damage produced [4] and in subsequent recovery [5]. However, many experiments have employed small bulk samples for which oxygen diffusion is very different than for

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fibers. Also, irradiation rate may be important, in addition to total dose received [6]. However, tests often employ rates orders of magnitude larger than actually experienced in order to compress many years of detector operation into manageable time intervals. In addition, most irradiations have been performed with X-rays, gammas from ^{60}Co, or electron beams, while hadrons constitute a large fraction of the flux in tracking detectors.

As part of a program to develop a scintillating-fiber tracking system for SDC and DØ, we have attempted to investigate some of these issues. We have exposed samples of ten different polystyrene-core fiber types for seven weeks in the Fermilab CØ area, thereby obtaining a hadronic irradiation at reasonably realistic rates. The fibers were maintained in atmospheres of air, dry nitrogen, argon, and vacuum. The large number of fibers -- almost 600 were irradiated -- was due to the fact that this was the last opportunity for several years. A change from the fixed-target to the collider mode was impending for the accelerator, and the flux in CØ is quite small in the latter mode.

Practical considerations, including time pressures, recovery effects that occur during exposure to air, and difficulties during the initial measurements, restricted measurements to about 100 individual fibers of the almost 800 involved. Thus, not all data for all fiber types, for all atmospheres, and for all irradiation levels are available. This report describes the work and presents results, with emphasis on fibers doped with p-terphenyl (pT) plus 3-hydroxyflavone (3HF), the current candidates for the SDC and DØ trackers.

II. FIBERS AND IRRADIATION

A. Fibers

The scintillating fibers tested were produced by Bicron Corp. [7] and are listed in Table I. They have an outside diameter of 830 μm and consist of a doped polystyrene core surrounded by a 15-μm-thick acrylic cladding. Types BI-1 and BI-7, BI-2 and BI-5, and BI-4 and BI-6 have the same compositions, respectively. However, because of the fiber-making procedure, the one with the higher number in each pair was expected to have a better core-cladding interface.

To simulate SDC conditions, the fibers were cut to 4.1 m lengths. After cleaning with ethyl alcohol, twenty bundles were formed consisting of four samples of each of types BI-1 through BI-8 and three samples (because of limited availability) of each of types BCF-9905 and BCF-10. To measure the received radiation dose, Solon Technologies thermoluminescence detectors (TLDs) type TLD-400 [8] were attached to the 15 bundles to be irradiated. The remaining five bundles were not irradiated and served as controls. In preparing the samples for irradiation and also in subsequent measurements, care was taken to minimize exposure to light.

Each of the twenty bundles was placed into a stainless-steel irradiation container 1 inch in diameter (0.065-in. wall thickness) and 4.4 m long. These containers allowed the fibers to be irradiated -- and the controls to be stored -- in selected atmospheres. The atmospheres used were ambient air at atmospheric pressure; dry air, dry nitrogen, and argon, each at 15 psig; and vacuum (about 0.2 torr). Unfortunately, safety issues precluded the use of oxygen. Every bundle/container was outgassed by pumping for 12 hrs to about 0.2 torr, filling with dry N_2 at 20 psig for 1 hr, and then repeating the pumping before being filled with its final atmosphere. Four containers were filled with each of the five atmospheres employed; of these, three were irradiated and one served to store the control fibers.

Table I

Bicron fibers irradiated in this test. Abbreviations: pT = p-terphenyl; BBOT = thiophene derivative; 3HF = 3-hydroxyflavone; BBQ = isoquinoline derivative; BPBD = oxadiazole derivative; DMPOPOP = phenyloxazol derivative.

Fiber Type	Color	Dopants
BI-1	blue	pT + BBOT
BI-2	green	pT + BBQ
BI-3	green	0.6% 3HF
BI-4	green	pT + 3HF
BI-5	green	pT + BBQ
BI-6	green	pT + 3HF
BI-7	blue	pT + BBOT
BI-8	green	BPBD + BBQ
BCF-9905	green	pT + 3HF
BCF-10	blue	pT + DMPOPOP

B. Irradiation

The fibers were irradiated in the CØ area of the Fermilab Tevatron, which was operating in the fixed-target mode. This area contains the Main Ring, the Tevatron Ring, and their abort tubes. The region is filled with a hadronic flux resulting from beam losses during injection and ramping, and from aborts.

The twenty filled irradiation containers were divided into four sets, a set consisting of one container of each of the five atmospheres used. One set was put aside to serve as controls. During the accelerator shutdown on 20 Nov. 1991, one of the remaining three sets was placed on each of three platforms of a rack constructed to hold the containers during irradiation. The platforms were spaced to provide three different irradiation rates, denoted by "high", "medium", and "low", with the containers oriented parallel to the accelerator pipes here running in a north-south direction. The containers remained in place until the end of the accelerator running period, an interval of 49 days.

While the CØ area provides a hadronic flux at realistic rates, neither the total dose nor the dose profile can be controlled. The total doses, measured to about $\pm$ 10% by the TLDs within the irradiation containers, were found to be significantly less than expected on the basis of data from previous irradiations [9]. Furthermore, there was considerable nonuniformity along the fiber lengths, as shown in Fig. 1. Unfortunately, these features were not known until late in the fiber measuring program. While peak doses were about 80 Krad, the average values were 36 Krad in the "high" region, 24 Krad in the "medium" region, and 4 Krad in the "low" region. These correspond to rates of 31 rad/hr, 21 rad/hr, and 3 rad/hr, respectively.

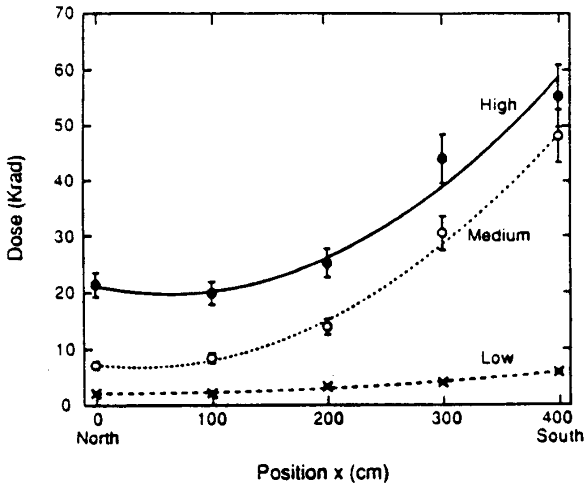

Fig. 1. Dose profiles for fibers irradiated in ambient air, showing the typical non-uniformities found at the three different irradiation levels.

For comparison, with the SSC operating at the design luminosity of 10^{33} $cm^{-2}s^{-1}$ the dose accumulated in one year at a distance $r_\perp$ (in cm) from the beam pipe is expected to be $D = 4x10^4$ $Krad/r_\perp^2$ [10]. Albedo neutrons, secondaries, and multiple hits from spiraling charged particles are not included. Introducing a factor of two for these effects, the anticipated annual dose at the 65.2-cm inner radius of the proposed SDC fiber tracker is 19 Krad accumulated at a rate of 2.2 rad/hr. Hence, the average doses received by fibers in the "high", "medium", and "low" regions correspond to 1.9 yr, 1.3 yr, and 0.2 yr, respectively, of SSC operation. The corresponding rates are 14, 9.5, and 1.4 times as great as at the SSC.

The radiation environment at the upgraded DØ detector is less severe. At a luminosity of $6x10^{31}$ $cm^{-2}s^{-1}$, the anticipated yearly dose is $D = 1.8x10^3$ $Krad/r_\perp^2$ [11], which includes a factor of 3 for spiraling particles, secondaries, and neutrons. The innermost fibers of the planned tracker are at $r_\perp = 12.5$ cm, and so will be subject to an annual dose of 12 Krad at a rate of 1.3 rad/hr. The "high", "medium", and "low" doses received by the irradiated fibers thus correspond to 3.0 yr, 2.0 yr, and 0.3 yr, respectively, at DØ; the dose rates are 24, 16, and 2.3 times as great as expected in operation.

While the irradiations achieved in this exposure occurred at reasonably realistic rates and correspond to a few years of actual fiber-tracking detector operation, little damage is expected for total doses below a few hundred Krad [12].

III. MEASUREMENTS

A. Preliminaries

Radiation can affect the operation of scintillating fibers by reducing scintillation efficiency via damage to the core base and dopants, and by reducing light transmission via increased core absorption and damage to the core-cladding interface. Untangling these effects depends on what fiber properties are investigated, and these in turn are defined by measurement and analysis procedures. It should also be noted that the effects are generally wavelength-dependent, so the spectral characteristics of the photodetector used greatly influence the results.

All irradiation containers were removed from CØ within two hours after accelerator shutdown. To reduce recovery effects, the six containers containing air atmospheres were evacuated and then filled with dry N_2 at 15 psig; all other fibers were left in their original atmospheres. Measurements began several hours after accelerator shutdown. To minimize exposure to oxygen, only two fibers were removed from a container at a time for measurement, and they were replaced as soon as measurements were completed. The containers were pumped down and refilled after each opening.

Just before measurement, one end of each fiber studied was fixed with 5-minute epoxy into a 1-inch-long aluminum ferrule. After the epoxy set, the protruding fiber end was cut flush with the ferrule with a razor blade and the surface polished with fine emery cloth. The ferrules served to couple the fibers to the photodetectors and also to remove the light traveling in the cladding. Care was taken to keep both exposure to light and time in air short.

Practical considerations limited the number of fibers that could be studied. The measurement philosophy was to emphasize fibers doped with pT+3HF, and to begin by looking for maximum and minimum effects by measuring fibers irradiated to "high" and "low" doses in N_2, Ar and air. (The actual doses, obtained from TLD readings, were not known for quite some time.) Furthermore, the BCF-10 fiber was badly crazed, so few samples were measured. As described below, the changes in fiber parameters were found to be fairly small, and so measurements concentrated on fibers irradiated at the "high" rate. In addition, samples of control fibers were measured several times during the 1-year interval since this test began.

B. Light yield

Light yield was measured by coupling the ferrule end of a fiber to the face of a Hamamatsu R2165-01 photomultiplier using optical grease and exciting the fiber with a collimated 25 μCi ^{207}Bi source a distance of 10 cm from the PMT face. Initially, the tube was operated with its cathode at negative high voltage, but experience showed that less noise and more consistent results were obtained with the cathode at ground potential and the anode at positive high voltage. The tube's quantum efficiency peaks near 350 nm, and decreases by about a factor of two between the blue and green.

The photomultiplier output was connected directly to a LeCroy Model 3001 qVt multichannel analyzer [13] operated in the charge mode and self gated. As shown in the pulse-height spectrum of Fig. 2, the tube is capable of resolving individual photoelectrons. To determine light yield, the spectra were fit with the sum of a decreasing exponential, re-

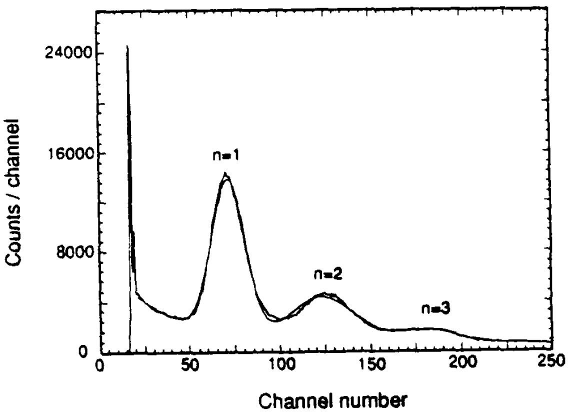

Fig. 2. Typical pulse-height spectrum from an irradiated BI-4 fiber. The smooth curve is a fit using the sum of a decreasing exponential background and three gaussians.

presenting background, and three gaussians for the photopeaks. The area of each peak was assumed to be proportional to the corresponding number of photoelectrons. As is well known, the average value $\bar{n}$ of a Poisson distribution is given by $\bar{n} = (n+1)P_{n+1}/P_n$, where P_n is the probability of observing n events. Although the spectrum from a round fiber is not expected to be Poisson in shape [14], the ratio of adjacent photopeak areas should nevertheless be a measure of the average number of photoelectrons. In what follows, the light yield of a fiber is taken to be proportional to the ratio of the third to second photopeak areas after correction for the photomultiplier quantum efficiency at the fiber's wavelength.

The results for the most interesting cases, normalized to the unirradiated BI-6 output defined as 1.00, are shown in Table II. Yields for irradiated samples are given as percentage changes relative to the corresponding control fibers. For these measurements, the light yields are affected by the total doses at the *detector ends* of the fibers; the doses at the far ends are included for reference. The uncertainties are due to measurement procedures and sample-to-sample variations, and are estimated to be about ±15%. The largest contribution resulted from fiber-to-fiber differences in the surface finish after the ferrule ends were polished with fine emery cloth, as described in Section IIIA. (This effect was later greatly reduced by using acrylic ferrules.)

The light-yield changes relative to their unirradiated values are mostly within the measurement uncertainty, so it appears that little if any changes have occurred. This is not surprising for the total doses experienced here.

C. Attenuation length

Attenuation lengths were measured by exciting the fibers at 10 cm intervals with ultraviolet light from an Oriel Model 6035 Hg(Ar) pencil lamp [15]. Light output was detected by coupling the ferrule ends of the fibers with optical grease to a UDT Instruments Model 221 silicon photodiode [16]. The detector's response is relatively flat in the region of interest, increasing only 15% between the blue and green. Thus, no wavelength corrections were applied. The detector current was measured by a Keithley Model 485 picoammeter [17] whose analog output was digitized.

The results of a typical measurement are shown in Fig. 3. The curve displays the familiar shape which is usually fit by the sum of two decreasing exponentials,

$$I(x) = I_1 e^{-x/\lambda_1} + I_2 e^{-x/\lambda_2} . \quad (1)$$

The steeper slope at small distances from the detector, corresponding to λ_1, is predominantly due to preferential absorption of the shorter-wavelength components, to off-axis rays, and partly to cladding light; however, most of the light traveling in the cladding is eliminated by the ferrule. The smaller slope at larger distances, corresponding to λ_2, represents absorption in the fiber core. We have determined λ_2 by fitting Eq. (1) to the data over the entire fiber length, but have found that fitting a single exponential to the data for $x \geq 1$ m yields more reliable results. This latter method is used in what follows.

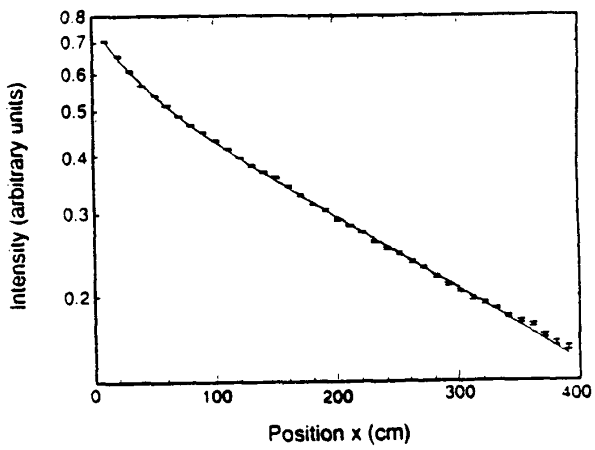

Fig. 3. Typical photodetector output from an unirradiated BI-6 fiber excited by uv light. The smooth curve is a fit using the sum of two decreasing exponentials.

Table II. Light yields before and after irradiation, relative to unirradiated BI-6 output defined to be 1.00. Yields for irradiated fibers are given as percentage changes with respect to values of the unirradiated controls.

Fiber Type	Unirradiated Control Fibers	Irradiated Fibers Percentage Change of Light Yield Relative to Control		
	Relative Light Yield	Atm : N_2 Rate: High Detector-end Dose: 18 Krad Far-end Dose: 61 Krad	Atm : Ar Rate: High Detector-end Dose: 68 Krad Far-end Dose: 27 Krad	Atm : Ambient Air Rate: High Detector-end Dose: 55 Krad Far-end Dose: 20 Krad
BI-1	0.61 ± 0.1			
BI-2	0.89 ± 0.1			
BI-3	0.93 ± 0.2		-8	-20
BI-4	0.95 ± 0.1	-1	-10	
BI-5	0.81 ± 0.1	-3	+15	+10
BI-6	1.00		-10	+4
BI-7	0.76 ± 0.1	+3	-4	-2
BI-8	0.88 ± 0.1	-3	-4	-12
BCF-9905	1.05 ± 0.1	0	-8	+5
BCF-10	0.91 ± 0.1			

The results for the most interesting cases are shown in Table III. Values of the core attenuation lengths are presented for the unirradiated control samples; the values after irradiation are indicated as percentage changes relative to the controls. As stated in Section IIB, the doses were nonuniform along the fiber lengths, a feature not known until the measurements were well underway. Because of the nonuniformity, the value of the core attenuation length obtained depends on which end of the fiber is coupled to the photodetector, so this is indicated in the table.

This effect may be understood by noting that the measured attenuation length is determined predominantly by the distant fiber region, while the region near the detector acts basically as a constant light attenuator. Thus, fibers whose far ends have experienced more damage than their detector ends will yield smaller values of λ_2 than fibers where the reverse is true. We have investigated this effect by measuring fibers from both ends, and have developed procedures, described elsewhere [18], for extracting more information from such data.

The uncertainties in the attenuation-length changes in Table III are estimated to be about $\pm 3\%$. The uncertainties in the values for the control samples are smaller, probably because these remained stable while the irradiated samples were recovering while measurements were being made (see Section IIID). Attenuation-length measurements are relatively insensitive to light amplitude, and the amount of light reaching the photodetector is much greater for ultraviolet excitation than for excitation with ^{207}Bi. Thus, in contrast to the light-yield measurements, variations in the surface condition of the polished ferrule ends did not affect the results. Table III shows that, for the conditions of this test, attenuation lengths shortly after irradiation decreased but little. This is not surprising for the total doses experienced here.

As mentioned, the values listed in Table III represent the first measurements after irradiation, and involve fiber exposures to air for about 2½ hrs. During exposure to air recovery occurs fairly quickly, and the tabulated changes are probably smaller than the decreases immediately after irradiation. This issue is discussed in the next section.

Table III. Core attenuation lengths before and after irradiation. Values for irradiated fibers are given as percentage changes with respect to values of the unirradiated controls.

Fiber Type	Unirradiated Control Fibers λ_2 (cm)	Irradiated Fibers Percentage Change of λ_2 Relative to Control: Atm : N_2 Rate: High Detector-end Dose: 18 Krad Far-end Dose: 61 Krad	Atm : Ar Rate: High Detector-end Dose: 68 Krad Far-end Dose: 27 Krad	Atm : Ambient Air Rate: High Detector-end Dose: 55 Krad Far-end Dose: 20 Krad
BI-1	148 ± 2			
BI-2	165 ± 2			
BI-3	188 ± 3	-14	-11	-12
BI-4	299 ± 3	-9	-4	
BI-5	179 ± 3	-10	-10	-6
BI-6	285 ± 3	-11	-5	-1
BI-7	152 ± 2	-8	0	-10
BI-8	159 ± 2	-2	-2	-4
BCF-9905	288 ± 4	-9		-8
BCF-10	217 ± 3			

D. Recovery

Previous work has shown that damaged plastic scintillator exhibits recovery effects after irradiation [5]. While some recovery has been observed in argon and nitrogen, it occurs more rapidly in air -- and even more so in oxygen -- atmospheres. This latter effect is attributed to diffusion of oxygen which combines with the radicals formed during irradiation. Because of their geometry, fibers recover more quickly than bulk samples.

Recovery effects were observed in our measurements. Because of the small damage experienced at these doses relative to the measurement uncertainties, little evidence is seen in the light-yield data. However, recovery after exposure to air is evident in measurements of attenuation lengths. An example for a BI-6 fiber irradiated in nitrogen at the "high" rate (18 Krad at the detector end and 61 Krad at the far end) is shown in Fig. 4.

The recovery of the core attenuation length λ_2 with time for a similarly irradiated BI-4 fiber is shown in Fig. 5. The recovery is well described by the form

$$\lambda_2(t) = \lambda_2^o - (\lambda_2^o - \lambda_2^{irr})\, e^{-t/\tau},$$

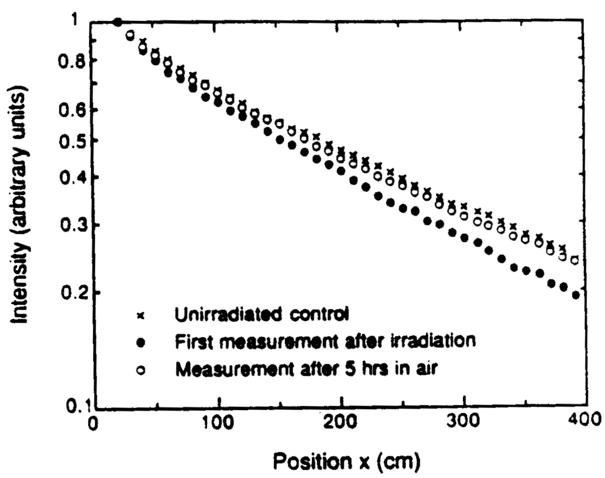

Fig. 4. Recovery in air for a BI-6 fiber irradiated in nitrogen. The dose varied from 18 Krad at the detector end to 61 Krad at the far end. The data are normalized at x = 22 cm.

where λ_2° is the value for the unirradiated fiber, λ_2^{irr} is the value immediately after irradiation, and τ is the characteristic recovery time. For the fiber in question, τ is about 20 hrs.

As mentioned, the initial preparation and first measurement of each fiber took about 2½ hrs, during which recovery was occurring. Thus, the relative decreases in core attenuation length, $(\lambda_2^{\circ} - \lambda_2^{irr})/\lambda_2^{\circ}$, given in Table III are probably smaller than the actual values immediately after irradiation.

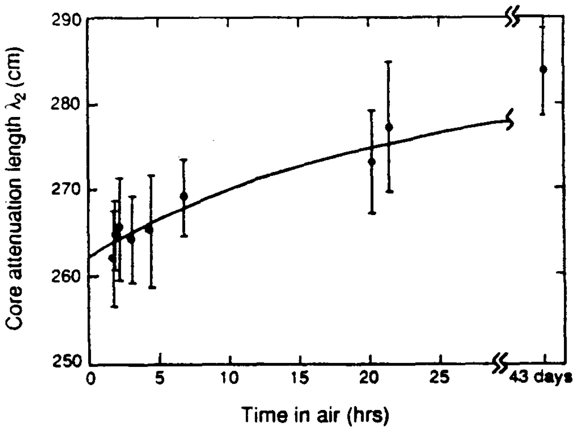

Fig. 5. Recovery of attenuation length of a BI-4 fiber irradiated in nitrogen as a function of time in air. The curve is a fitted exponential function.

IV. SUMMARY

In a recent test, samples of 10 different Bicron polystyrene-based fibers were irradiated by hadrons at realistic rates. The fibers were maintained in atmospheres of air, dry nitrogen, argon, and vacuum, and were irradiated for 7 weeks. Maximum doses achieved were about 80 Krad. Fiber properties, particularly light yield and core attenuation length, were measured over the one-year period since the end of the irradiation.

Our emphasis has been on fibers doped with pT+3HF, the current candidates for the SDC and DØ trackers. The properties of the three such fiber types studied (BI-4, BI-6, BCF-9905) were found to be essentially the same. Within measurement uncertainties, they have the same light yield and attenuation length, the latter averaging (291 ± 3) cm before irradiation. The BI-3 fiber, doped only with 0.6% 3HF, has almost the same light yield but a smaller attenuation length of (188 ± 2) cm, presumably because of increased self-absorption.

The attenuation lengths of unirradiated control samples kept in darkness have remained unchanged over more than one year. Because of initial large uncertainties and subsequent apparatus improvements, it is not possible to compare light yields after one year to the initial values; however, we expect that no changes have occurred for the control samples.

At the radiation doses achieved in CØ, corresponding to a few years of actual fiber-tracking detector operation, changes in light yield were mostly less than the $\pm 15\%$ initial measurement uncertainty, and core attenuation lengths measured soon after the end of the irradiation decreased by about 10%. These relatively small changes are consistent with other measurements showing little damage for doses less than a few hundred Krad. No effects specifically attributable to hadrons as irradiating particles have been noted.

The pT+3HF fibers were found to recover after exposure to air, the characteristic time being about one day. Although we have not made a consistent study, this feature is presumably due to the low doses encountered and the large surface-area-to-volume ratio inherent to fibers, and so is probably common to all our fiber types.

Clearly, additional studies involving higher total doses -- and, of necessity, higher dose rates -- are required. Such a program, employing irradiation by 6 MeV X-rays, and possibly 24 MeV electrons, from radiation therapy machines at the University of Illinois Hospital, will begin soon.

V. ACKNOWLEDGEMENTS

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