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Effects of light on scintillating fibers

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ABSTRACT

Tracking detectors based on scintillating-fiber technology are being developed for the Solenoidal Detector Collaboration at the Superconducting Super Collider and for the DØ collaboration at Fermilab. An important part of the work is to insure that the fibers will not be damaged by environmental conditions in the course of detector construction.

This paper presents preliminary results of the effects of ambient fluorescent light on scintillating fibers containing 3-hydroxyflavone (3HF) waveshifter. Six fiber types having 3HF concentrations between 100 ppm and 6000 ppm were studied; both single-clad fibers from Bicron and Kuraray and a new Kuraray multiclad fiber were included. A blue fiber containing no 3HF was used to provide a comparison.

Investigations consisted of exposing fiber samples to ambient fluorescent light, at about half normal table-level illuminance, for various times, and measuring the resulting changes in fiber effective light yields and attenuation lengths. All 3HF fibers exhibited the same basic behavior: no changes were observed in light yields, but attenuation lengths decreased noticeably during exposure and then recovered when the fibers were kept dark. Recovery was almost total in about 10 days after exposures less than about 5 hrs, but larger exposures produced permanent damage. The decrease in attenuation length immediately after exposure seems to be related to the logarithm of the 3HF concentration. In contrast, the blue fiber showed no changes in characteristics even after a 139-hr exposure. Damage to the 3HF fibers could be prevented, even at high illuminance, by covering the fluorescent lamps with an orange filter which transmits only wavelengths greater than 520 nm.

In the course of measurements, it was observed that fibers phosphoresce following exposure to room light. The photon emission has a short-term component of a few minutes, and a longer-term component of a few hours.

1. INTRODUCTION

Scintillating-fiber technology shows great promise for charged-particle tracking systems for use in both collider detectors and in fixed-target experiments. Among the systems under development are central trackers for the Solenoidal Detector Collaboration (SDC) at the Superconducting Super Collider[1] and for the DØ Collaboration at Fermilab.[2] Scintillating-fiber tracking is also under consideration for fixed-target experiments.[3] An important aspect of the development work is to insure that the fibers will not be damaged by environmental conditions in the course of detector construction, and that they will operate satisfactorily in the anticipated detector radiation flux.

Investigation of these questions is part of the program of the Fiber Tracking Group (FTG), a collaboration of twelve institutions working to develop the SDC and DØ trackers.[4] While results of FTG radiation studies have been reported,[5,6] this paper is the first presentation of continuing investigations of environmental effects. Specifically, this work presents preliminary results of the effects of ambient fluorescent light on scintillating fibers containing 3-hydroxyflavone waveshifter. While this waveshifter is known to be photosensitive, and anecdotes exist -- about fibers that somehow deteriorated and then mysteriously recovered after being carried in a briefcase for a few days -- this is, to our knowledge, the first systematic investigation of this effect.

2. FIBERS AND MEASUREMENTS

2.1. Fibers

Because of their superior radiation resistance, scintillating fibers doped with p-terphenyl (pT) plus 3-hydroxyflavone (3HF) waveshifters are of primary interest for the SDC and DØ trackers. Consequently, such fibers were emphasized in this investigation. Both single-clad fibers from Bicron[7] and Kuraray[8] and a new Kuraray multiclad fiber were studied. The single-clad fibers have a doped polystyrene core enclosed in an acrylic cladding. The multiclad fiber has an outer fluorinated-polymer cladding over an inner acrylic cladding. This construction produces a larger light-capture cone and so a brighter fiber.[6,9] All scintillating fibers studied have an outer diameter of 835 μm. A list of the fibers is given in Table I; one blue fiber (containing no 3HF) was studied to provide a comparison.

Table I. Scintillating fibers studied. The Bicron BI-7 fiber (blue), doped with BBOT (no 3HF), was used to provide a comparison.

Fiber type		Dye concentration	
		pT (%)	3HF (ppm)
Bicron single-clad	BI-3	0	6000
	BI-6	1	100
	BI-12	1	100
	BI-14	1	500
Kuraray single-clad		~1	1000
Kuraray multiclad		~1	1500
Bicron single-clad	BI-7 (blue)	1	BBOT

Four-meter-long samples of fiber were used. Both ends of every fiber were fixed with 5-minute epoxy into 1-in.-long black Noryl[10] ferrules. After the epoxy set, the protruding fiber ends were cut flush with the ferrules with a razor blade and the surfaces polished with fine emery paper. The ferrules served to couple the fibers to the photodetectors and to remove light traveling in the cladding. Fibers were stored in the dark, and except for deliberate exposure to light all work was performed with fluorescent lamps covered with Kodak type 0302 orange filters transmitting only wavelengths greater than 520 nm.[11]

2.2. Fiber characteristics

The fiber properties studied were effective light yield and attenuation length. In a simple model, the light intensity reaching a photodetector attached to one end of a scintillating fiber excited a distance x away is given by

$$I(x) = I_0 \exp(-x/\lambda) \quad . \tag{1}$$

Here, I_0 is related to the effective light yield and λ is the attenuation length. Environmental damage to a fiber can result in a decrease in either of these properties.

Fiber characteristics before and after exposure to light were studied using a test facility employing a 5.1-m-long dark box and the systems described below. Data taking was controlled by a PC which also performed the analysis.

2.3. Effective light yield

Effective light yields were measured by coupling the desired ferrule-terminated end of a fiber to the face of a Hamamatsu R2165-01 photomultiplier tube[12] using optical grease, and exciting the fiber with conversion electrons from a 54 μCi ^{207}Bi source a distance of 10 cm from the PMT face. The tube's quantum efficiency peaks near 350 nm and decreases by a factor of two between the blue and green.

The PMT 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. 1, the tube is capable of resolving individual photoelectrons. Effective light yield was determined from an estimate of the average number of photoelectrons detected. As is well known, the average value, $\bar{n}$, for 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 Poisson in shape,[14] the ratio of adjacent photopeak areas should nevertheless be a measure of the average number of photoelectrons. The light yield of a fiber was usually taken to be proportional to the ratio of the second to the first photopeak areas.

2.4. Attenuation length

Attenuation lengths were measured by exciting fibers at 10-cm intervals with ultraviolet (uv) light from an Oriel Model 6035 Hg(Ar) pencil lamp.[15] Because uv light produces damage, the lamp output was collimated to a very thin line. Fiber light output was detected by coupling one fiber end to a Graseby Optronics Model 221 silicon photodiode.[16] This detector's spectral response increases by about 15% from the blue to the green. The photodiode current was measured by a Keithley Model 485/4853 autoranging picoammeter having a GPIB interface.[17] A typical result of such a measurement is shown in Fig. 2. Attenuation lengths were determined by fitting Eq. (1) to the data for $x \geq 100$ cm.

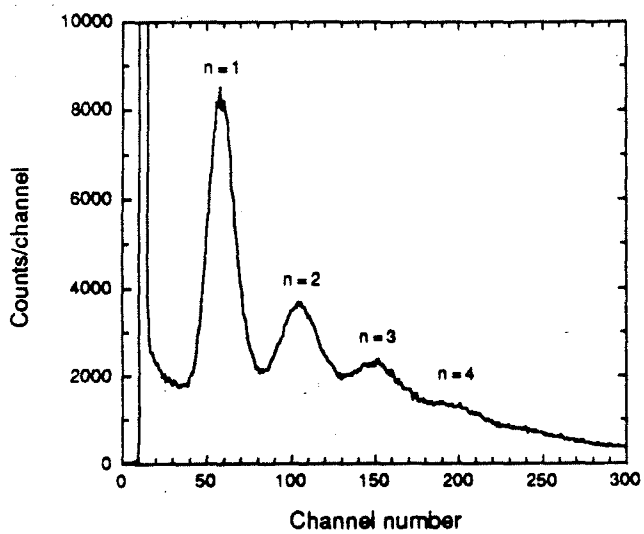

Fig. 1. Typical pulse-height spectrum obtained in effective light yield measurements. The data shown are from an unexposed Kuraray multiclad scintillating fiber excited by conversion electrons from ^{207}Bi.

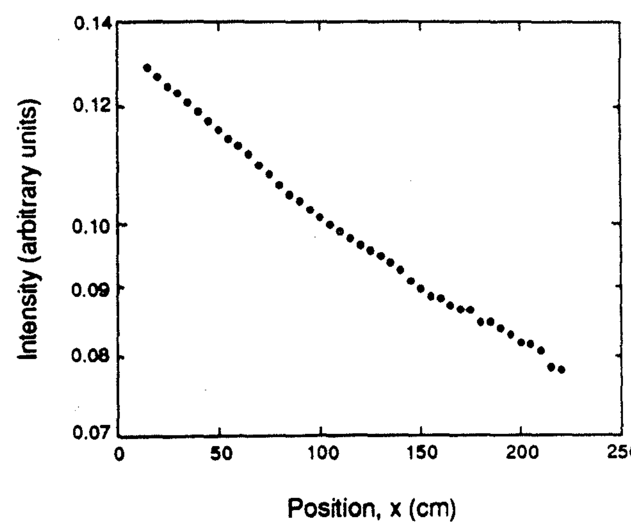

Fig. 2. Typical photodiode output obtained in attenuation length measurements. The data shown are from an unexposed Kuraray multiclad scintillating fiber excited by uv light at 10-cm intervals.

Because of concern that repeated scans with the uv lamp might cause damage, initial attenuation length measurements were made using electron excitation from ^{207}Bi. These measurements took considerably longer, since counting for at least five minutes was required at each position along a fiber's length to obtain statistically significant results. It should be mentioned that attenuation lengths measured in this way tend to be somewhat longer than those measured with uv excitation. This may be due to the light generated by penetrating electrons and that generated by incident uv having somewhat different spatial distributions and ray propagation modes in a fiber.

To justify the faster measurements afforded by uv excitation, a test of possible damage was performed by subjecting a BI-14 fiber to 200 consecutive uv scans, each taking a total of about 4 minutes. At the 1% level, no changes in attenuation length were observed. Thus, this technique was employed for most of the measurements. On the other hand, extended illumination by the bare Hg(Ar) lamp caused significant damage. Figure 3 shows the results after a 6-hr exposure of a 5-cm-long segment of a Kuraray single-clad fiber. The damage is evident, as is partial recovery after storing the fiber in the dark for some time. Spectroscopic examination of the light exiting the damaged fiber showed, as expected, greater reduction of the blue portion of the spectrum than of the green. The BI-7 blue fiber was found to suffer less damage when exposed to uv light.

3. EFFECTS OF LIGHT

To establish baseline values, both light yield and attenuation length were measured for each fiber type. One fiber at a time was then exposed to ambient room light after having been mounted in the measuring apparatus using filtered illumination, as mentioned previously. With the four dark-box doors (located along one vertical side of the box) fully open, the filtered lamps were turned off and the normal room fluorescent lights -- four rows, with four fixtures each, oriented at right angles to the dark box -- were turned on. Each fixture contains four 40 W, 4-ft.-long, Cool White tubes covered by a thin solid plastic diffuser. The spectral distribution of the ambient room light is shown in Fig. 4; also shown is the spectrum when the orange filter is employed.

The spectrally integrated illuminance incident on a fiber mounted in the dark box was measured using a CdS photocell. The variation with position is shown in Fig. 5. The three dips are shadows from three vertical supports between the four open doors. The average illuminance is about 850 lux (1 lux = 1 lumen/m^2), roughly half that at table level in the room.

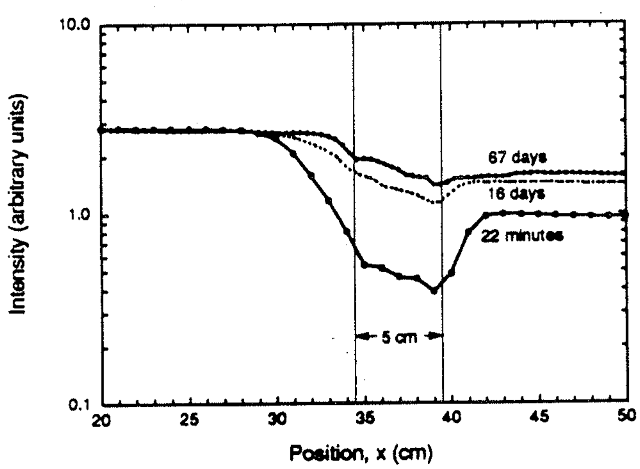

Fig. 3. Damage and subsequent recovery caused by intense uv illumination of a 5-cm-long segment of a Kuraray single-clad fiber. The measurements were made 22 minutes, 16 days, and 67 days after the exposure, with the fiber kept in the dark during recovery.

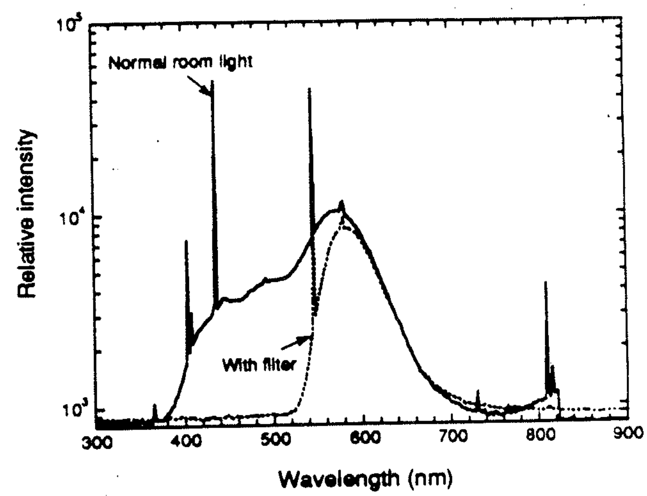

Fig. 4. Spectral distribution of ambient light from room fluorescent lamp fixtures. The distribution when a lamp is covered with an orange filter is also shown. The normalization between the amplitudes of the two spectra is arbitrary.

Since the fiber under test was already mounted in the apparatus, interim measurements could be made during the light exposure by simply closing the dark box doors for a few minutes. Also, measurements could begin immediately after the exposure, and the time dependence of the subsequent recovery in the dark could be observed.

All fibers containing 3HF exhibited the same basic behavior after exposure to room light. No changes (within the estimated ± 5% measurement uncertainties) were observed in light yields. Attenuation lengths, on the other hand, decreased noticeably during exposure, and then recovered when the fibers were kept in the dark. Recovery was virtually total for exposures less than about 5 hours; longer exposures resulted in permanent damage. The former effect is illustrated in Fig. 6, which shows the time dependence of the attenuation lengths of Kuraray single-clad and multiclad fibers following a 2-hr exposure to ambient light. The initial attenuation-length decrease, about 5% for both fibers, is fully recovered after keeping the fibers in the dark for some 10 days. The largest decrease after a 2-hr exposure was exhibited by the BI-3 fiber, which has the largest 3HF concentration. The effect of longer exposures is demonstrated by Fig. 7. The data show the decrease in the attenuation length of a Kuraray single-clad fiber during a 137-hr light exposure and the subsequent partial recovery. The initial decrease is 50%; the permanent change after some 100 days in the dark is 38%.

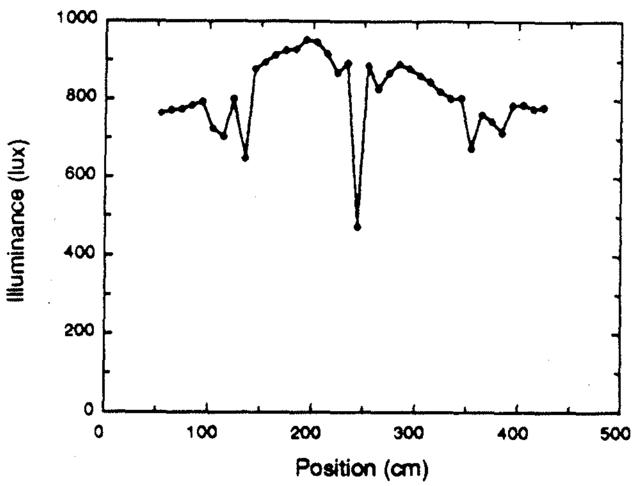

Fig. 5. Variation of ambient light illuminance along the length of a fiber mounted in the dark box. The three dips are shadows from three vertical supports between the four open doors.

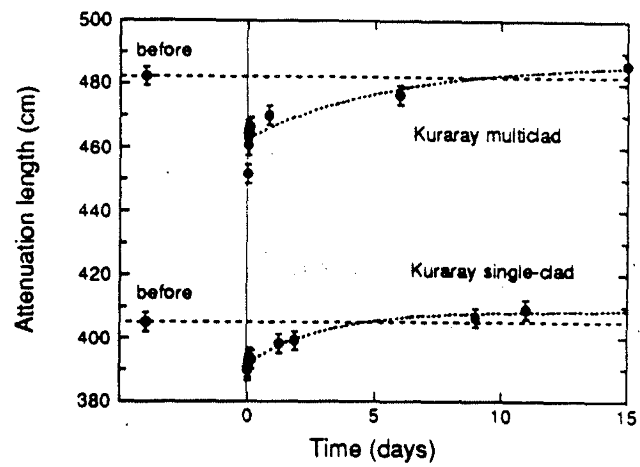

Fig. 6. Attenuation lengths of Kuraray single-clad and multiclad fibers before and after a 2-hr exposure to ambient light. Recovery is complete after the fibers are kept dark for about 10 days. A smooth curve has been drawn through the data points. (The advantageously larger attenuation length of the multiclad fiber is evident.)

In contrast to these results, no changes were observed in either the light yield or the attenuation length of the blue BI-7 fiber after 139 hrs of exposure to ambient room light. The effect of the orange filter mentioned previously was checked by exposing a BI-6 fiber to filtered fluorescent light of illuminance about 3000 lux for 15 hrs, and a Kuraray single-clad fiber to the same light at an illuminance of about 50 lux for 20 hrs; in both cases the illuminance was measured with a CdS photocell. No changes were produced by these exposures.

The relation between the damage produced by ambient light and the amount of waveshifter was examined by plotting the decrease in attenuation length immediately after the 2-hr exposure as a function of the 3HF concentration of the fibers. The result, shown in Fig. 8, suggests a correlation with the logarithm of the concentration.

While, as described, exposure to ambient room light produced no changes in fiber light yields, an interesting phenomenon was observed in the course of these measurements: fibers exposed to light emit photons afterwards.

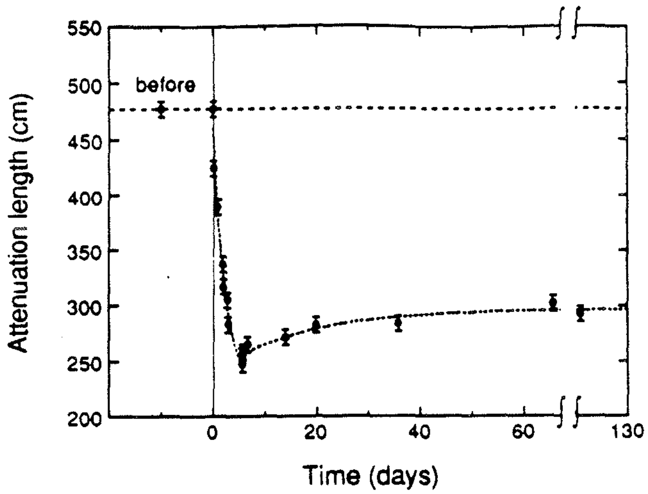

Fig. 7. Attenuation length of a Kuraray single-clad fiber before, during, and after a 137-hr exposure to ambient light. A smooth curve has been drawn through the data points. A permanent decrease of 38% remains after the fiber is kept dark for about 100 days.

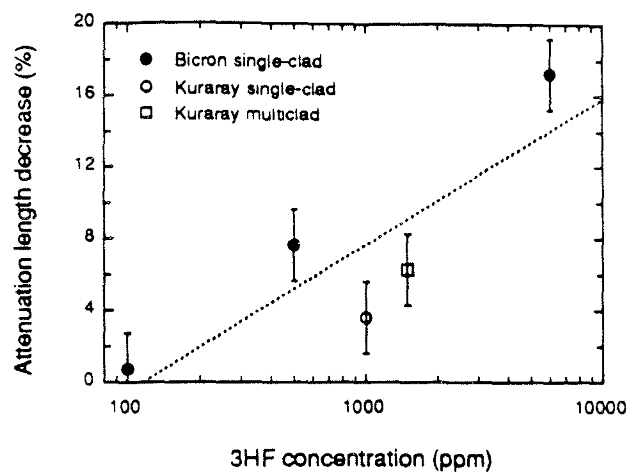

Fig. 8. Dependence of the decrease in attenuation length immediately after a 2-hr exposure to ambient light on fiber 3HF concentration. The curve shown is a fit using the log of the concentration.

This feature was found by noting that the single-photoelectron peak (see Section 2.3 and Fig. 1) increased in size when an exposed fiber was coupled to the PMT even with the ^{207}Bi source removed. This phosphorescence is illustrated in Fig. 9, which shows the time dependence of the n = 1 photopeak amplitude for a Kuraray multiclad fiber exposed to very bright fluorescent light by being taped for three hours to the underside of one of the lab light fixtures. A considerably larger effect was produced by a 1-hr exposure to a "black light" fluorescent lamp. In both cases the phosphorescence exhibits a short-term component followed by a longer-term component, with characteristic times of a few minutes and a few hours, respectively. This phosphorescence was found in all the fibers examined, including the blue fiber.

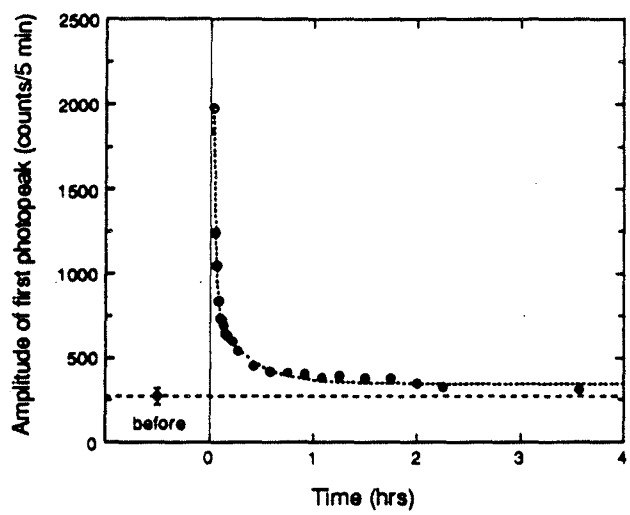

Fig. 9. Time dependence of the phosphorescence of a Kuraray multiclad fiber following a 3-hr exposure to very bright fluorescent light. The curve shown is a fit containing two exponential functions.

Phosphorescence has also recently been observed during the recovery in air of irradiated fibers containing 3HF.[6] However, while recovery -- and associated light emission -- of irradiated fibers is inhibited by storage in nitrogen and vacuum -- storage in these atmospheres produced no changes in the recovery or phosphorescence of the 3HF fibers exposed to ambient light.

4. SUMMARY

This paper presents preliminary results of a systematic study of the effects of ambient fluorescent light on scintillating fibers containing 3HF. The investigation consisted of exposing samples of six types of fibers -- having 3HF concentration between 100 ppm and 6000 ppm -- to light, at about half normal table-level illuminance, for various times. A blue fiber containing no 3HF was also included to provide a comparison. The effects of light were determined by measuring effective light yields and attenuation lengths, the principal fiber characteristics, before and after exposure.

All 3HF fibers exhibited the same basic behavior: no changes were observed in light yields; attenuation lengths, however, decreased noticeably during exposure, and then recovered when the fibers were kept dark. Recovery was almost total after about 10 days following exposures less than about 5 hrs, but larger exposures produced permanent damage. The degree of permanent damage increased with increasing exposure time but appeared to approach saturation for very long exposures. In contrast, the blue fiber showed no changes in characteristics even after a 139-hr exposure. The fibers containing 3HF showed no changes -- even after a 15-hr exposure at high illuminance -- when exposed to fluorescent light passed through an orange filter transmitting only wavelengths above 520 nm.

Since the observed effect of exposure to ambient light -- decrease in attenuation length -- was not observed for the blue fiber, it must be related to the presence of 3HF waveshifter. The effect appeared to be smallest in the BI-6 and BI-12 fibers having the lowest concentration of 3HF, and largest in the BI-3 fiber, which has the highest concentration. A correlation between damage and the logarithm of the 3HF concentration is suggested.

Finally, an interesting phenomenon was observed while making light yield measurements: both the 3HF fibers and the blue fiber phosphoresce following exposure to room light. The photon emission has a short-term component of a few minutes, and a longer-term component of a few hours.

5. ACKNOWLEDGEMENTS

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