Fermi National Accelerator Laboratory

FERMILAB-Pub-89/189

Lead Fluoride: An Ultra-Compact Cherenkov Radiator for EM Calorimetry *

D. F. Anderson
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510 U.S.A.

M. Kobayashi and Y. Yoshimura
National Laboratory for High Energy Physics (KEK)
Oho-machi, Tsukuba-gun
Ibaraki 305, Japan

C. L. Woody
Brookhaven National Laboratory
Upton, New York 11973 U.S.A.

September 1989

* Submitted to Nucl. Instrum. Methods A

Operated by Universities Research Association, Inc., under contract with the United States Department of Energy

FERMILAB- Pub-89/189
September 1989

Lead Fluoride: An Ultra-Compact Cherenkov Radiator for EM Calorimetry

D.F. Anderson[1], M. Kobayashi[2],
C.L. Woody[3], and Y. Yoshimura[2]

(Submitted to Nuclear Instruments and Methods A)

Abstract

We have tested the material PbF_2 and found that it is a Cherenkov radiator suitable for electromagnetic calorimetry. It has a density of 7.66 g/cm^3, a radiation length of 0.95 cm, a refractive index of 1.8, and an optical cutoff at about 280 nm. An electromagnetic shower is 15% shorter longitudinally, and its apparent lateral extent has a 1/3 smaller radius in PbF_2 than in BGO. We have measured 1300 photoelectrons per GeV of deposited energy and have set an upper limit on the energy resolution of $5.1\%/\sqrt{E}$. The first measurements show PbF_2 to be much more radiation resistant than lead glass; also, when damaged, it almost fully recovers after a short exposure to UV light.

---

1. Particle Detector Group, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
2. National Laboratory for High Energy Physics, KEK, Oho, Tsukuba, Ibaraki, 305, Japan
3. Brookhaven National Laboratory, Upton, NY 11973, USA

1. Introduction

In a recent search for new scintillators, lead fluoride, PbF_2, was found to be a Cherenkov radiator. It was later discovered in a review of the literature that this material was briefly considered for electromagnetic calorimetry by E.B. Dally and R. Hofstadter over 20 years ago[1]; to the best of our knowledge, no PbF_2 has been grown since that work. We have subsequently been working with Optovac, Inc. (N. Brookfield, MA) to develop the techniques for growing the material.

To help put PbF_2 in perspective, Table I shows some of its properties, as well as those of four high-density scintillators considered for electromagnetic calorimeters. The most outstanding properties of PbF_2 are its density of 7.66 g/cm^3 in the cubic lattice form (8.24 g/cm^3 in the orthorhombic lattice form) and its radiation length, X_o, of 0.95 cm. This radiation length is 15% shorter than the most compact scintillator, BGO. Two major advantages of PbF_2 over BGO are that it is much less expensive and, being a Cherenkov radiator, its performance is not limited by a long decay constant. Also, the Moliere radius of PbF_2 is only about 82% that of BGO. But the apparent lateral shower size in a Cherenkov radiator is about 20% smaller in radius than the radius of the energy deposited because the soft particles at the outside of the shower produce very little Cherenkov light[14]. Thus, the apparent shower size in PbF_2 has a radius of only about 2/3 that of BGO.

Table II shows the properties of PbF_2 and three lead glasses. As a Cherenkov radiator, PbF_2 is certainly the most compact with X_o only 37% that of SF-5.

PbF_2 is a clear optical material with a transmission that extends to about 280 nm, as can be seen by the curve marked "Best Sample" in Fig.1. This sample was a 2.4 cm cube, obtained from the Engelhart Corp. (originally Harshaw/Filtrol), which was believed to have been produced at the time of the earlier work by Dally and Hofstadter. Table III gives the refractive index of PbF_2 at various wavelengths. As can be seen, it has a high refractive index which is good for the production of Cherenkov light, but somewhat hinders the efficient coupling of the crystal to a photomultiplier tube, PMT.

Mechanically, PbF_2 has about the same hardness as LiF and is easily polished. The only precaution taken while polishing the crystals is that lubricating solvents such as triethylene glycol were used. The use of water as a solvent in polishing should be avoided because it causes local stresses leading to cracks. The solubility of PbF_2 in water is 6.4×10^{-2} g/100 g water, which is about 50% and 25% of the solubilities of BaF_2 and LiF, respectively[15]. PbF_2 is stable in air and is unaffected by moisture. Testing a single 1 cm^3 sample yielded a lower limit on its compression strength of 200 kg/cm^2, making it strong enough to stack for a calorimeter. We have also measured its coefficient of thermal expansion to be $20\times10^{-6}\,^{\circ}C^{-1}$.

PbF_2 appears to be one of the least expensive crystalline materials considered for use in high-energy physics. This is particularly true if one considers the cost per $cm^2{\cdot}X_0$, which is the relevant unit for calorimetry. The starting material is inexpensive and its melting point of 855°C greatly reduces the energy costs of production.

In this work we will present the test-beam results of two crystals, one tested at Brookhaven National Laboratory and the other at KEK in Japan. We will also present measurements of radiation effects on PbF_2.

2. BNL Test-Beam Results

The PbF_2 used in the BNL test was a cylinder 4.4 cm in diameter and 13.4 cm long ($4.6\ X_0\ \phi \times 14\ X_0$). Figure 1 shows the transmission of this crystal (labeled "BNL Test") through the 13.4 cm length. As one can see, the BNL crystal had poor transmission and was yellow in appearance. Even with the poor quality and short length of this crystal, the test results were still very good.

The PbF_2 was put in an electron test beam at the Brookhaven AGS with an energy of 3 GeV. The crystal was wrapped in Teflon tape as a reflector and coupled to the PMT (Hamamatsu R1828-01) with silicone oil. Due to the size of the crystal and the poor collimation of the electron beam, there was a great deal of leakage of the shower out of the sides as well as the rear of the crystal. Fitting the pulse-height spectrum from 50% of the peak height on the low-energy side to 10% of the peak height on the high-energy side to reduce the leakage effects, an energy resolution of 4.2% was obtained. This implies a resolution of 7.2% (1σ) at 1 GeV. The estimated number of photoelectrons, p.e., was 970 for 1-GeV electrons. With an estimated shower containment of 90%[16], this yields about 1100 p.e./GeV of deposited energy.

3. KEK Test-Beam Results

A second PbF_2 crystal was grown for a test at the KEK PS. This crystal was 13.3 cm ($14\ X_0$) long and had an octagonal cross section 4.3 cm flat-to-flat. Figure 1 shows the transmission of this crystal (labeled "KEK Test") through the 13.3 cm length. As can be seen, this crystal has a better transmission at short wavelengths than the BNL crystal. Even so, it fell short of our best sample and had a faint yellow color, along with several zones with scatter. (The apparent lower absolute transmission of the KEK and BNL crystals compared to our best sample is at least partially due to scatter in the material.) The crystal was wrapped with aluminum foil and coupled to the PMT (Hamamatsu R1828-01) with silicone oil. It was placed in the test beam with two 1 cm^2 scintillation counters to precisely define the beam hitting the center of the crystal.

The beam consisted mainly of pions along with a small fraction of electrons and muons. Measurements were made at momenta of 0.5, 0.75, 1.0, and 1.5 GeV/c. Figure 2 shows the pulse-height spectrum (with pedestal subtracted) for a momentum of 1 GeV/c. A simple fit to the electron line gives a resolution 5.3%. This result contains a small (10%) correction for a non-linearity in the PMT response at the highest energies, but no correction for shower leakage and beam momentum dispersion (<3%).

Figure 3 shows a plot of the energy resolution as a function of energy. Both the raw data and the data corrected for pulse-height saturation are displayed. A fit to the data yields a resolution of $5.1\%/\sqrt{E}$.

Figure 4 shows the signal for 1.5 GeV/c pions taken directly from the PMT terminated into 50 Ω on the oscilloscope. The horizontal scale is 5 ns/div. The signal has a rise time (10-90%) of 3 ns and a fall time (90-10%) of 11 ns. The estimate of the number of photoelectrons for 1-GeV electrons is about 1200 p.e./GeV. Since there is only 90% containment in the crystal this number becomes 1300 p.e./GeV of deposited energy. This number is 40% higher than that quoted for SF-6 lead glass and over a factor of 2 higher than for SF-5 lead glass[9]. Recently, a yield of about 1800 p.e./GeV was reported by the OPAL collaboration [17] for CEREN 25 lead glass with optimized index matching between the lead glass and PMT window. With similar care in optical matching and improved crystal quality, the photoelectron yield of PbF_2 should be substantially increased

4. Radiation Hardness

Radiation hardness is one of the key considerations in choosing materials for detectors in high-rate environments such as at the SSC, LHC, or in high-rate fixed-target experiments. Because of its speed, this is just the environment where PbF_2 may be most useful. To study the radiation hardness of PbF_2, the 2.4 cm cube of high-quality material was cut into polished, 1-cm cubes. Two of these were irradiated with neutrons and gamma rays at the Ford Nuclear Reactor at the University of Michigan.

Figure 5 shows the transmission of the PbF_2 samples before irradiation (curve A) and after irradiation. Curve B shows the transmission after irradiation with 1×10^5 rad of gamma rays and 3×10^5 rad of neutrons. Curve C shows the transmission after irradiation with 1×10^6 rad of gamma rays and 3×10^6 rad of neutrons. These measurements were taken several days after irradiation. The absorption feature at about 580 nm is an artifact of our measurement. Although these results are somewhat disappointing, a comparison with radiation damage reported for F-2 lead glass[18] shows that PbF_2 is at least 500 times more radiation resistant. (See ref. 19 and 20 for a comprehensive work on radiation damage in lead glasses.)

A promising discovery was made when the irradiated crystals were exposed to a UV (365 nm) light source for 10 minutes. Figure 6 shows the same crystals as in Fig.5 after exposure to the UV light. The sample irradiated with 4×10^5 rad (curve B) shows complete recovery, and in fact has a slightly higher transmission than before irradiation. The sample irradiated with 4×10^6 rad shows some permanent damage at the shortest wavelength. The effect of much of this residual damage can be removed by using a filter on the PMT to cut out the bluest light.

This result was unexpected because, although the recovery of lead glass with UV light is well know, it is much less common for a crystalline material. A similar result was seen with two samples of PbF_2 that were doped with 1% CdF_2. The samples, which had never been irradiated, were exposed to UV light and their transmission showed improvement. The sample with the worst initial transmission showed the greatest improvement.

5. Discussion

We estimate the number of photoelectrons from the piece of PbF_2 of the purity used for the KEK test to be 1300 p.e./GeV of deposited energy. Neglecting any increase in detected light due to better material and better optical coupling, this gives a limiting resolution due to photon statistics of only $2.8\%/\sqrt{E}$. Thus, at high energies the resolution will be limited by systematics. Since PbF_2 is a Cherenkov radiator, all clear material should produce the same amount of light, both from crystal to crystal as well as from region to region within a single crystal. This is not the case with scintillators. An example is NaI(Tl), which not only has crystal to crystal variations in light output, but its energy resolution is dominated by non-uniformities in the distribution of the Tl dopant.

There is still a lot of work to be done on radiation damage studies of PbF_2. Although all the samples that have been irradiated have come from the same piece, there are likely to be variations in material from different growths. In the case of BaF_2, there is a strong dependence of the radiation hardness on the purity of the material[21]. There is also the hope that an additive can be found that will make PbF_2 more radiation hard. As examples, the addition of oxides of Ce[18], Ge, Ti, Fe, Tl, Nb, and As[19] to lead glass have been shown to suppress the visible coloring due to radiation.

The development of PbF_2 as a Cherenkov radiator for electromagnetic calorimetry is well on its way. We feel that the techniques for the production of single pieces large enough and clear enough to make a good calorimeter will soon be in hand. The production of the large quantities necessary to build a full calorimeter is another question. This will require signs of interest from the physics community to encourage industry to commit the needed resources.

Acknowledgments

The authors would like to thank Rob Sparrow and Optovac, Inc., for their willingness to work on the development of PbF_2 and the extra efforts made to produce the two crystals on short notice for the beam tests. We are grateful to Engelhart Corp. for the generous donation of the 2.4 cm cube of high-quality material which was used in the radiation damage studies. For their help in the radiation studies, we would also like to thank Byron Roe and the people at the Ford Nuclear Reactor, University of Michigan. We are indebted to Masa Mishina for his efforts in arranging the measurements at KEK. We would also like to thank Greg Bock, Janice Enagonio, Taku Yamanaka (all from Fermilab), and Hitoshi Yamamoto from the University of Chicago for encouragement and many useful discussions, as well as to the members of Fermilab Experiment 760 for support with the BNL test beam.

This work supported in part under Department of Energy Contract DE-AC02-76CH00016

References

1. E.B. Dally and R. Hofstadter, Rev. Sci. Instr., 39 (1968) 658; IEEE Trans. Nucl. Sci. NS-15 #3 (1968) 76.

2. D.F. Anderson, "Technical Memo on PbF_2 as a Cherenkov Radiator for EM Calorimetry, Fermilab TM-1602, June 26, 1989.

3. Harshaw/Filtrol (now Engelhart Corp.), "Scintillation Detectors: A Reference Guide"

4. R. Sumner, Nucl. Instr. and Methods A265 (1988) 251.

5. C.L. Woody and D.F. Anderson, Nucl. Instr. and Methods A265 (1988) 291.

6. H. Kobayashi et al., "Pure CsI; New Fast Scintillator for γ-Detectors", KUNS-900, November 1987.

7. S. Kubota et al., Nucl. Instr. and Methods, A268 (1988) 275.

8. S.Sakuragi et al.,"Development and Applications of Pure CsI Scintillator with 10 ns Decay Time at Room Temperature," presented at the 2nd Technical Meeting of KEK on "Radiation Detectors and Dosimetry," Jan.19, 20, 1987, at KEK.

9. U. Buchner et al., Nucl. Instr. and Methods A272 (1988) 695.

10. D.F. Anderson, "Cerium Fluoride: A Scintillator For High-Rate Applications", Fermilab-Pub-89/169, submitted to Nucl. Instr. and Methods.

11. S. Iwata, Nagoya University report DPNU-3-79 (1979).

12. S. Pordes, private communications on Fermilab Experiment 760.

13. W.G. Driscoll, ed.,"Handbook of Optics," McGraw-Hill Book Company, New York, 1978.

14. H. Yamamoto, University of Chicago, private communications

15. Harshaw/Filtrol (now Engelhart Corp.), "Crystal Optics"

16. E. Longo et al., Nucl. Instr. and Methods 128 (1975) 283.

17. P.W.Jeffreys et.al.,"Development Studies for the OPAL End Cap Electromagnetic Calorimeter Using Vacuum Phototriode Instrumented Leadglass" Rutherford Lab Report RAL-89-060, July 1989

18. G.T. Bartha et al., Nucl. Instr. and Methods A275 (1989) 59.

19. Y. Yoshimura et al., Nucl. Instr. and Methods 126 (1975) 541.

20. M.R. Adams, Nucl. Instr. and Methods 238 (1985) 333.

21. C.L. Woody et al., IEEE Trans. Nucl. Sci. NS-36 (1989) 536.

Table I

Properties of PbF_2 and Some Scintillators

	PbF_2[2]	BGO[3,4]	BaF_2[5]	CsI[6-9]	CeF_3[10]
Density (g/cm^3)	7.66	7.13	4.87	4.51	6.16
Radiation length (cm)	0.95	1.1	2.1	1.9	1.7
Moliere radius (cm)	2.22	2.7	4.4	3.8	2.6
Decay constant (ns)	Č	300	0.6, 620	10, 36, >1000	5, 30

Table II

Properties of PbF_2 and Some Lead Glasses[2,11,9]

	PbF_2	F-2	SF-5	SF-6
Density (g/cm^3)	7.68	3.61	4.08	5.20
Pb (% by wt)	85	42	51	66
Radiation Length (cm)	0.95	3.22	2.54	1.69
Moliere radius (cm)	2.22		3.7	2.70
Critical Energy (MeV)	9.04	17.3	15.8	12.6
Index of Refraction	1.82	1.62	1.67	1.81
Resolution (%1σ)	<5.1	4.0[12]	4.2	3.6
Photoelectrons/GeV	1300		600	900

Table III

Refractive Index of PbF_2 at 20°C[13]

Wavelength (nm)	n
300	1.937
400	1.818
500	1.782
600	1.765
700	1.755
800	1.749

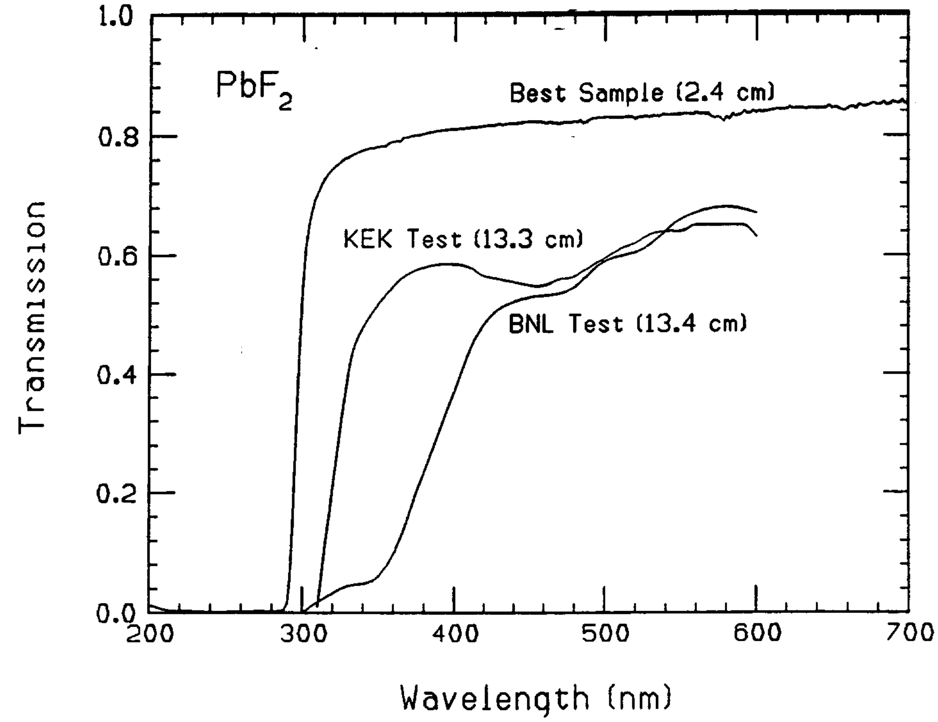

Figure 1 Transmission as a function of wavelength of the best sample, and of the crystals used in the BNL test and in the KEK test.

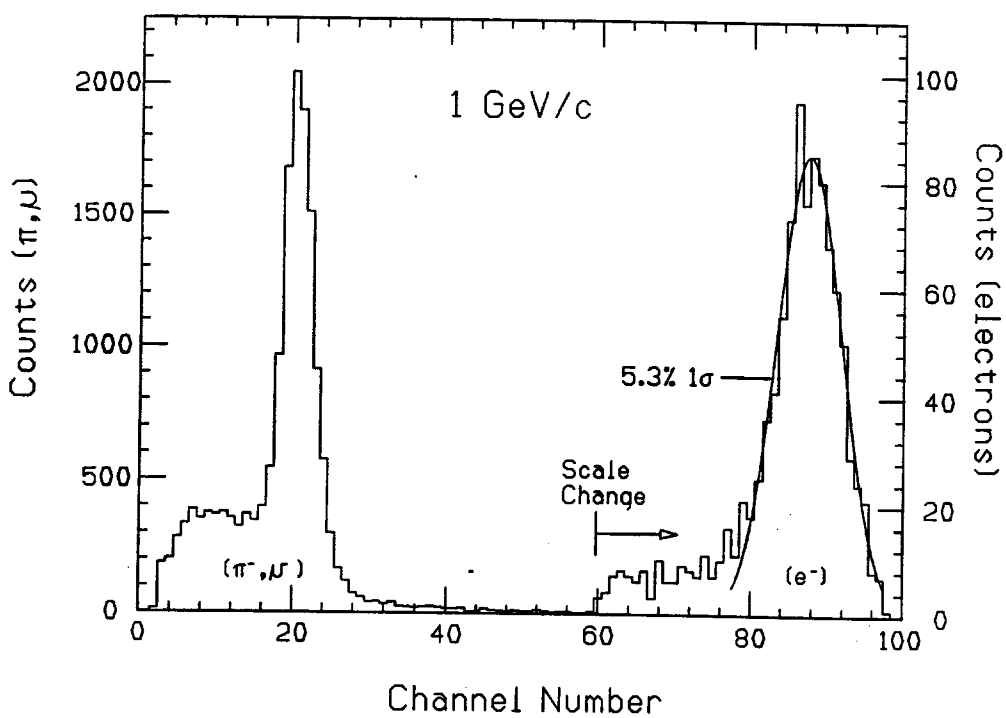

Figure 2 Pulse-height spectrum (with pedestal subtracted) for a momentum of 1 GeV/c. Note the scale change for the electron peak.

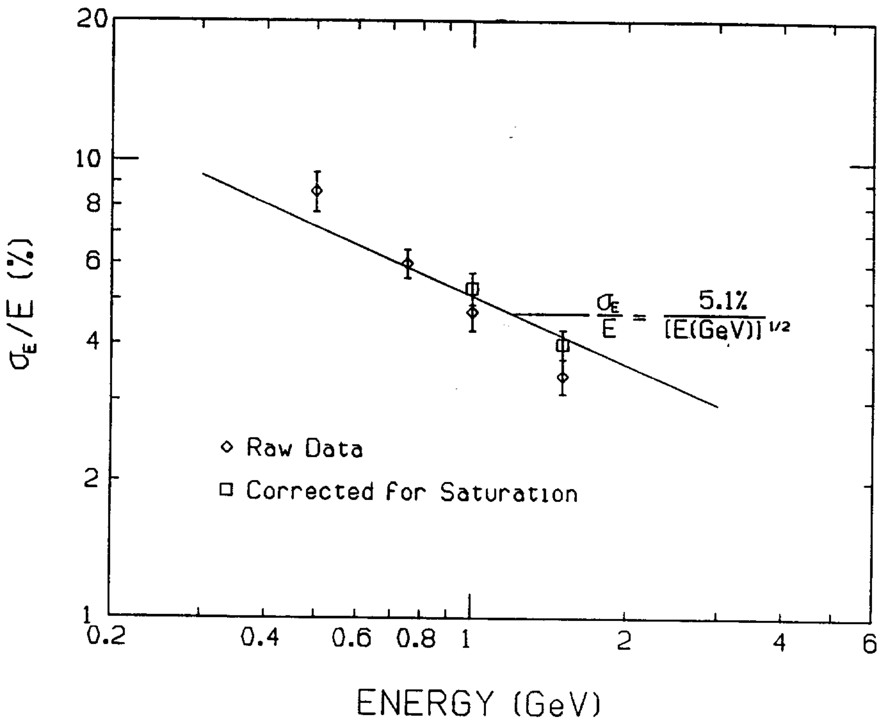

Figure 3 Energy resolution as a function of electron energy.

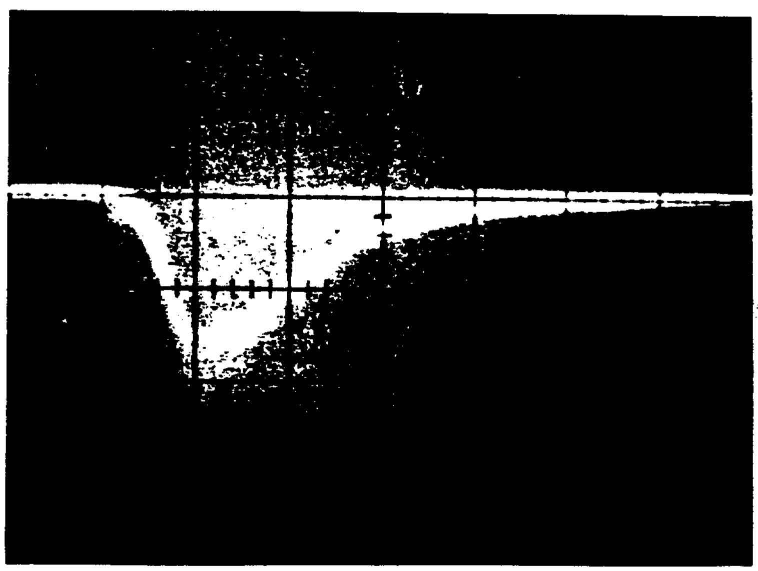

Figure 4 Signal for 1.5-GeV/c pions from the PMT terminated into 50 Ω on the oscilloscope. The horizontal scale is 5 ns/div.

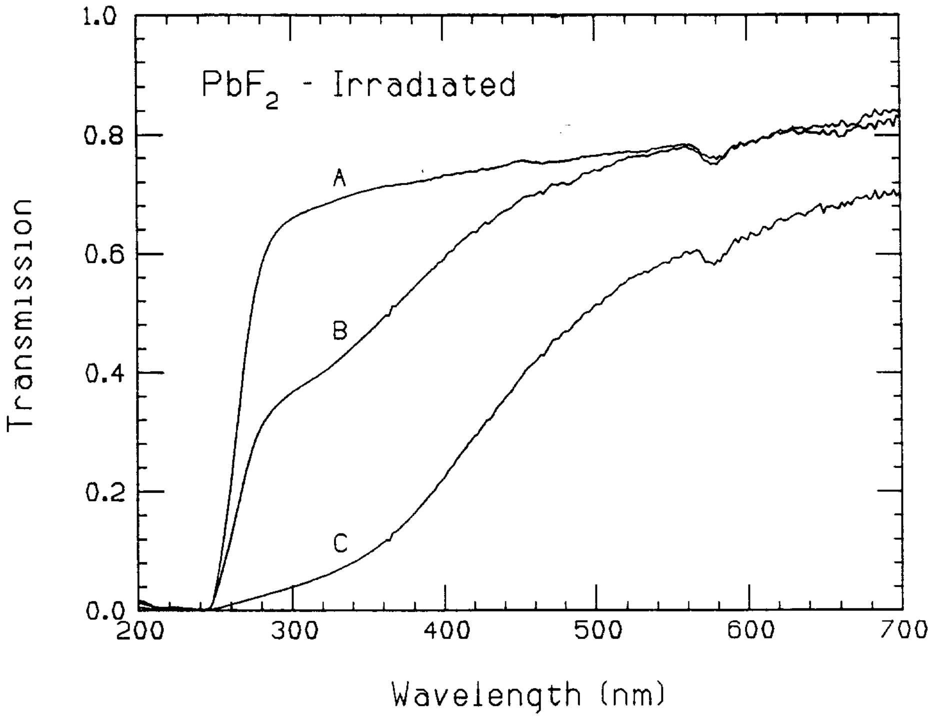

Figure 5 Transmission as a function of wavelength for samples of PbF_2: A) before irradiation, B) after $3x10^5$ rad of neutrons and $1x10^5$ rad of gamma rays, and C) after $3x10^6$ rad of neutrons and $1x10^6$ rad of gamma rays. The absorption feature at about 580 nm is an artifact of the measurement technique.

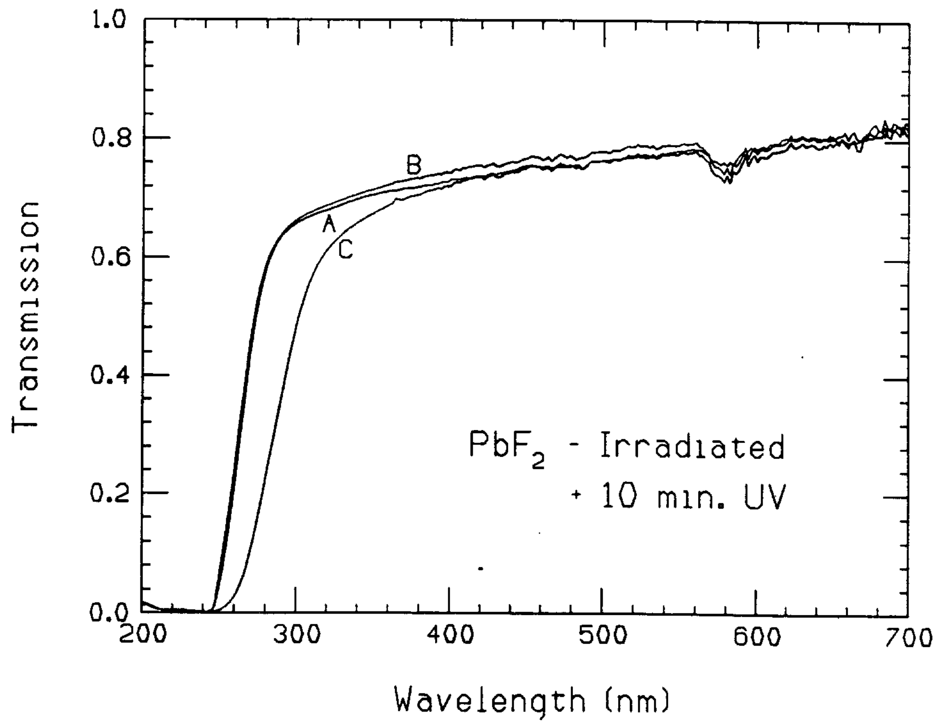

Figure 6 Transmission of the same PbF_2 samples as in Fig. 5 after a 10 minute exposure to UV light (365 nm).