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Recent Developments in High-Speed, Non-Sampling Electromagnetic Calorimetry*

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RECENT DEVELOPMENTS IN HIGH-SPEED, NON-SAMPLING ELECTROMAGNETIC CALORIMETRY

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ABSTRACT

Brief discussions are given of the work that has been done on the suppression of the slow component in BaF_2, the developments in the understanding of undoped CsI, and the properties of the new scintillator CeF_3. The properties of the Cherenkov radiator PbF_2 along with test beam results are presented. Monte Carlo simulations indicate that, with the addition of a small amount of scintillator, PbF_2, can be made hadron compensating off-line so that the resolution of a compensating hadron calorimeter will not be degraded by its presence.

1. Introduction

Through the years there has been a continuous interest in non-sampling, EM calorimetry. For this application lead glass and the inorganic scintillators BaF_2, BGO, CsI(Tl), and NaI(Tl) have found the widest applications. The advantage of lead glass is that it is inexpensive and has good energy resolution. Its major disadvantage is that it is very radiation soft.

The advantages of scintillators for EM calorimetry are that they have very good energy resolution as well as a very low detection threshold. However, as can be seen in Table I, which list the properties of several inorganic scintillators, BaF_2, BGO, CsI(Tl), and NaI(Tl) all have decay constants in the hundreds of ns range, with CsI(Tl) and NaI(Tl) having components that are much longer. Thus, these scintillators are only useful in what is now considered low-rate applications.

Table I: Properties of various inorganic scintillators [1]

			CeF_3	**BaF_2**	**BGO**	**CsI**	**CsI(Tl)**
Density (g/cm^3)		6.16	4.9	7.13	4.53	4.53	3.67
Radiation length (cm)		1.7	2.1	1.1	1.86	1.86	
Moliere radius (cm)		2.6	4.4	2.7	3.8	3.8	
Decay constant-short		≈5	0.6	300	≈10, 36	>1000	230
(n sec) -long	30	620		>1000		150 ms	
Peak emission-short			310	220	480	300	415
(nm) -long	340	310			>400		
Light yield[NaI(Tl)≡100]		4-5	5(s) 16(l)	7-10	3.7	85	100
Hygroscopic	No	Slight	No	Slight	Slight	Yes	

With the growing attention given the proposed large hadron colliders, the LHC and the SSC, two requirements have been added to the specification of an EM calorimeter: high rate capability and radiation hardness. The development of compensating hadronic calorimeters has also added the concern that the EM calorimeter not degrade the hadronic resolution.

Recently there have been several relevant developments in non-sampling calorimetry. Among the scintillators there is the doping of BaF_2 to reduce the "slow" component and the introduction of two new scintillators: undoped CsI and CeF_3. In the field of Cherenkov radiators, there has been the re-introduction of PbF_2 which offers the possibility of being the first non-sampling EM calorimeter that is hadron compensating. These developments will be discussed below.

Because of the limited space, and because the work on the scintillators can be found in the references, most of this work will be dedicated to PbF_2 with much of the work unpublished elsewhere.

2. Developments in Inorganic Scintillators

2.1. Barium Fluoride

BaF_2 is the fastest inorganic scintillator with a "short" or "fast" component of 0.6 ns. It also has a reasonably short radiation length of 2.1 cm, its short component is insensitive to temperature, and it is believed to be the most radiation hard of the scintillators ($\approx 10^8$ rad). It has two major disadvantages. The first is that the fast component is in the UV and therefore requires a quartz photomultiplier tube, PMT. This greatly increases the expense of large arrays of crystals, such as for positron emission tomography. (This UV light has been detected by photosensitive wire chambers. See ref. 2 for a review of the subject.)

The second disadvantage of BaF_2 is that it has a "long" or "slow" component with a decay time of 620 ns. This is a problem for spectroscopy at the high rates of interest. One of the most promising solutions to this problem is the addition of a small amount of lanthanum to the crystal to suppress the slow component and then viewing the scintillation with a "solar blind" PMT with a CsTe photocathode[4]. The net result of the use of both techniques is that the fast component goes from constituting about 16% of the total signal to over 60% of the signal. This is done at a cost of about 50% of the fast component. The addition of La also preserved the radiation hardness of the material.

2.2. Undoped Cesium Iodide

Recently, it has been reported that undoped CsI exhibits a fast emission at around 310 nm with a decay constants of about 10 ns and 35 ns[5]. There is also a longer decay constant of over 1 μs that contributes from 20-35% of the scintillation light, depending on the sample. This material, as well as readout schemes, has been studied extensively by Woody et al.[6] One point of interest is the temperature dependence of the scintillation yield and the fast decay constants. At room temperature the light yield changes with temperature by $\approx -1.5\%/^\circ C$ and increases by about a factor of 6 at -150°C. The decay constants increase as the temperature is lowered from 10 ns and 35 ns to about 180 ns and 340 ns, respectively, at liquid nitrogen temperature. This temperature dependance put severe restrictions on the temperature control of any high resolution EM calorimeter using undoped CsI.

In the above work[6], the UV light was used to excite plastic scintillators and read out similarly to wavelength shifter readout used in calorimetry. The result is that there is a reduction of 75% in the detected light. It had been believed that the μs component was at longer wavelengths than the the fast components, but these measurements proved that that is not the case. The ratio of pulse heights for long and short gates for the wavelength shifter readout (sensitive only to the shortest wavelengths) was the same as for the direct readout.

Samples of undoped CsI have been irradiated with gamma rays to doses of 1.5×10^6 rad. The result is that there is about a 10-35% lost in scintillation light, depending on the sample. The conclusion was that the amount of damage is considerably less than has been reported for CsI(Tl).

2.3. Cerium Fluoride

CeF_3 is a new scintillator that may find an application in EM calorimetry[1]. As can be seen from Table I it has a short radiation length and Moliere radius, 1.7 cm and 2.6 cm, respectively. With decay constants of 5ns and 30 ns, and no slow component, it is the fastest of the scintillators listed. Its scintillation yield also has a very small dependence on temperature. The change is scintillation yield with change in temperature is about +0.08%/°C. This is almost a factor of 20 less than for undoped CeI. It is also believed that CeF_3 is at least not radiation soft, and possibly quite radiation hard.

One disadvantage with CeF_3 is that it is not presently available in large quantities. Although it is not difficult to grow, and the starting material is relatively inexpensive and readily available, it is only grown by one manufacturer (Optovac, Inc., North Brookfield, MA, USA) on a development bases. There is a need for more effort on the part of industry before CeF_3 will be a material that can be considered for calorimetry.

3. The Cherenkov Radiator Lead Fluoride

There has recently been a renewed interest in the Cherenkov radiator lead fluoride, PbF_2[7]. Its properties and those of three lead glasses are given in Table II. PbF_2 has a density of 7.77 g/cm^2, a radiation length of only 9.3 mm, and a Moliere radius of 2.2 cm. It should be noted that, for a Cherenkov radiator, the "apparent" Moliere radius is 20% smaller than the radius in the literature because the particles at the outside of the shower are very soft and produce very little light[8]. Therefore, the "apparent " Moliere radius for PbF_2 is only 1.8 cm. By comparing its properties with those of BGO, we see that an EM shower is 15% shorter longitudinally and has an apparent lateral extent that is 1/3 smaller in radius in PbF_2. The optical cutoff of this material is at about 280 nm; much lower than for conventional lead glasses.

Like CeF_3, PbF_2 is a material that is still under development by industry. The pieces that we have tested have been grown by Optovac, Inc. who can now make pieces about 6 cm in diameter and greater than 18 Xo long fairly routinely.

In calculating the cost of the material for an EM calorimeter in a collider environment, an appropriate unit of measure is the cost per Moliere radius squared radiation length,

Table II: Properties of PbF_2 and some lead glasses[7]

	PbF_2	F-2	SF-5	SF-6
Density (g/cm^3)	7.77	3.61	4.08	5.20
Pb (% by wt)	85	42	51	66
Radiation Length (cm)	0.93	3.22	2.54	1.69
Moliere radius (cm)	2.2		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
Photoelectrons/GeV	1300		600	900

$R_M^2 \bullet Xo$. R_M^2 is related to how close the calorimeter can be place to the interaction region for a given two-particle resolution. Xo, is of course, a measure of how thick the calorimeter must be. A comparison of the cost in this unit for PbF_2 and for the three most popular scintillators is given in Table III. The relative cost of a PbF_2 calorimeter is on the order of 20%, 6%, and 2% that of CsI, BGO, and BaF_2, respectively.

Table III: Estimated cost for a calorimeter in a 4π detector

	PbF_2	CsI	BGO	BaF_2
Approx. Cost ($\$/cm^3$)	2-3	1.5	15	8
Moliere radius** (cm)	1.8	3.8	2.7	4.4
Cost (\$ per $R_M^2 \bullet Xo$)	6-9	40	120	325

**"apparent" Moliere radius used for PbF_2

3.1. Energy Resolution

A PbF_2 crystal, 13.3 cm (14 Xo) long and with an octagonal cross section 4.3 cm flat-to-flat has been tested at the KEK PS. Although the crystal was not of optimum quality and had a light yellow tinge, the results were quite good. Figure 1 shows the pulse height spectrum for 1 GeV electrons as well as for pions and muons of the same momentum. With only 90% containment of the shower in the crystal and no corrections made for leakage, the resolution was measured to be 5.3% (1σ). The light detected was measured to be 1300 photoelectrons per GeV of energy deposited. Neglect-

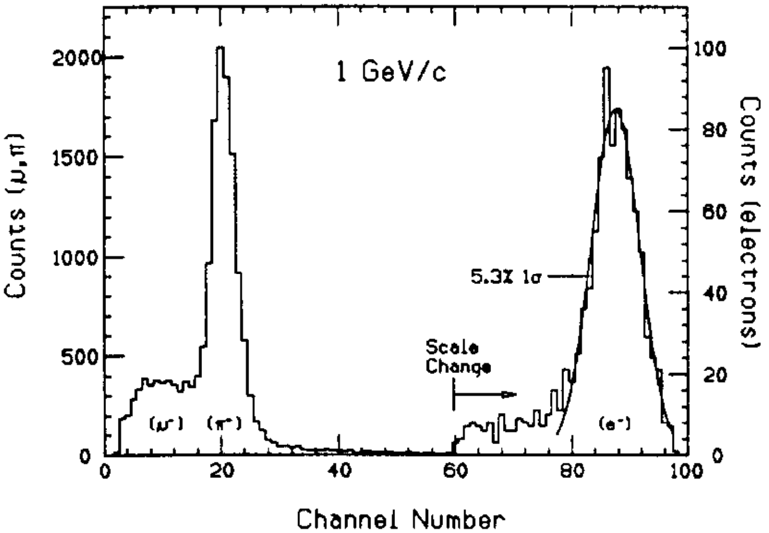

Fig. 1. Pulse height spectrum for 1 GeV electrons along with pions and muons of the same momentum.

ing any increase in the detected light due to better material and better optical coupling, this gives a limiting resolution due to photon statistics of $2.8\%/\sqrt{E}$. 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 optical non-uniformities.

This crystal was then tested with cosmic muons in order to determine how fast a signal could be generated from a PbF_2 calorimeter. In principle, the spread in the photon arrival time (neglecting multiple bounces) should be on the order of 1 ns. This is consistent with the experimental results where the signal seen was determined by the speed of the PMT (signal width ≈5 ns at the base). This would suggest that such a calorimeter should be suitable for time-of-flight measurements.

3.2. Hadron Compensation

Hadron compensation has become more and more important in calorimetry design. Without compensation, the energy response of a hadron calorimeter does not scale linearly with E and the resolution does not improve as $1/\sqrt{E}$. Because of this, there is a great reluctance to place a non-compensating EM calorimeter in front of a compensating hadronic calorimeter.

From the work by Wigmans[9] and others it is clear that passive hadron compensation is only possible for sampling calorimeters, where the electron response is suppressed and the hadron response is enhanced. Off-line corrections have been successfully achieved by identifying the EM core of the shower with fine lateral segmentation and correcting the energy measurement[10]. To use this technique with a non-sampling EM calorimeter however, would require that the crystals be very small in the lateral direction which would make the readout very expensive and greatly complicate the calibration and operation of the instrument.

A more promising technique, suggested by Mockett[11], is to use wave form analysis on a scintillator to separate the Cherenkov component from the scintillation. In principle, the ratio of these two components should be different for EM and hadronic showers and different components of the shower should be identifiable. The problem with this technique is that the Cherenkov component would be a small fraction of the signal from a scintillator. An alternative technique has been suggested by Winn[12] in that the two components be separated by wavelength rather than pulse shape. The problem here is that it requires a double readout with filters and the wavelength region of the scintillation (where most of the Cherenkov radiation occurs for blue scintillators) is not available for Cherenkov detection.

A more promising approach is a variation on the first technique. We propose the addition of a small amount of scintillating material to PbF_2 in such a concentration that the Cherenkov and scintillation components for an electron be comparable. One would also like the scintillation decay time to be short enough to allow high rates and yet long enough to allow easy separation of the two components. This approach has the advantage that the amount of scintillation can be adjusted to optimize the technique.

3.2.1 Possible Scintillator Additives

Lead has often been considered a poison for scintillators and there are very few lead based scintillators. We have added CeF_3 and TbF3 to PbF_2. The mixture with CeF_3 did not fluoresce under a UV light but the TbF_3 did. Dopings of 0.5%. 1% and 2% of TbF_3 all fluoresced. Unfortunately, we have not been able to measure the decay constant, but from measurements of Tb doped CeF_3, we believe that its decay constant is in the few tens of ns range.

From the work of Derenzo et al.[13] there are several other scintillators that we can investigate. These are listed in Table IV. These scintillators do not produce enough light to be of interest in themselves, but the required scintillation efficiency of the doped PbF_2 would only be about $3x10^{-4}$ that of NaI(Tl). Of the scintillators listed in the table, HfF_4 certainly looks appealing. A decay constant of 30 ns would be about perfect. Doping of PbF_2 with these scintillators and others is work that we hope to accomplish in the near future.

Table IV: Some fast scintillators[13]

		λ	lifetimes (ns) and fraction		
Compound	**Formula**	**(nm)**	**fast**	**medium**	**slow**
Cadmium fluoride	CdF_2	420	4.8(29%)	24(28%)	78(43%)
Hafnium fluoride	HfF_4	350	29(100%)		
Lead tungstate	$PbWO_4$	490	2.5(25%)	11(29%)	98(46%)
Lead chloride	$PbCl_2$	500	2.9(41%)	20(32%)	179(27%)

3.2.2. Monte Carlo Simulations

Simulations have been made, with the GEANT Monte Carlo, of the performance of a PbF_2 with a scintillator added. The scintillation intensity was adjusted to be equal to the Cherenkov radiation for EM showers. The simulation involved electrons and pions with energies of 5, 10, 20, 50, 100, and 200 GeV. The program had a minimum energy cutoff of 1 MeV for all generated particles. It was assumed for these calculations that the scintillation intensity would be proportional to the ionization of the PbF_2.

The difference in the ratio of the Cherenkov signal to the scintillation signal, C/S, for hadrons and electrons is quite dramatic. Figure 2 shows the number of counts as a function of C/S for 20 GeV: electrons, pions, and for the purely hadronic component of the pion shower. This shows that this is in fact a powerful tool. The fraction of the pions that would be confused with electrons in this simulation is about 10^{-4}.

Figure 3 shows the energy measured by scintillation divided by the true energy of the particle, E'/E, as a function of C/S. This figure is the average for pion with the energies mentioned above. The data does not go to values of $C/S \leq 0.2$ because there were too few events with this value to be statistically significant. In the simulations that follow, the energy corrections were made on the event-by-event basis by determining the C/S for the event, looking up the corresponding value of E'/E and correcting the measured E'.

To further simulate a complete calorimeter with EM and hadronic sections, the calorimeter was divided at 25 Xo ($\approx 1\ \lambda$). The results for the energy resolution (normalized at 1 GeV) vs particle energy are shown in Fig. 4, while the relative pulse height normalized to 1 at 10 GeV is shown in Fig. 5 . Curves (A) are the response for the total calorimeter without compensation. Curves (B) are for a calorimeter with a compensated hadronic section but a non-compensating EM section. Curves (C) are the response for a calorimeter with both sections compensating, either compensated separately and added or compensated as a single detector. These two figures show the damaging effects on the performance of a compensating hadronic calorimeter if it is preceded by a non-compensating calorimeter. They also show that the performance can be restored if the EM can be made compensating and added. The fact that curve C in Fig.5 is not equal to 1 at higher energies indicated that we have still not optimized our corrections.

3.3 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. Figure 6 shows the transmission of two 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

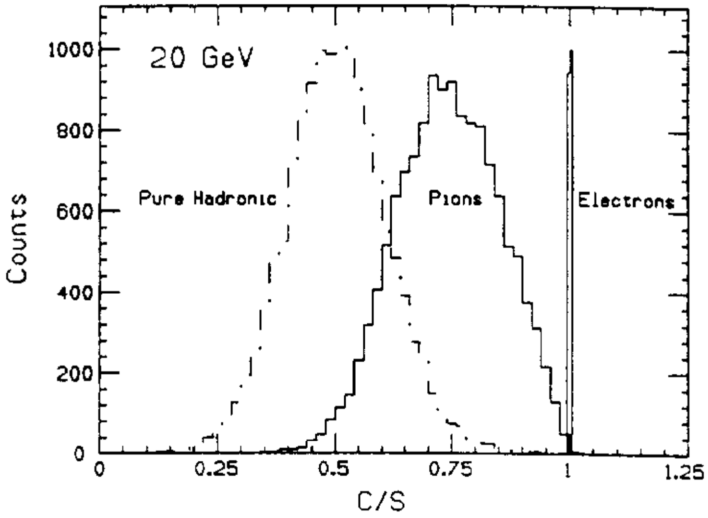

Fig. 2. Counts as a function of the ratio of C/S for 20 GeV pions and electrons, as well as for the pure hadronic component of the hadron shower.

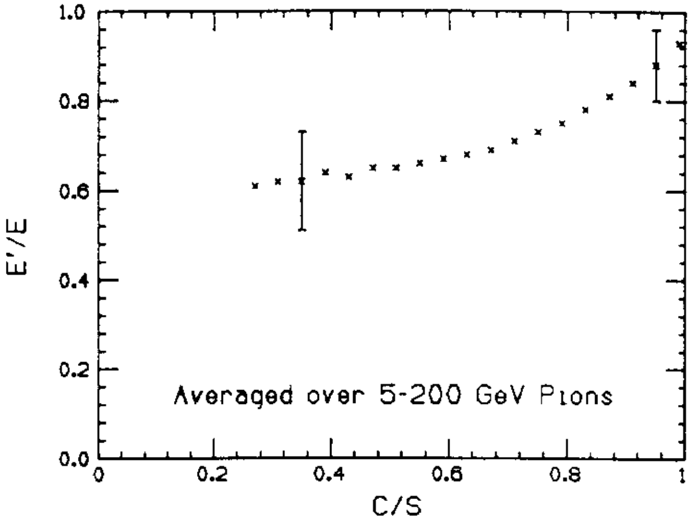

Fig. 3. Energy measured by scintillation divided by the true particle energy, E'/E, as a function of C/S for pions in the 5-200 GeV range.

radiation damage reported for F-2 lead glass[14] shows that PbF_2 is at least 500 times more radiation resistant.

A promising discovery was made when the irradiated crystals were exposed to a UV (365 nm) light source for 10 minutes. Figure 6 also shows the same crystals as as above 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 (curve A*) 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.

There is a lot of work to be done on radiation damage studies of PbF_2. All the samples that have been irradiated have come from the same piece, and there are likely to be variations in material from different growths. So these results should be considered a minimum on the radiation hardness of the material. In the case of BaF_2, there is a strong dependence of the radiation hardness on the purity of the material. 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, Ge, Ti, Fe, Tl, Nb, and As[14] to lead glass have been shown to suppress the visible coloring due to radiation.

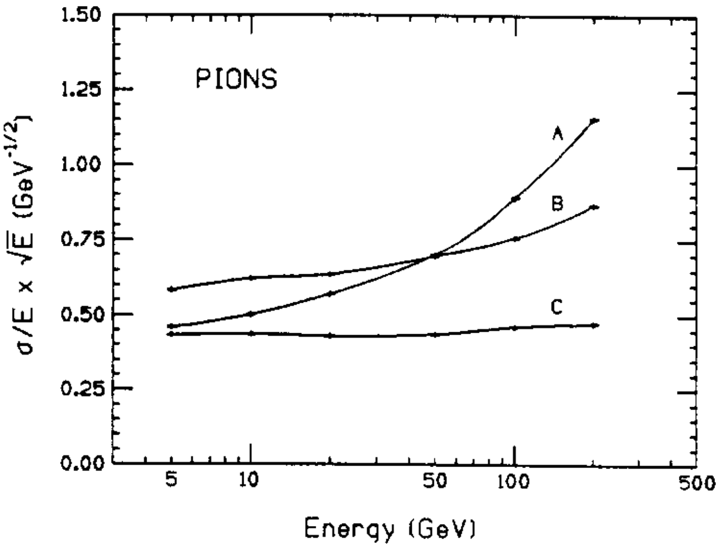

Fig. 4. Energy resolution of pions as a function of energy (A) without compensation, (B) with compensation only in the hadronic section, and (C) with compensation in both sections (compensated separately and added or added then compensated).

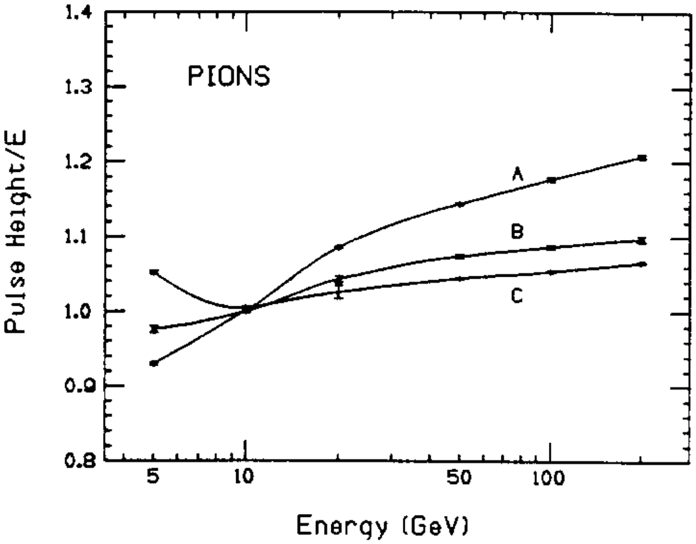

Fig. 5. Relative pulse height of pions as a function of of energy (A) without compensation, (B) with compensation only in the hadronic section, and (C) with compensation in both sections.

4. Discussion

PbF_2 is the fast and the most compact material for a non-sampling EM calorimeter. It may even be sufficiently fast to by used for time-of-flight measurements. In a collider environment, it is also the least expensive. Since it is a Cherenkov radiator, it may have a much smaller constant term and be easier to calibrate than a scintillator.

Simulations have shown that, in principle, PbF_2 can be made compensating by the addition of a very small amount of scintillator. If this can be realized, it would yield a calorimeter that would not degrade the performance of the hadron calorimeter that follows.

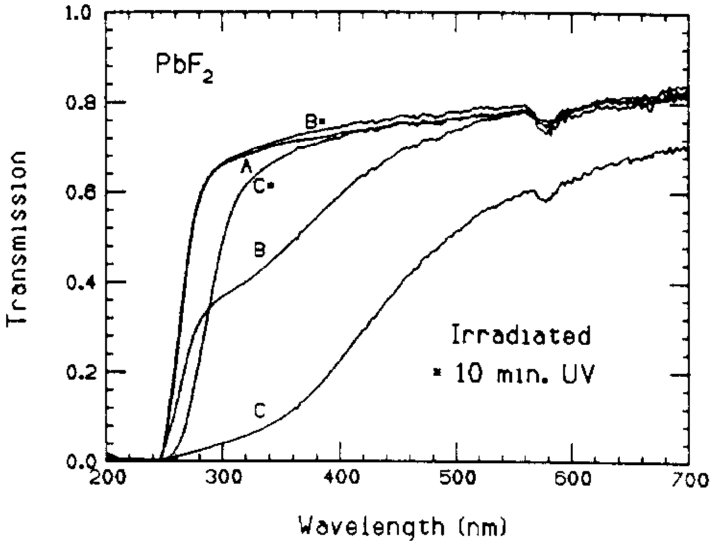

Fig. 6. Transmission of PbF_2: (A) before irradiation, (B) after 4x10^5 rad, and (C) after 4x10^6 rad (B*) and (C*) are the same as (B) and (C) but cured with 10 minutes of UV light.

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To save space, the number of references will be shortened in cases where there are many references (e.g.Table I) by referencing papers containing the appropriate references.

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