ELECTROMAGNETIC SHOWER DETECTOR-CALORIMETERS

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INTRODUCTION

Electromagnetic shower detectors are distinguished from hadron detectors primarily by the amount and type of material they contain. Typical materials for EM detectors have a ratio of radiation length to absorption length of 20 to 25. Thus, for electromagnetic shower containment, which requires from 20 to 30 radiation lengths for high resolution, we are speaking of 1 to 1-1/2 absorption lengths; hardly enough to contain a hadronic shower. A special problem exists for photons (as with neutrons in hadron detectors) in that one requires high detection efficiency - a requirement that is obviously compatible with shower containment.

SHAPE OF THE ELECTROMAGNETIC SHOWER

Figure 1^1 shows the by now famous image intensified photograph of an electromagnetic cascade in NaI. In fact, the amount of the shower seen here is not enough to obtain high resolution calorimetry. A more quantitative picture is shown in Figure 2^2 where the longitudinal and transverse development of the electromagnetic cascade is shown for 40 GeV electrons entering a steel scintillator sandwich detector. The integral of the curves as a function of depth at nearly the same energy is shown in Figure 3^3 along with the prediction of an analytic shower theory (Approximation A of Rossi and Greisen⁴). Summing the energy deposition in regions gives an amount of energy which a module of a detector will see and is a slowly varying function of energy as shown in Figure 4^3 . Similar measurements of the transverse development

of the cascade exist as indicated by Figure 5⁵. This figure shows the fraction of energy contained in a region as the entry point of the impinging particle trajectory moves into the region from the side. Taking the same modules as indicated in Figure 4 gives the fraction of energy contained in each layer of modules as the impinging trajectory enters the region from the side (Figure 6)³.

These shower shapes (for which theory - both analytic and Monte Carlo - also exist in the literature) are now well documented and the design of an electromagnetic shower detector is a potentially rational exercise.

DETECTOR CHOICE

In this presentation I will concentrate on three types of absorption calorimeters;

(1) lead-scintillator hodoscopes and sandwiches,

(2) lead glass total absorption calorimeters, and

(3) sodium iodide crystal devices.

I will pay special attention to the last two of these since (as with developmental types) the lead-scintillator devices are being reported on by others today and tomorrow. First, a quick view of examples of each. Figures 7^1 , 8^3 , and 9^2 show typical arrangements of NaI, lead glass and lead-scintillator devices. Some of these devices get quite beautiful (complicated) and it is little wonder that their users become exhuberant (delighted to finally get the thing working).

One of the results of the PFP Summer Study was Table I⁶ which compares the properties of many types of electromagnetic calorimeters. Ranges of design parameters are given: for example, the rms energy resolution as a function of sampling depths (e.g., t = 1 implies 1 radiation length lead absorber between scintillators) and incident energy E_0 , rms spatial resolution and cost in dollars per radiation length of depth and square meter of area. I don't want to dwell on the table except to make a few observations.

The choice of detector is always a compromise among cost, energy resolution and spatial resolution. In photon detectors, spatial resolution may play an overriding part since there will be no incoming trajectory information available. Di-photon states are interesting and it may be required to separate spatially the two photons entering a single array. Some very nice work in this direction has been done by E-111 at Fermilab⁷, Bushnin, et. al.² at Serpukov and by Rubbia, et. al.⁸ at CERN. I will leave it to these groups to circulate the beautiful mass plots of $\pi^{O's}$, $\eta^{O's}$, etc. The point here is that the price paid for this spatial resolution (for example, going from sandwiches to hodoscopes) is typically a large factor.

Similarly, the cost of energy resolution is large. Although not shown, the cost of lead-scintillator sandwiches and hodoscopes is inversely proportional to the sampling increment. The gain in resolution from these devices to lead glass is inversely proportional to the cost. The same can be said roughly for the gain in resolution in going from lead glass to NaI. In this regard it should be noted that the prices for lead glass and NaI have been coming down in recent years. Harshaw now has competitors and buyers of lead glass have become experts on the floating rates of the Yen and Deutsche Mark. I should like to emphasize the incompatibility of good spatial and energy resolution in these devices. I will come back to this when I come to the limitations on energy resolution.

Finally, I would like to change the "good" rating of lead glass for background rejection to "excellent". This change is in view of

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the 10^4 hadron rejection obtained event by event (10^5 rejection after background subtractions when needed) by E-70 at Fermilab³.

STATE OF THE (OLD) ART

The last half of my talk is a discussion of the current limits on energy resolution and a quick sweep of what has been obtained recently in hadron rejection.

Most have probably seen the 0.7% resolution curve¹ (Figure 10) for electrons of 15 GeV in NaI. This old curve remains something to aim for - even by Hofstadter's group with their more recently purchased crystals⁹. A slightly less PR developed graph with a suppressed zero is shown in Figure 11 for the resolution obtained for 50 GeV electrons in lead glass³. A more direct comparison of results is shown in the log-log plot of resolution versus energy of Figure 12. NaI is the highest resolution device. I have been told that the $E^{-1/4}$ dependence does not continue below about 1% FWHM as the energy is increased⁹. Next comes lead glass for which $(1.5 + 10/\sqrt{E})$ FWHM has been obtained with SF5 glass from both Germany¹⁰ and Japan³. Notice, however, that poorer resolution has been obtained with the clearer SF2 glass used at Cornell¹¹. In fact, the resolution of this system is not so much better than that obtained with lead-scintillator devices. A few points are shown for these last devices along with the curve $25/\sqrt{E}$ which seems to be a limit on what one can do with sampling devices with sampling increments near 1 radiation length. Coincidentally, the resolution (5% FWHM at 7 GeV) obtained with the liquid argon sampling device just described by P. Rehak fits on the lead glass curve.

That the entire electromagnetic cascade must be detected in

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order to obtain the highest resolution is shown by the three curves in Figure 13³ where the amount of lead glass in the longitudinal development of the shower is reduced and in Figure 14¹ where the fractional transverse energy leakage in NaI is shown to have a magnified effect on the fractional change in resolution.

Assuming that the entire shower is contained (a condition necessary for linear response with incident energy), what limits the resolution? Several effects have been isolated - all the dominant ones related to the uniformity of response to energy deposition. Inhomogenieties and variable light collection efficiencies combine with fluctuations in the shower development (especially the longitudinal development in the current round of devices) to limit results. Figure 15¹ shows the inhomogeniety at a boundary between two modules of NaI viewed by the same photomultipliers. Clearly, a fluctuation in which more or less of the energy is deposited in the higher gain downstream side of the boundary will give a much higher output than the opposite fluctuation. Similarly, for phototubes glued onto the sides of a large NaI block, azimuthal gain variations limit the energy resolution. Recent progress in randomizing the light collection has helped in these regards⁹ (at a consequent reduction in the copious scintillation light given off by NaI crystals used at high energy). Similar effects exist for lead glass, as shown in Figure 16³. Two separate purchases of glass from Ohara in Japan were quite different in their properties. Fortunately, the latest techniques used have led to consistently better glass: at lower cost !!! The Cornell lead glass views particles longitudinally, as in the back layers of glass in Figure 8. It may be that the largest difference in the Cornell and Columbia-Fermilab or

CERN-Columbia-Rockefeller¹⁰ results is in just this effect, longitudinal shower fluctuations causing variations in the light collection efficiency for various events. The Cornell lead glass blocks have smaller areas in order to obtain spatial resolution for photons. The extra reflections in these blocks may also couple to shower fluctuations to reduce the energy resolution.

The agreement with shower theory shown in Figure 3 for lead glass is not shared by lead-scintillator devices. Figure 17¹² shows the ratio of scintillator light to the same shower theory used in Figure 3. The end of the shower has many times more light than predicted by the simple theory. This is probably due to the nuclear fragments which must be more common in that part of the shower. These particles are many times minimum ionizing and even saturate the scintillation process. Fluctuations in these fragments may well be responsible for a large part of the loss in resolution over the ideal in lead-scintillator devices. Where individual pulse heights are recorded for each scintillator sheet, it should be possible to improve the resolution by choosing an appropriate weighting factor (less than single minimum ionizing particle weights) for the back layers.

Figure 18^1 shows the energy deposited in a NaI crystal by noninteracting particles, interacting pions and positrons in a beam at SLAC. For comparison, the same quantity is shown for 40 - 45 GeV charged particles at large angles at Fermilab (Figure 19a³). The absence of an electron peak is not simply a result of poorer resolution. The difference is that at SLAC, the positrons are about 10^{-1} of the incident particles while in the Fermilab experiment the ratio is 10^{-4} . By applying cuts in the minimum energy deposition in the first two

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layers of lead glass detector and then on the distribution of energy deposition in the array (the longitudinal shower development), the spectrum of Figure 19a is converted to that of Figure 19b and then 19c. The effect of all these cuts on hadrons is shown also (Figures 19d and 19e). The peak is real electrons, not cuts-induced, and the rejection event by event is 10^{-4} . The cuts applied depend on the modularization of the array. In the lead glass array, the electromagnetic shower was positioned in the array in such a way as to maximize hadron rejection with the available modules. Figure 20 shows the fraction of energy in the three layers of lead glass with various amounts of lead in front of the array for electrons (solid curve) and for those hadrons which deposit all their energy in the lead glass (dashed curve). The separation of electrons from these hadrons is apparent. In the older NaI detectors, similar modularization was not used and the consequent hadron rejection, even with the better energy resolution (Figure 21¹), does not match that obtained with the lead glass. 13

Thus, the choice of detector is best made only with a clear picture of the experimental requirements in cost, spatial resolution, energy resolution and hadron rejection.

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Ref.	Detector Type	Detection Efficiency	Energy Threshold	Energy Resolution	Spatial Resolution	PHA-Time Resolution	Trigger Functions	Background Rejection	Ease of Handling	\$/X
, 1	MWPQ	100%	~150 MeV	$\pm 29\% (t/E_0)^{1/2}$	±3 mm	100 ns	Poor	Poor	Difficult	5,000
2	РТС	100%	~150 MeV	$\pm 29\% (t/E_0)^{1/2}$	±1 cm	100 ns	Poor	Poor	Moderate	3,000
3	Pb-lucite	100%	-150 MeV	$\pm 30\% (t/E_{0})^{1/2}$	±3 mm	20 ns	Good	Good	Easy	5,000
4	Pb-lucite	100%	-150 MeV	$\pm 12.5\% (t/E_0)^{1/2}$	±5 cm	20 ns	Good	Good	Easy	700
3	Pb-plastic scintillator	100%	~150 MeV	$\pm 25\% (t/E_0)^{1/2}$	±3 mm	20 ns	Good	Fair	Easy	5,000
4	Pb-plastic scintillator	100%	~150 MeV	$\pm 10\% (t/E_0)^{1/2}$	±5 cm	20 ns	Good	Fair	Easy	1,000
5	Pb-liq. scint.	100%	~150 MeV	$\pm 10\% (t/E_{0})^{1/2}$	±5 cm	20 ns	Good	Fair	Difficult	1,000
6	Ph-liq. argon	100%	~ 50 MeV	$\pm 11\% (t/E_0)^{1/2}$	±5 mm	0.3 -1 .0 µs	Poor	Poor	Difficult	1,000
7	Liq. scint.	100%	< 10 MeV	±6%/E ₀ 1/2	±5 cm	20 ns	Good	Good	Moderate	1,000
8	Pb-glass	100%	< 20 MeV	±6%/E ₀ 1/2	±3 cm	20 ns	Good	Good	Easy	5,000
8	Pb-glass	100%	< 20 MeV	±6%/E ₀ 1/2	±10 cm	20 ns	Good	Good	Easy	3,000
9	Liq. PTC	100%	< 10 MeV	similar to Nal ?	±1 cm	500 ns	Poor	Excellent?	Moderate	3,000 ·
10	NaI	100%	< 10 MeV	$\pm 1.0\%/E_0^{1/4}$	±3 cm	< 200 ns	Good	Excellent	Moderat e	15,000 -
11	Pair-spectr.	x/X _o	0.015 BL	x/4X ₀	±1 mm		Good	Excellent	Moderate	20,000 · pe
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Fig. 4





Fig. 5



Fig. 6



Fig. 7



Fig. 8



Schematic diagram of the hodoscope spectrometer. Stell convertors are shown by thick lines.



The scintillation counters of the hodoscope spectrometer. Dimensions are given in mm. The first three blocks of the spectrometer are made with counters of type a and b. The fourth block is made with type c. The scintillator dimensions are: thickness (in the beam direction) 1 cm. width 1.5 cm (a and b) and 12.5 cm (c), length, L varies from 67 to 100 cm.











Fig. 13



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Fig. 15



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Fig. 17





Fig. 19





Fig. 21