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Neutron Physics Division

HADRONIC- AND ELECTROMAGNETIC-CASCADE DISCRIMINATION
IN A THIN LEAD-ARGON CALORIMETER*

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Abstract

Calculations have been carried out to determine methods or a combination of methods for discriminating between high-energy (≥ 15 GeV) hadrons and leptons or photons incident on a thin lead-argon calorimeter. Some of the methods considered involve fluctuations in shower development, the centroid of the shower, and ratios of the pulse height obtained from various locations within the device. Of these, the latter appears the most promising.

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1. INTRODUCTION

Calorimetric discrimination between incident hadrons and leptons or photons is a challenging and often frustrating problem that has to be solved for many experimental setups. Unfortunately, no one solution is applicable in all situations due to the wide diversity of calorimeter design. Presented in this paper is a series of calculations in which several different approaches have been taken to solve this problem for a thin [27 radiation lengths (r.l.), 1.24 interaction lengths (i.l.)] lead-argon calorimeter. These types of calorimeters, whose theory and design are well documented¹⁻⁵), are proving to be very versatile and accurate devices for measuring the position and energy of the hadrons, leptons, and photons.

The particular device considered in this work is to be used at the Fermi National Accelerator Laboratory in a mixed particle field to detect photons in the energy range of 10 to 100 GeV and specifically those photons that result from the decay of neutral pions produced through dissociation processes⁶). For comparison with a more conventional shower detector, calculations were also carried out for hadrons incident on a lead-plastic scintillator detector of the Caltech variety⁷).

In sect. 2 the geometry of the calorimeters and the methods of calculation are described and in sect. 3 the results are presented and discussed.

2. GEOMETRY AND CALCULATIONAL METHODS

As shown in fig. 1, the calorimeter has a total of 70 unit cells, each consisting of a 2-mm lead plate, a 1-mm gap for liquid argon, a 1/16-in.-thick sheet of G-10 (see table 1) having copper readout strips 1 cm wide etched on both sides (one for x and one for y), and a second 1-mm gap for liquid argon. The cross-sectional area of the calorimeter is $70 \times 70 \text{ cm}^2$.

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Fig. 1. Schematic diagram of the lead-argon calorimeter used in the Monte Carlo calculations.

The properties of the materials used in this detector are given in table 1. A depth of ~ 27 r.l. was chosen so as to contain (within a few percent) a 100-GeV photon shower. However, this amount of material is ~ 1.24 -i.l. thick, so that the number of interactions of hadrons in the detector is substantial.

The lead-plastic design is essentially that of the Caltech detector⁷⁾, with 0.25-in. lead plates separating alternate x and y planes of 0.25-in.-thick by 1-cm-wide scintillator fingers for a total of 10 x and 10 y planes. This detector has a total of 23 r.l. and 0.9 i.l.

The calculational procedures employed for obtaining detailed descriptions of the three-dimensional hadronic and electromagnetic cascades within multimedia calorimeters have been described previously⁸⁾ and will not be discussed here. It is sufficient to state that the code system has been compared many times with different experimental data and reasonable agreement has been obtained⁸⁾.

3. RESULTS

Using the simple attenuation law $N(z) = N_0 \exp(-z/\lambda)$, it is expected that $\sim 30\%$ of the incident hadrons will pass through the detector without interacting. This is verified in table 2 for incident protons. Since the energy deposited by a minimum ionizing particle may be at about the noise level of the readout electronics, these particles will not be considered in the results to follow unless explicit remarks are made to the contrary.

The total energy deposited* in argon by hadrons and electrons is shown in fig. 2. Since there is not enough material in the detector to fully develop a hadronic shower, there are large fluctuations in the total energy deposited by hadrons. Electrons deposit $\sim 9.5\%$ of their energy in the argon

*The words "energy deposited" and "pulse height" will be used to mean the same thing.

Table 1
Properties of Materials Used in the Calorimeter

Material	Density (g/cm ³)	Minimum Ionization Energy Loss (MeV/cm)	Radiation Length (cm)	Number of Radiation Lengths	Inter- action Length (cm)	Number of Inter- action Lengths
Pb	11.35	12.8	0.56	25.0	18.5	0.76
Liquid A	1.4	2.2	13.5	1.0	65.0	0.22
G-10 ^a	1.9	3.2	12.6	0.9	42.0	0.26

a. For lack of better information, G-10 was assumed to be an equal atomic mixture of H, Al, and C.

Table 2
Minimum Ionizing Protons

Energy (GeV)	Fraction of Incident Protons Not Interacting (%)	Energy Deposited in Argon (MeV)
50	26 ± 4	47.8 ± 0.5
150	25 ± 5	54.8 ± 0.6
250	35 ± 6	79.9 ± 0.8

Fig. 2. Pulse height for (a) incident hadrons which interact in the detector and (b) incident electrons. All curves have been normalized to 100 counts (statistics for the high-energy particles are poorest).

for incident momenta from 15 to 50 GeV/c. The energy resolution in this range is $\sim 10\%/\sqrt{E(\text{GeV})}$ full width at half maximum (FWHM) - this is for the ideal case of total charge collection and no noise. A prototype lead-argon calorimeter has been tested in an electron beam with momenta up to 10 GeV/c⁹). This detector is ~ 14.7 r.l. thick and uses a 1.2-mm argon gap. The results of this test give an intrinsic energy resolution $\Delta E/E \approx 27\%/\sqrt{E}$ FWHM which is much worse than the above Monte Carlo results. However, if Monte Carlo data from only the front half (~ 13.5 r.l.) of the calorimeter are used, the predicted resolution is $37\%/\sqrt{E}$ FWHM. This emphasizes the necessity of containing the electromagnetic shower. For the whole calorimeter, $\sim 4\%$ of the energy leaks out, whereas for the front half $\sim 15\%$ escapes. From these results, it can be concluded that electron/hadron discrimination based on the total pulse height is feasible for only narrow ranges of electron energies.

Figure 3 shows the average lateral energy deposition for both hadrons and electrons. Considering that the threshold for firing a strip (integrated over the z direction) will be at least the minimum ionizing level (~ 50 -100 MeV), it is clear that high-energy hadron showers are very similar in character to low-energy electron showers. The fact that hadron showers do not spread too much will be an asset when it comes to subtracting off-line these showers from the desired photon or electron showers. For the case of charged hadrons, information will be available experimentally on particle trajectories upstream of the shower detector. Figure 4 shows how accurately positions of incident hadrons can be determined in the detector. These results were obtained by taking an energy-weighted sum of the strip positions^{4,10}); i.e.,

$$\langle x \rangle = \frac{\sum_{i,j} x_i E_{ij}^x}{\sum_{i,j} E_{ij}^x} , \quad (1)$$

Fig. 3. Average lateral spread of showers. The energy deposited in each 1-cm strip is summed over the z direction, and in the averaging, both x and y strips were combined due to the symmetry expected for a particle incident at the center of the detector. The curves for incident hadrons include only those that interacted in the detector.

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Fig. 4. Dispersion of hadron position as determined by Eq. (1). Only interacting hadrons were considered, and each curve has been normalized to 100 counts.

where x_i is the position of the center of the i th strip and E_{ij}^x is the energy deposited in this strip in the j th unit cell. A similar expression is used to determine the y position. The results indicate $\sigma_{\langle x \rangle} \leq 1$ cm for hadrons.

Figure 5 displays the basis for electron/hadron discrimination through differences in longitudinal energy deposition. Electron showers peak at $\sim 6-8$ r.l., whereas a hadron shower is still in an early stage of development throughout the entire calorimeter. As a measure of the fluctuations, the level of rms deviation from the mean is indicated on these figures (i.e., the solid curves are for $\bar{E} + \sigma_{\langle \bar{E} \rangle}$).

Various hadron-rejection schemes based on the longitudinal shower shape were tested. The simplest method (and the one most amenable to triggering needs) is to look at the pulse height from a given region of the detector. This, however, is quite crude as fig. 6 shows. A factor of 5-10 reduction in hadron background (above the minimum ionizing level) may be obtained by cutting on the pulse height in the first five or so radiation lengths, but this will also result in $\geq 10\%$ electron losses, with a strong bias against low-energy electrons. Using the signal from the region at about the peak of an electron shower gives comparable rejection and somewhat fewer losses, though still biasing strongly against lower energy electrons.

The really significant difference between the two showers is the slope of the longitudinal curve beyond the first quarter of the detector. A very efficient hadron-rejection scheme based on this observation is shown in fig. 7. Here the pulse height in the peak region of the electron shower is compared with the pulse height at the back of the detector. The results from all incident hadrons were combined and analyzed according to the total

Fig. 5. Longitudinal shower curves for (a) incident hadrons and (b) incident electrons. The energy deposited in a unit cell is shown as a function of depth in the detector, cell 0 corresponding to the front of the detector. The solid curves indicate the rms deviation from the mean values. For hadrons the minimum ionizing level is also indicated.

Fig. 6. Pulse height in the front 14 cells for (a) incident hadrons interacting in the detector and (b) incident electrons. All curves are normalized to 100 counts. The arrows in (a) indicate the level at which the hadronic signal is down by a factor of 10.

Fig. 7. An efficient scheme for electron/hadron discrimination compares the pulse height at the peak of the electron shower to the pulse height at the back of the detector. In (a) hadrons depositing < 2 GeV are compared with 15-GeV electrons (minimum ionizing hadrons have been removed), and in (b) hadrons depositing ≥ 2 GeV are compared with 50-GeV electrons.

energy deposited in the argon. Those hadrons depositing < 2 GeV are compared with 15-GeV electrons and those depositing ≥ 2 GeV are compared with 50-GeV electrons. The efficiency for low-energy electrons is excellent in this scheme, while high-energy electrons will suffer some losses. The statistics are too poor to determine what exact division of the detector is optimal, but it seems clear that the ratio of the pulse height near the peak of the electron shower to that at the back of the detector would be an excellent indicator of the nature of the shower. For low-energy electrons, it should be possible to obtain at least a factor of 50 rejection with $\leq 2\%$ losses, whereas for high-energy electrons a factor of 20 in rejection with $\leq 8\%$ losses is quite feasible.

Monte Carlo results for 50- and 150-GeV protons incident on a lead-plastic calorimeter (described in sect. 2) were compared with the lead-argon results. The lateral spread and determination of position were comparable though somewhat poorer in the lead-plastic design due to the increase in the sampling fluctuations. Although plastic scintillator inherently has a faster response time, the lead-argon design, particularly with methane doping to speed up drift times, should be quite adequate for a large aperture experiment with $\sim 10^5$ interactions/sec. The lead-argon calorimeter is obviously much more versatile when it comes to dividing the detector into longitudinal sections (which is necessary for good hadron rejection). This, plus better energy resolution, makes a lead-argon calorimeter the best choice when hadron rejection is important.

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