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LEAD-SCINTILLATOR ELECTROMAGNETIC CALORIMETER WITH STEREO READOUT

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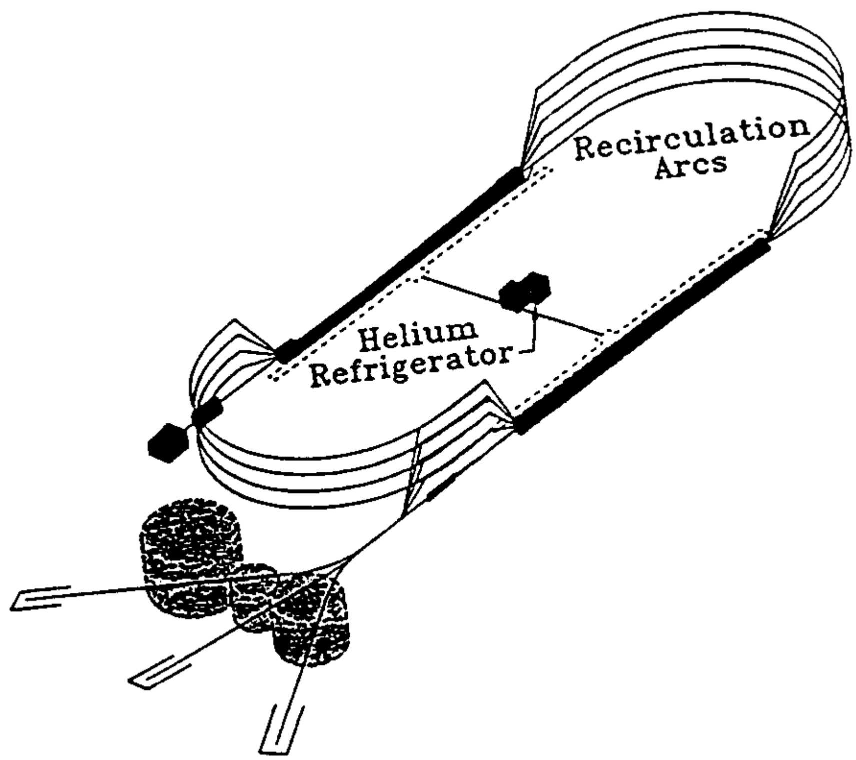

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Lead-scintillator Electromagnetic Calorimeter with Stereo Readout*

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Abstract

We describe an electromagnetic calorimeter consisting of 39 layers of 1 cm thick plastic scintillators alternating with 2 mm thick layers of lead. The calorimeter has a triangular shape with sides 127 cm long. Each scintillation layer is made of 11 scintillators, 10 cm wide, placed parallel to one edge of the triangle, with scintillators in successive layers parallel to successive edges of the triangle. The calorimeter is divided into front (15 layers) and rear (24 layers) sections to improve electron/pion discrimination. Light emerging from one end of each scintillator is absorbed in a wavelength shifter strip placed perpendicular to the scintillator. Reemitted light from the waveshifter is detected by a photomultiplier tube. The device has been tested with a beam of pions and electrons with energies of 1,2,3 and 4 GeV. The measured average energy resolution for electrons was $9.3\%/\sqrt{E(GeV)}$. Efficiencies for identification of electrons and rejection of pions are discussed.

I Introduction

CEBAF is a 4 GeV electron accelerator under construction in Newport News, Virginia, with the first experiments expected to begin in 1994. One of its experimental facilities will be a large multi-purpose particle detector called the CEBAF Large Acceptance Spectrometer, or CLAS. This detector is designed around a toroidal superconducting magnet that will provide a field with approximate axial symmetry along the incident electron beam. The trajectories of charged particles traveling through the magnetic field after emerging from a target on the beam line will be measured in several layers of wire drift chambers. From the curvatures of the paths it will be possible to determine the momenta of the particles with a precision of 0.25 - 0.5% (σ).

To help with the identification of electrons as well as to detect neutral particles we plan to use a total absorption electromagnetic calorimeter[1] for forward angles, 5^0 to 45^0. A calorimeter designed to absorb all the energy of an electron with energies in the GeV range will typically absorb only about 250 MeV of energy from an energetic charged pion, unless the pion undergoes a nuclear interaction. In such an interaction a variable amount of energy (ranging up to the entire energy of the pion) is converted into the kinetic energy of a number of charged particles. Thus a pion, with its energy determined by the wire drift chambers, may sometimes deposit the same amount of energy as an electron. We had estimated that for an energy measurement with a precision better than $10\%\ /\sqrt{E}$ it would be possible to identify 98% of the electrons while rejecting 99.3% of the pions of the same energy at 2 GeV.

The CLAS detector consists of six symmetric sectors around the beam line. Sectors are separated by the superconducting coils of the toroidal magnet. Figure 1 shows that in the forward direction, 5-45^0, the ideal detector would fill the regions between the coils, while the regions in the coils' shadows would be available for any infrastructure needed to extract the signal.

To resolve multiple showers in the same event, the ideal calorimeter would employ a tower like structure, such as used by many collider experiments in high energy laboratories. However, since we expect an average multiplicity of only 4-5 particles in the full 4π solid angle, we can use a scheme with somewhat less granularity, which is also less expensive, an important consideration when the total area is of the order of 50 m^2. Furthermore, the calorimeter will define the normalization of the cross sections so that we cannot tolerate the cracks associated with the tower geometry.

We propose to fill the triangular regions with alternating layers of scintillator and lead. The scintillator converts the

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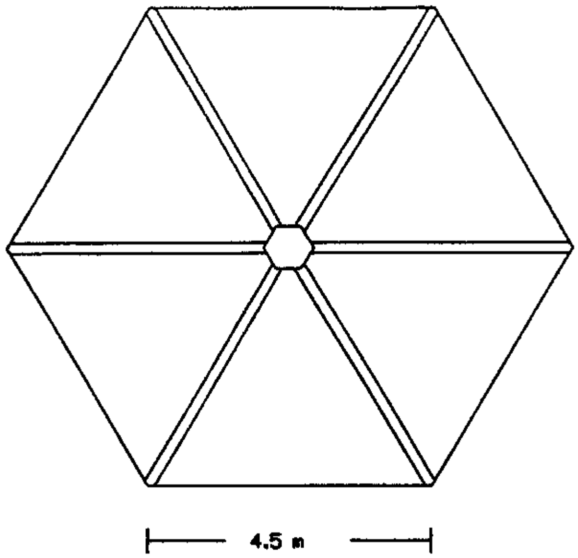

Figure 1: End-cap region of the CLAS detector

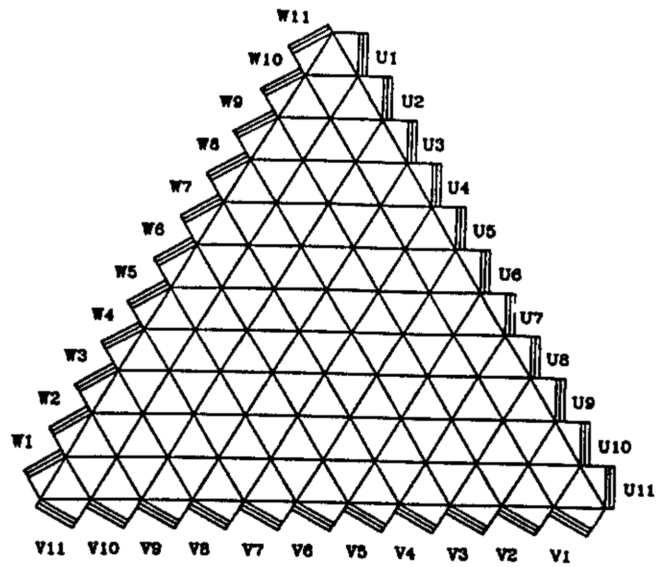

Figure 2: Plan view of the calorimeter

energy of charged particles into light, while the lead provides the high Z material to convert the electron energy to low energy shower particles in a compact region. We have chosen to measure the location of the incident particle by triangulation[2]. Thus the scintillators are oriented in three directions. To achieve a compact light readout that will fit behind the magnet coils we are using wavelength shifters[3-5] to redirect the light perpendicular to the scintillators.

The following sections describe the design, and the results of beam tests on a prototype detector.

II The prototype detector

To test the feasibility of the concept for the large detector required, we first checked to see whether the attenuation length of commercial scintillator was long enough. Our measurements of 2.8 m for bars of NE110 scintillator 10 cm wide, 1 cm thick and 3 m long encouraged us to proceed with the project. From tests of wavelength shifter bars, made of NE172 by the NE Corporation, we determined that for each photon reaching the wavelength shifter approximately one photon of longer wavelength was re-emitted. From this we calculated that about 50 photons per MeV of energy deposited in the scintillator would reach the cathode of a photomultiplier connected by a light pipe to the end of the wavelength shifter.

The prototype electromagnetic calorimeter uses 39 layers of 1 cm thick plastic scintillator alternating with 2 mm thick layers of lead, for a total thickness of 14.6 radiation lengths (r.l.). EGS4[6] and GEANT[7] calculations show that about 1/3 of the electron energy is deposited in the scintillator material. The thickness is about 0.9 nuclear interaction lengths, so that about 40% of incident pions are expected to pass through the detector without a nuclear interaction. Each layer, which is made of 11 scintillator bars 10 cm wide, is in the shape of an equilateral triangle with a height of 110 cm, and a side 127 cm long.

The sides of the triangle define three axes that we label U,V, and W, as shown in Figure 2. The pattern is alternated so that the first layer is a U, the second a V, and third a W, after which the succession is repeated. The cells defined by the intersections of the three orientations are equilateral triangles, 11.6 cm on each side.

Simultaneous particles in non-adjacent cells will always give signals in different scintillators in at least one of the U, V, W planes. Thus multiple particle events can be resolved. This feature is particularly important for detection of pairs of γ rays from π^0 decay, and should help in rejection of background radiation.

To read out the scintillator light, a wavelength shifter 1 cm thick by 10 cm wide and oriented perpendicular to the scintillator planes is coupled to one end of each scintillator strip. The location of the wavelength shifters is shown in Figure 2. The wavelength shifters absorb the blue and ultra-violet light from the scintillator and re-emit light in the green region of the spectrum. The wavelength shifters are each coupled by a light guides to a photomultiplier tube (PMT). To avoid loss of light from the wavelength shifter back into the scintillator bars, it is necessary to leave a slight air gap between the scintillator and the wavelength shifter. Since any number of layers of scintillator can be coupled to a common wavelength shifter, it is not necessary to provide a separate photomultiplier for each scintillator.

To improve the efficiency for pion rejection, the calorimeter is segmented into a front section consisting of the first 15 layers (5.5 r.l.), and a back section consisting of 24 layers (9.1 r.l.). Separate sets of wavelength shifter bars are used to capture the signals from the front and rear segments. This is accomplished by making the rear scintillators 1 cm shorter than the front so that the rear wavelength shifter bars around the perimeter were inside the space filled by the front wavelength shifter bars. The use of two sets of wavelength shifters is also illustrated in Figure 2. Altogether, the calorimeter uses 66 wavelength shifter bars to read the out light from the 421 scintillator bars.

At the front of the detector is a 0.5" triangular aluminum plate with 33 holes drilled around its perimeter for 5/16" threaded rods to pass through. Additional holes were drilled near the each of the three vertices for 3/4" threaded rods. During assembly the front plate was placed flat on a table with the threaded rods in place. For each scintillator layer a frame-work of aluminum bars were placed around the perimeter and held in place with the threaded rods. A layer of white paper was put down, followed by the scintillator bars. The bars were optically decoupled by separating them with strips of 0.001" aluminum foil. They were then covered with another layer of white paper followed by a layer of 2mm thick antimonial lead. Then the next frame-work of aluminum bars was put in place and the process was repeated. After all the layers were in place, an aluminum plate 1.0" thick was placed over the the assembly. Nuts on the 5/16" rods were then tightened to squeeze the layers together, providing a very rigid and stable assembly. Wavelength shifters pass through slots in the top cover plate. After insertion of all the shifters with light pipes glued to them, a third aluminum plate (the PMT plate), located about 50 cm above the top-plate, was attached to the three 3/4" rods . The light guides passed through this plate and were connected to PMT's fastened to the plate. The entire assembly was sealed against light leaks with aluminum flashing and tape.

III Test procedure and results

The calorimeter was mounted in the test beam at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL). The particles in the beam have a momentum distribution with a width of about 2%. A pair of scintillators in the beamline defined a 10 cm by 10 cm square on the detector. The beam, predominantly π^- mesons, had a small component of electrons (3.5 % at 2 GeV) which were selected by two gas Cerenkov counters. Extraneous background was reduced by the use of slits upstream of the beamline detectors. The total material in the beam was only 0.05 r.l. so that the probability of electrons interacting before they reached our detector was small. The detector was supported by a platform that allowed us to move it both horizontally and vertically to study the response of different regions.

Coincident signals from the beam line scintillators served to indicate the passage of a charged particle into the calorimeter. Coincident signals from two gas Cerenkov counters were used to set flags. The signals from the calorimeter PMT's were split into two pulses, one going directly to a CAMAC analog to digital converter (ADC) and the other going to a discriminator whose output signal was used to stop a TDC that had been started by the beam signal. Information was read into a computer via a CAMAC system, using the Q data acquisition software provided by the Los Alamos Meson Physics Facility (LAMPF).

III-A Calibration of PMT outputs

Those pions that pass through the detector without nuclear interaction deposit an average of 2 MeV of energy in each scintillator. The direction of a pion is hardly changed as it passes through, so that it excites the same corresponding scintillator bar in each layer. A distribution of pion pulse heights shows a distinct peak associated with minimum ionizing pions and a tail at larger pulse heights from pions that undergo nuclear interactions. The position of the peak was compared to the known minimum ionizing energy loss to obtain a preliminary energy calibration for the affected wavelength shifter. Next, the signals associated with electrons were studied. Because of the lateral spread in the showers, these signals usually involved more than one scintillator in each plane. The bulk of the energy was deposited in two adjacent ones, but for best resolution it was necessary to sum over four adjacent strips. The energy calibration of the calorimeter was then improved in a two-step process. First the averaged values of the summed signals from the front U, V and W bars were equalized, as were the averaged values of the summed signals from the rear U, V and W bars. Second, the total energy deposited in the front section and the total energy deposited in the rear section were adjusted with calibration factors common to U, V, and W so that on the average the total energy in the calorimeter was independent of how it was divided between the two sections.

III-B Energy response to pions

A typical energy spectrum for 2 GeV pions is shown in Figure 3. The minimum ionizing peak and the nuclear interaction tail are clearly visible in this figure. The shape of the minimum ionizing peak is due to a folding of the dE/dx energy loss spectrum with a statistical broadening due to collection of a finite number of photoelectrons at the cathode of the photomultiplier. We have calculated the expected line shape for this process and determined that pions yield 3.5 photoelectrons per MeV.

III-C Energy response to electrons

A typical energy spectrum obtained for 2 GeV electrons is shown in Figure 4. The spectrum is characterized by a peak corresponding to the total absorption of the shower energy in the calorimeter. Only about 1/3 of the energy is actually deposited in scintillator, and the energy scale has been adjusted to put the peak at the full electron energy. The width (σ) of the peak is 6.1% of the full energy. The resolution improves with increasing energy, as expected.

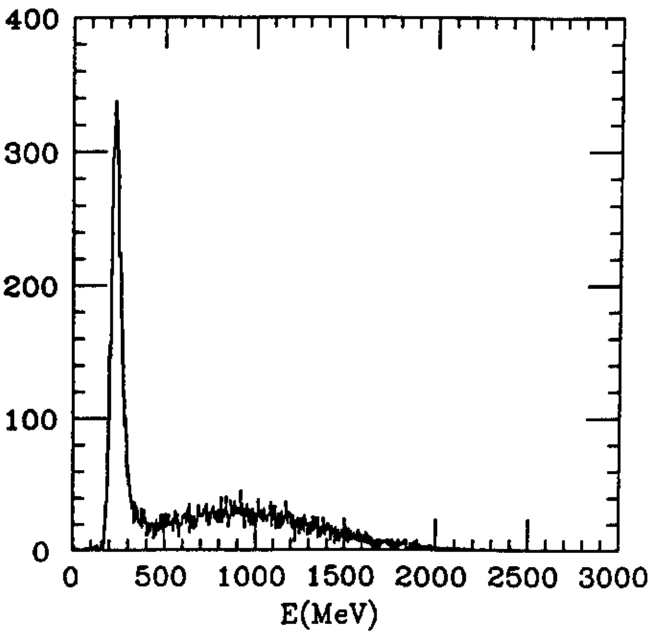

Figure 3: Calorimeter response to 2 GeV pions

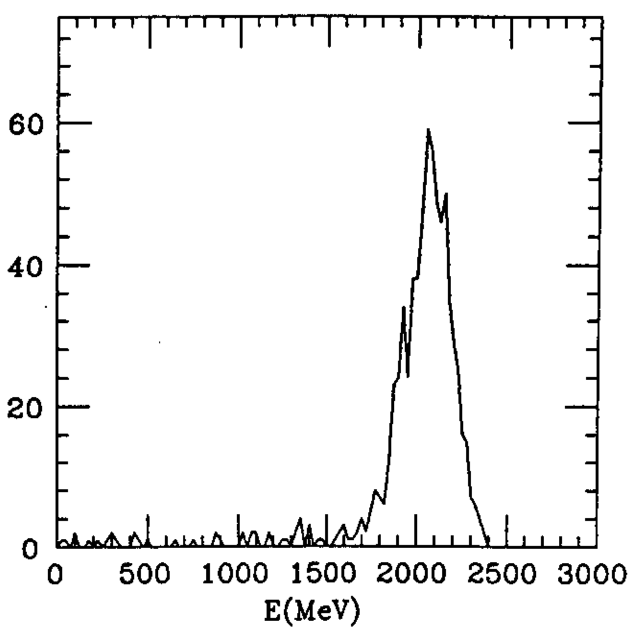

Figure 4: Calorimeter response to 2 GeV electrons

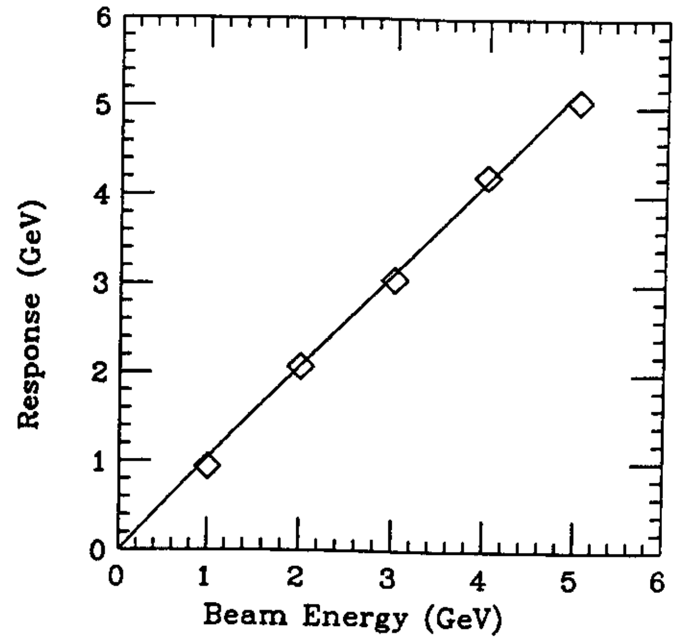

Figure 5: Measured electron energy vs. beam energy

Some results are shown in Table I, and can be summarized by the formula, $\frac{\sigma}{E} = \frac{9.3\%}{\sqrt{E(GeV)}}$.

The measured energy resolution can be compared to Monte Carlo simulations made using the EGS4[6] and GEANT[7] programs which yielded an energy resolution of $\frac{6.4\%}{\sqrt{E(GeV)}}$. This resolution arises from statistical fluctuations in the fraction of energy sampled by the scintillator. Additional contributions from the fluctuations in the number of photoelectrons produced at the PMT cathode, and in variations in optical coupling and propagation in the scintillator and wavelength shifters must be added. A 1 GeV electron deposits approximately 330 MeV in the scintillator, which on the basis of the analysis of the measured pion pulse shape yields 1150 photoelectrons. The associated statistical fluctuation is 2.9%. Variations in optical coupling and in attenuation might contribute as much as 5% to the resolution. The combination of these effects approximately accounts for our measurements.

The linearity of the energy response for electrons is illustrated in Figure 5, which shows a plot of measured peak energy versus beam energy for the central region of the detector, using the same calibrations at all energies. Also shown is a straight-line fit.

The tail on the low energy side of the electron peak appears to be from low energy electrons, that were probably produced by slit scattering. Tests with other detectors in the beam line are consistent with this interpretation.

III-D Position resolution

The distribution of scintillator outputs can be used to locate the position of a particle in the detector. For minimum ionizing particles the precision is mostly limited by the size of an intersection cell. For electron showers, which spread into neighboring cells, the distribution of en-

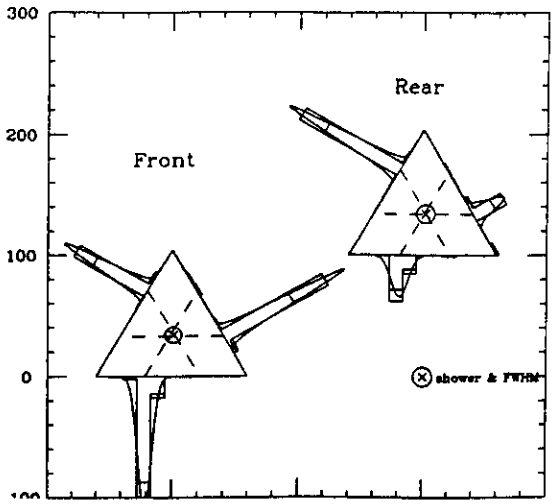

Figure 6: Centroid of electron shower

ergy deposition should allow an improved determination of the centroid. A typical distribution is illustrated in Figure 6. Here, the pulse height measured in each wavelength shifter is denoted in a plot along the corresponding side of the triangle. After calculating the U, V and W centroids, lines parallel to the three axes and passing through these centroids are drawn. Their intersection determines the centroid of the shower. There is no guarantee that the three lines will intersect at a point, and the size of the circle of confusion defining the intersection is a measure of the quality of the event. We are still developing techniques to make optimum use of this information for centroid determination.

III-E Pion-electron discrimination

Pions and electrons of the same energy are largely separated by the distinctly different energy deposition in the calorimeter. However, a few percent of the pions deposit the same energy as an electron. This fraction generally decreases as the energy resolution improves with increasing energy. It can be further reduced by using the front/rear division of the calorimeter. Some pions that deposit large amounts of energy due to a nuclear interaction in the rear section and very little in the front can can be removed with energy cuts that do not affect the electron efficiency. The results for the number of pions within 3σ of the shower peak are shown as f_π in Table I. In this table entries with the same beam energy, E, correspond to runs with the beam entering at different positions. The pion rejection is not quite as good as expected, particularly at the higher energies.

Table I

E	σ /E	$\sigma/\sqrt{E}$	f_π
(GeV)	%	%	%
1.0	9.3	9.3	5.4
2.0	6.2	8.7	1.4
2.0	5.9	8.3	1.5
2.0	6.6	9.4	1.3
3.0	5.5	9.5	1.5
4.0	4.7	9.4	1.2

III-F Variations with position

For the most part no significant differences in energy resolution were observed for particles entering at different points on the face of the detector. Some deterioration in energy resolution was observed for particles that entered within about 10 cm of the edge of the detector. This is to be expected from leakage of shower particles out through the edge of the detector.

IV Conclusions

We have built and tested a lead/scintillator sandwich calorimeter with a stereo read-out geometry. It measures electron shower energies with a resolution of $\frac{9.3\%}{\sqrt{E}}$, and its front-rear segmentation can be used to reject more than 98% of the pions at 2 GeV. We are continuing to improve techniques for pattern recognition. A full-scale version for the CLAS detector is being designed.

V Acknowledgements

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