**DESIGN AND TEST OF A PROTOTYPE GAS-SAMPLING
ELECTROMAGNETIC CALORIMETER OF HIGH GRANULARITY
FOR THE CPLEAR EXPERIMENT**

The CPLEAR Collaboration

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Abstract

We have designed and tested a gas-sampling calorimeter of high granularity as a prototype for the electromagnetic calorimeter of the CPLEAR experiment. The prototype calorimeter, consisting of 18 layers of 1.5 mm thin lead converters interleaved with a total of 1152 high-gain tubes and 2304 pick-up strips, was tested in a tagged photon beam with photons in the energy range of 50 to 350 MeV. It fulfilled well the requirements of a good detection efficiency for photons above 50 MeV with a spatial resolution $\sigma \approx 5$ mm for the photon conversion point and an energy resolution $\sigma(E)/E \approx 15\%/\sqrt{E}(\text{GeV})$.

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1. INTRODUCTION

The CPLEAR experiment, which is installed at the Low-Energy Antiproton Ring (LEAR) at CERN, is measuring CP-violating parameters in the $K^0/\bar{K}^0$ system [1]. The use of tagged K^0 's and $\bar{K}^0$'s allows the study of interference effects in the neutral kaon system in various decay channels. An electromagnetic calorimeter is needed to detect the photons produced in the decays of the $K^0/\bar{K}^0$ involving neutral pions and electrons. Since the momentum of the initial K^0 from the proton-antiproton annihilation at rest is on an average about 500 MeV/c, the photons from the decay $K^0 \rightarrow 2\pi^0$ have a mean energy of only ≈ 160 MeV.

The measurement of time-integrated asymmetries of the kaonic decay rates does not imply the reconstruction of the decay-time of the neutral kaon and therefore requires only a good detection efficiency for the photons down to 50 MeV. To measure interference effects as a function of the decay-time, it is necessary to reconstruct the decay vertex of K^0 and $\bar{K}^0$. As Monte Carlo studies using the GEANT-3 code [2] have shown, a good vertex reconstruction for the decay of the kaon into neutral pions can be achieved by accurately measuring the conversion points of the photons, even if the resolution on their energy measurement is rather poor (see fig. 1).

The CPLEAR calorimeter should therefore fulfil the following requirements:

- a high spatial resolution of the photon conversion point ($\sigma \lesssim 5$ mm);
- a good detection efficiency for photons of energies as low as 50 MeV;
- an energy resolution $\sigma(E)/E \approx 15\%/\sqrt{E(\text{GeV})}$.

In this paper we report on the design and test of a prototype calorimeter. In section 2 the design of the prototype is described. The efficiency for detecting photons is shown in section 3, whilst the measured energy resolution is discussed in section 4. Section 5 is devoted to the spatial resolution for detecting photons as well as charged particles.

2. PROTOTYPE CALORIMETER DESIGN

To achieve a desired spatial resolution of ≈ 5 mm on the photon conversion point we decided to build a gas-sampling calorimeter of high granularity, consisting of successive layers of high-gain tubes and strip boards interleaved with lead converter sheets. The prototype represents a small planar sector of the final cylindrical CPLEAR calorimeter, with an active surface of 44×32 cm², and it allows the detection of photons with incident angles up to 30°. As in the final calorimeter, its thickness is ≈ 21 cm, corresponding to 18 layers and 5.8 radiation lengths. (An existing magnet had to be used in the CPLEAR experiment and the total thickness reserved for the calorimeter is only 22 cm).

A layer consists of a converter plate followed by a set of two sheets of pick-up strips (called U- and V-strips in the following) placed above and below eight chambers (see fig. 2). The converter consists of 1.5 mm thick lead plates reinforced by 0.3 mm thick aluminium foils glued on each side of the plate, resulting in a total thickness of 2.3 mm. These converter plates are held by a mechanical structure on two sides, so that they form a self-supporting skeleton for the chambers and strips (see fig. 3). For mechanical reasons, the first converter plate is replaced by a 1.5 cm thick aluminium plate.

One chamber 50 cm long, 4.3 cm wide, 6.2 mm thick, contains eight tubes of 4.5×4.0 mm² cross-section. The sense wire spacing is 5 mm. The development and performances of these small high-gain tubes and their special design, allowing an external strip read out by detecting the induced pulses through high-resistive cathode walls, have been described elsewhere [3]. The tubes are operated in a high-gain mode at 3200 V using CO₂ saturated

by pentane at 14° C, which allows the signal to be read out from the wires without any amplification. The typical pulse from a wire is 20 mV and 30 ns on a 50 Ω load.

A pick-up strip board 0.7 mm thick contains 64 strips, 5.3 mm wide and separated by a 1 mm gap. They are placed above and below the chambers and have an angle of +30° (U-strips) or -30° (V-strips) with respect to the wire direction. The signal induced in the strips is typically 20 μ A. It is fed into a current-to-voltage preamplifier (1.2 mV/ μ A) in order to give a signal similar to the one from the wire.

In total the prototype contains 1152 tubes and 2304 pick-up strips. The 3456 analog channels are read out digitally by an RMH system [4].

3. EFFICIENCIES

We carried out the test of the prototype at the Paul Scherrer Institute (PSI), with muons, positrons and tagged photons.

The efficiency of a tube for detecting an ionizing particle has been measured with 250 MeV positive muons incident perpendicular to the prototype and traversing all the 18 layers, by counting the number of layers which had at least one tube hit. A typical muon track is shown in fig. 4 demonstrating well the good efficiencies of the tubes and strips as well as the small multiplicity of the strips. Since the chambers of the different layers were aligned, this method evaluates the efficiency of the active volume of the tube. We measured an average tube efficiency of $(96 \pm 1)\%$.

The efficiency of the strips has also been measured with muons, by asking whether at least one strip was hit when exactly one tube had fired in a layer. As discussed elsewhere [3], the pulse height on the strips, and therefore the efficiency, varies rapidly with the distance between the tubes and the strips. We therefore took care, when assembling the calorimeter, that the strip boards were uniformly pressed onto the chambers. The average efficiency of all the strips of the prototype was measured to be $(97 \pm 4)\%$. When selecting tracks with exactly one tube hit per layer, the average multiplicity of strips hit per tube hit was 1.3 ± 0.2 .

The detection efficiency for photons was measured in a tagged photon beam. Photons in the energy range of 50 to 350 MeV were produced by positron bremsstrahlung in a thin wolfram foil and tagged by analysing in a spectrometer the momentum of the outgoing positrons.

The detection efficiency for photons is given by the number of detected photons per number of tagged photon triggers. A photon is defined as being detected when the number of tubes fired is ≥ 3 . This rejects background due to noise. Owing to the high intensity and the substantial impurity of the initial beam, false photon triggers could occur, which were not accompanied by bremsstrahlung. Therefore, the efficiency thus defined is only a lower limit. Figure 5 shows this lower limit, for the photon-detection efficiency as a function of the photon energy. It is better than 90% for photons above 100 MeV.

To obtain a more realistic value, we have estimated the fraction of false triggers using in the same beam an 11 radiation lengths BGO calorimeter, which is assumed to be fully efficient for γ detection. After this correction, we obtain a detection efficiency for the prototype calorimeter of 95% for energies above 75 MeV as shown in Fig. 5.

As indicated in the same figure, a detailed Monte Carlo simulation gives a detection efficiency $\geq 95\%$ for photons of more than 100 MeV (93% and 85% for 75 MeV and 50 MeV respectively), which agrees well with the measured efficiency.

4. ENERGY MEASUREMENT

Monte Carlo studies have shown that, in such a sampling calorimeter, for photons with energies of a few hundred MeV only, the best energy resolution is obtained by counting track segments in a purely digital way, rather than measuring the energy deposited in the gas.

Figure 6 shows the three projections (wires, U-, and V-strips) for a typical 150 MeV photon showering in the prototype. The mean number of tubes hit in the calorimeter as a function of the energy of the detected photon and the resolution on the distribution of the number of hits has been measured with tagged photons of 50 to 350 MeV energy. For example, from the hit distribution in fig. 7 one can see that photons of 150 MeV correspond to a mean hit multiplicity $\langle N \rangle = 13.2$ with a resolution $\sigma(N)/\langle N \rangle \approx 0.35$.

In fig. 8 is plotted the measured, as well as the simulated, mean hit multiplicity as a function of the energy for all photons converting in the calorimeter. The Monte Carlo simulation [2] is in very good agreement with the data. The deviation of the plotted points from a straight line is due to the limited thickness of the calorimeter, leading to shower leakages especially for photons converting deep inside the calorimeter.

This is nicely demonstrated in fig. 9. The non-linearity is reduced when selecting only photons which convert in one of the first four layers. Also for positrons, which start to shower in the first or second layer, the measured number of tubes hit as a function of the energy does indeed show a very linear behaviour and is compatible with that of the early converting photons.

The number of hits as a function of the penetration depth (conversion layer) is shown in fig. 10 for three different energies. For a photon of 50 MeV the mean number of hits is nearly independent of the layer where it converted, whereas, for a 250 MeV photon, leakage effects can already be seen for conversions occurring after a few layers.

The resolution on the hit distribution for different photon energies is shown in fig. 11 for all photons, as well as for photons converting in the first four layers. The difference in resolution between early converting photons and all photons is growing with increasing energy and is again due to shower leakages. In this energy range we can parametrize our energy response [5], and we obtain for the prototype with 18 layers a resolution $\sigma(E)/E$ for all converting photons of $(12 \text{ to } 20)\%/\sqrt{E \text{ (GeV)}}$ for the energy range of 50 MeV to 350 MeV and of $(10 \text{ to } 13)\%/\sqrt{E \text{ (GeV)}}$ for photons converting in the first four layers.

From Monte Carlo simulations, in Figs. 11 and 12, it is clear that a thicker calorimeter, for example of 50 layers corresponding to ≈ 18 radiation lengths (which unfortunately does not fit into the CPLEAR detector) would have considerably improved the linearity, giving rise to a resolution better than $10\%/\sqrt{E}$.

5. SPATIAL RESOLUTION

It has been shown with Monte Carlo simulations that the optimal spatial resolution on the photons is obtained by detecting the shower particles as close as possible to the conversion point of the photon. This is why, unlike many high energy experiments, we have an independent readout of every wire and strip.

The spatial resolution for reconstructing the conversion point could not be measured directly with the tagged photons. To measure an expected resolution $\sigma \approx 5$ mm a collimation of a few millimetres would have been necessary, which was difficult to achieve with an acceptable trigger rate.

We therefore measured the spatial resolution with charged muons and estimated the resolution on the photon conversion point by a Monte Carlo simulation taking also into account the efficiencies of the chambers and strips (see section 3).

For a muon track, using only one-direction strip planes (U- or V-strips) the coordinate (v or u) perpendicular to the strip axis is reconstructed with a resolution $\sigma_v = \sigma_u = 3.15$ mm, as can be seen from fig. 13. The resolution of the coordinate perpendicular to the wires is estimated by the distance of 5 mm between the wires, to be $\sigma_{w_\perp} = 1.5$ mm. Along the wire the coordinate $w_\parallel$ has to be reconstructed using the information of the strips. Since the streamer develops very near to the wire, $w_\parallel$ is given by the coordinate along the wire of the crossing point between the axis of the two corresponding U- and V-strip. From the distribution shown in fig. 14 we measure $\sigma_{w_\parallel} = 3.9$ mm.

The above values for σ_u, σ_v and $\sigma_{w_\parallel}$ include a multiple scattering contribution. We have then computed the difference between the known wire position w and the value of the coordinate perpendicular to the wire, $w_\perp(u, v)$, for the crossing of the two strip axis in the same layer. The corresponding distribution is shown in fig. 15. From its width $\sigma_{w_\perp}(u, v; w) = 1.1$ mm we can infer $\sigma_{w_\parallel}(u, v; w) = \sqrt{3} \sigma_{w_\perp}(u, v; w) = 2.25$ mm; both values are free from multiple scattering uncertainty. By folding these measured resolutions in a Monte Carlo simulation we have estimated that the photon conversion point is given by the first tube hit with a 5 mm resolution.

6. CONCLUSIONS

We have constructed a very compact electromagnetic gas-sampling calorimeter of high granularity to detect photons in the 100 MeV region, consisting of successive layers of wire chambers and pick-up strips interleaved with lead converter plates. The 3456 channels are read out in a digital way.

The performances of the calorimeter have been tested with charged particles as well as with tagged photons in the energy range of 50 to 350 MeV. The tube efficiency for detecting charged track segments has been measured to be $(96 \pm 1)\%$ and the efficiency of the strips per wire hit was found to be $(97 \pm 4)\%$. The overall detection efficiency of the calorimeter is $\approx 95\%$ for photons of more than 75 MeV. The energy of a photon is determined by counting the track segments of a shower. For a calorimeter of 18 layers and 5.8 radiation lengths we measured an average resolution of $\approx 15\%/\sqrt{E(\text{GeV})}$. It has been shown that, with a thicker calorimeter, a better resolution of the order of $11\%/\sqrt{E(\text{GeV})}$ could be obtained for higher energies. The spatial resolution on the reconstruction of the shower conversion point is ≈ 5 mm.

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Figure 1: Monte Carlo simulation of the K^0 decaying into $\pi^0\pi^0 \rightarrow 4\gamma$, showing the resolution on the reconstructed K^0 vertex as a function of the spatial resolution and the energy resolution for detecting the photons.

Figure 2: Photograph of one chamber consisting of eight tubes positioned on a strip plate with 64 strips.

Figure 3: Photograph of the 18 layer calorimeter skeleton.

Figure 4: The three projections (wires, U- and V-strips) of a 250 MeV muon track in the calorimeter prototype.

Figure 5: The measured and the simulated photon detection efficiency as a function of the photon energy. The error bars indicate the lower limits.

Figure 6: The three projections (wires, U- and V-strips) of a 150 MeV photon showering in the calorimeter prototype.

Figure 7: Distribution of the number of tubes hit for 150 MeV photons.

Figure 8: Measured and simulated mean number of tubes hit as a function of the photon energy for an 18 layer calorimeter.

Figure 9: Mean number of tubes hit as a function of the photon energy for all converting photons, for photons converting in the first four layers, and for positrons. Also shown is a Monte Carlo simulation for a 50 layer calorimeter.

Figure 10: Mean number of tubes hit as a function of the layer where the photon converted for different photon energies.

Figure 11: Resolution on the number of tubes hit as a function of the photon energy for all converting photons, for photons converting in the first four layers, and for positrons.

Figure 12: Resolution on the number of tubes hit as a function of the photon energy as obtained by Monte Carlo for the 18 and the 50 layer prototype simulations.

Figure 13: Distribution of the difference between the measured value u (or v) of the coordinate perpendicular to the strip axis and the value corresponding to the muon track as reconstructed using only V- (or U-) strip planes.

Figure 14: Distribution of the difference between the measured value $w_{||}$ of the coordinate along the wire axis and the value corresponding to the reconstructed muon track when using U- and V- strip planes.

Figure 15: Distribution of the difference between the known wire position and the value of the coordinate perpendicular to the wire axis as obtained from the strip crossing in the same layer.