TEST BEAM STUDY OF THE KOPIO SHASHLYK CALORIMETER PROTOTYPE

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The Shashlyk calorimeter prototype for the KOPIO experiment have been designed, constructed, and experimentally tested using the $220 \div 370$ MeV photon beam of LEGS setup at Brookhaven NSLS. The energy $(2.9 \pm 0.1)\%/\sqrt{E\ (\mathrm{GeV})}$ and time (90 ± 10) psec$/\sqrt{E\ (\mathrm{GeV})}$ resolutions have been obtained. The photon detection inefficiency was experimentally tested.

1. Introduction

We have developed an improved Shashlyk based calorimeter to be used in the KOPIO experiment [1] at Brookhaven National Laboratory. The experiment places great demand on the calorimeter since it involves measuring the branching ratio of the very rare decay mode for $K_L \to \pi^0 \nu\bar{\nu}$ which, in the standard model, is $\approx 3 \times 10^{-11}$. Comparison with the intensities of the potential backgrounds $\mathrm{Br}(K_L \to \pi^0\pi^0) = 0.0009$, $\mathrm{Br}(K_L \to \pi^- e^+ \nu\gamma) = 0.0036$, $\mathrm{Br}(K_L \to \pi^+\pi^-\pi^0) = 0.1255$ illuminates the experimental challenge of the measurement. This is "nothing to nothing" decay with a very low branching ratio and a very high background, in which only one (π^0) of three emitted particle may be observed. For such an experiment, photon detection with high efficiency and high resolution is necessary.

The requirements for the photon calorimeter were found in the preliminary simulation of the KOPIO detector:

- Energy resolution $\leq 3.5\%/\sqrt{E\ (\mathrm{GeV})}$

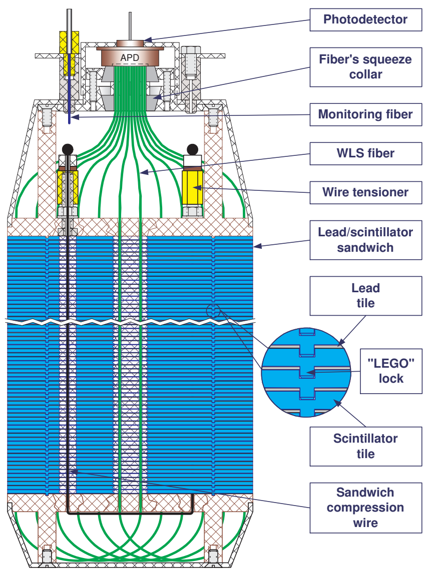

Figure 1. Design of a Shashlyk module, a lead-scintillator sandwich which is read out by means of wave length shifting (WLS) fibers passing through holes in scintillator and lead.

- Time resolution ≤ 100 psec/$\sqrt{E\ \text{(GeV)}}$
- Photon detection inefficiency $\leq 10^{-4}$
- Granularity 10×10 cm^2
- Physical Length ≤ 60 cm
- Active area $\geq 5 \times 5$ m^2

In the original proposal for the KOPIO experiment a CsI calorimeter was considered. The Shashlyk technique [2] (Figure 1) allows us to obtain the adequate calorimeter performance for about 1/10 the cost of CsI. The decision to use the Shashlyk calorimeter was based on the result of a test beam study of the prototype modules in which an energy resolution of 4% for 1 GeV/c positrons was achieved [3]. This module contained 240 layers of 0.35 mm lead and 1.5 mm scintillator tiles. Analysis of the contributions to the energy resolution [3] showed that the main directions for improving energy resolutions up to 3%/$\sqrt{E\ \text{(GeV)}}$ are: (i) sampling; (ii) photo-statistics, and (iii) light collection uniformity.

2. New Shashlyk module with energy resolution of 3%/$\sqrt{E\ \text{(GeV)}}$

The main parameters of the new Shashlyk module are listed in Table 1.

The important innovation in the mechanical design of the module is the

Table 1. Parameters of the $3\%/\sqrt{E\ (\mathrm{GeV})}$ Shashlyk module.

Lateral dimensions	110×110 mm^2
Scintillator thickness	1.5 mm
Gap between scintillator tiles	0.350 mm
Lead absorber thickness	0.275 mm
Number of layers	300
WLS fibers per module	72×1.5 m = 108 m
Fiber spacing	9.3 mm
Hole diameter (lead/scint.)	1.3 mm
Diameter of WLS fiber (Y11-200MS)	1.0 mm
Fiber bundle diameter	14.0 mm
External wrapping (TYVEK paper)	150 μm
Effective radiation length, X_0	34.9 mm
Effective Moliere radius, R_M	59.8 mm
Effective density	2.75 g/cm^3
Active depth	555 mm ($15.9X_0$)
Total depth (without photo-detector)	650 mm
Total weight	18 kg

"LEGO" type locks for the scintillator tiles. These locks, four per tile, fix the position of the scintillators with the 350 μm gaps, providing sufficient room for the 275 μm lead tiles without optical contact between lead and scintillator. The new mechanical structure, compared to previous designs, involves removing 600 paper tiles between scintillator and lead, reducing the diameter of the fiber's hole from 1.5 mm to 1.3 mm, and removing the compressing steel tapes at the side of the module. Compared to the $4\%/\sqrt{E\ (\mathrm{GeV})}$ prototype [3], the hole/crack and other insensitive areas were reduced from 2.5% to 1.6%, and the module mechanical properties such as dimensional tolerances and mechanical stiffness were significantly improved. Removing of the paper tiles allowed us to reduce the effective radiation length X_0 from 4.0 cm to 3.5 cm.

The *sampling*, i.e. the relation between the thicknesses of lead and scintillator tiles, dominates in the energy resolution of the Shashlyk module. However, there is not much opportunity for improving it. Decreasing the lead thickness and keeping the scintillator thickness will increase the length of the module, while the proportional decreasing of the lead and scintillator thicknesses will reduce the light collection efficiency. Nonetheless, due to the removal of the paper between lead and scintillator we were able both to improve the sampling and keep the length of the module.

The main contributions to improving photo-statistics are (i) new scintillator with improved optical transparency and improved surface quality and (ii) and new photo-detector (Avalanche Photo Diode) with high quantum efficiency.

New scintillator based on the BASF143E polystyrene was manufactured in the IHEP, Protvino. The most important property of the new scintillator tiles is high efficiency (about 97%) of the light reflection from the surface of the scintillator. Compared with the $4\%/\sqrt{E\ (\mathrm{GeV})}$ module with effective light reflection efficiency of 93%, the light collection was increased by a factor 1.6. Also, there was almost no light yield variation over the distribution of yields from many new tiles.

To further increase photo-statistics, we used an Avalanche Photo Diode, 630-70-74-510 produced by Advance Photonix Inc., with 16 mm diameter sensitive area, high quantum efficiency ($\sim$ 93%), good photocathode uniformity (quantum efficiency non-uniformity $\leq 3\%$) and good short and long term stability. A typical APD gain was 200, excess noise factor is $F \approx 2.4$.

With new scintillator and APD photo-detector, the effective light yield in the module became $N_{ph.e.} \sim 55$ photoelectrons per 1 MeV of incident photon energy, resulting in negligible photo-statistic contribution of $\sqrt{F/N_{ph.e.}} \approx 0.7\%/\sqrt{E\ (\mathrm{GeV})}$ to the energy resolution of the calorimeter.

The dominant source of the non-uniformity of the light collection is the light losses on the edges of the scintillator tile. For improvement the reflection efficiency on the edge sides of the scintillator tile is crucial. The new module was wrapped with TYVEK paper (reflection efficiency about 80%). In addition, the WLS fiber density on the edges was effectively increased by the reducing the size of the scintillator tile. The transverse size of the tile, 10.97 cm, is smaller that “uniform” size of 11.16 cm for 12 fibers with 0.93 cm spacing. The result was that the light collection efficiency on the edge of the scintillator tile is only 2.3% smaller than in the center of the tile for a pointlike light source. In case of a 250 MeV photon shower, the difference is only 0.5%, which is negligible compared to the energy resolution of about 6% for such photons.

3. Test beam measurements

Test beam measurements of the prototype of the Shashlyk calorimeter with energy resolution of $3\%/\sqrt{E\ (\mathrm{GeV})}$ were done using photon beam of the LEGS setup at Brookhaven NSLS [4]. A $\sim 3 \times 10^5$ Hz photon beam was produced by laser photons Compton backscattered by storage ring electrons, and had a small size of $\sim$ 1.5 cm and small angular spread of $\sim$ 2 mrad.

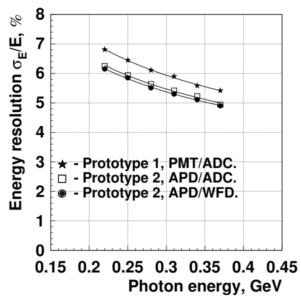

Figure 2. Energy resolution of the prototypes of Shashlyk calorimeter for KOPIO.

The photon energy was tagged with an accuracy of $\delta E_\gamma/E_\gamma \approx 1.5\%$ by the detection of the scattered electron. Several monochromatic photon energy lines in the range of $220 \div 370$ MeV were triggered in our measurements.

Two arrays of 3×3 modules have been tested. The first array (prototype 1) contained modules with conventional design (paper between lead and scintillator) with a 30 mm diameter photo-multiplier, 9903B of Electron Tube Inc. The signals were digitized by the conventional 12-bit ADC. The second array (prototype 2) contained new design modules equipped with the 16 mm diameter APD 630-70-74-510 of Advanced Photonix Inc. Both 8-bit 140 MHz wave form digitizers (WFD) and 12-bit ADC were used for the digitizing of the APD signal.

4. Results

The energy resolution was measured for both prototypes, 1 and 2. The photon beam was directed to center of the nonets of modules. The results are displayed in Fig. 2. For the APD with WFD readout, the fit gives

$$\sigma_E/E = (1.96 \pm 0.1)\% \oplus (2.74 \pm 0.05)\%/\sqrt{E\ (\mathrm{GeV})}$$

where $\oplus$ means quadratic summation. The relatively large constant term of about 2% may be explained by the short, $15.9X_0$, radiation length of the module. However, this term is not essential for the KOPIO photon energies of about 250 MeV for which resolution may be approximated as

$$\sigma_E/E = (2.9 \pm 0.1)\%/\sqrt{E\ (\mathrm{GeV})}$$

To estimate the time resolution, the 340 MeV photon beam was directed between two modules. Only events with full photon energy deposited in these two modules were selected. The distribution of the time difference of the signals in two modules allows us to estimate the time resolution of the modules. The time difference dispersion as a function of the energy

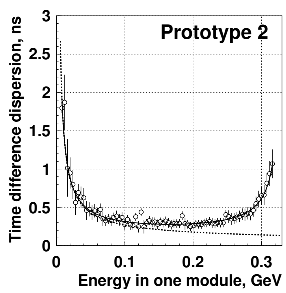

Figure 3. The dependence of the time difference r.m.s. for the signals in two modules on the energy deposited in one module. The total energy in two modules is 340 MeV. The rise of the dispersion for energy above ~ 0.3 GeV is due to the small energy deposited in the second module. The reconstructed time resolution in a single module is shown by dotted line.

deposited in one module is shown in Fig. 3. The derived time resolution in a single module is

$$\sigma_T = (90 \pm 10)\ \text{psec}/\sqrt{E\ (\text{GeV})}$$

To estimate photon detection inefficiency due to cracks and holes one prototype nonet was located behind other. The absence of the signal in the front prototype while total photon energy was deposited in the second was interpreted as a penetration of the photon through the first prototype without interaction. For the photon incident angles greater than 5 mrad, the photon detection inefficiency was found to be independent of angle and equal to $\sim 5 \times 10^{-5}$. This value agrees well with the probability of the photon interaction in 8.25 cm of lead and 45 cm of scintillator.

The PMT and APD gains were monitored using LED signals during the entire run time of 24 hours. The variation of the APD gain did not exceed $\leq 1\%$. No APD gain dependence on the photon beam intensity was observed.

5. Conclusion

The results of the $220 \div 370$ MeV photon test beam measurements of the prototype of the Shashlyk calorimeter showed that this prototype has significantly improved performance characteristics over previous designs, and it satisfies the requirements of the KOPIO experiment. We plan to build a new 10×10 prototype and test it in 2005. The construction of the Shashlyk Calorimeter for KOPIO will begin in 2006.

References

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