Photon sandwich detectors with WLS fiber readout

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Abstract

A photon detector for BNL experiment E949 is described. The detector consists of a lead scintillator "sandwich" of 25 layers of 5 mm thick scintillator BC404 and 24 layers of 2 mm lead absorber. Readout is implemented with 30-60 cm long WLS fibers (BCF 99-29AA) glued into grooves in the BC404. Average yield was measured with cosmic rays to be about 43 p.e./MeV. Extruded plastic scintillation counters developed for sandwich detectors of photons for the KOPIO experiment are also described. For a 7 mm thick counter with 4.3 m long WLS fibers spaced at 7 mm a light yield of 18.7 p.e./MeV and time resolution of 0.71 ns were obtained. A prototype photon veto module consisting of 10 layers of 7 mm thick extruded plastic slabs interleaved with 1 mm lead sheets was tested.

1 Introduction

BNL experiments KOPIO [1] and E949 [2], to search rare kaon decays $K_L^0 \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$, respectively, require extremely high detection efficiency of charged particles and photons to suppress the dominant background from ordinary kaon decays that are 10 orders of magnitude more frequent. For this purpose new photon detectors were designed and built. Their common features are the wavelength shifter fiber readout and Pb-scintillator sandwich design. In this work we report on the E949 collar endcap photon detector and the KOPIO photon veto prototype module.

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2 Collar detector for E949

The E949 collar detectors (CO) are located at the upstream and downstream ends of the detector, outside of the endcaps and near the beam axis. Their purpose is to detect photons emitted from kaon decays in the kaon stopping target under small polar angles. They cover the very forward region (from $0.995 > |cos\Theta| > 0.97$) as a part of the E949 photon veto system.

2.1 Collar design

The assembly view of downstream CO is shown in Fig. 1. The upstream and down-
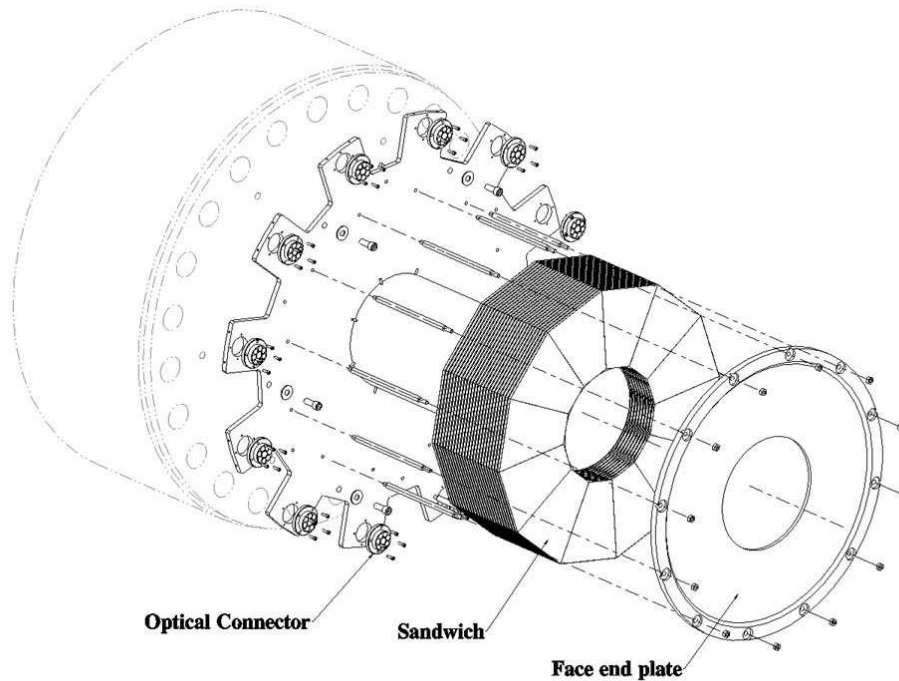

Figure 1: Assembly view of the collar sandwich detector.

stream CO are similar in design, the difference is in the geometrical size. The CO consist of 25 layers of 5 mm thick scintillator BC404 (Bicron, [3]) and 24 layers of 2 mm lead absorber interleaved by 0.1 mm Tyvek reflector paper. The total radiation thickness is limited by available space to $\sim 9X_0$.

A single plastic scintillator layer is segmented in 12 wedges (petals) forming 12 identical azimuthal sectors. The petal length is 165 mm. Light from the petals is read out by 16 multiclad wave length shifting (WLS) fibers (BCF99-29AA from

Bicron) which are glued into grooves in the scintillator to obtain a high light yield [4]. The grooves diverge radially along a petal with average spacing of 6 mm. The inner end of the fiber is polished and aluminized. All 400 fibers for each sector are bent under angle of 90° and terminated in a connector. Fiber length is variable with an average of about 45 cm.

Each absorber layer is composed of two halves of a 2 mm thick lead semicircular annular disk. The Pb layers are laid out with a rotation angle of 30° relative to the neighboring layer, providing coverage of the cracks between the Pb halves in subsequent layers. The gaps between scintillator petals are also staggered so that there is no projective cracks for photons over the CO face.

The sandwich assembly is compressed between a base plate and an endplate disk by 12 standoffs. The standoffs prevent the collar elements from shifting down due to gravity.

2.2   Construction and assembly

The scintillator petals were cut from cast sheets of BC404 scintillator with 0.1 mm tolerance. Since the sheet has significant thickness variation (range from 4.8 to 5.2 mm), petals were hand selected in groups of similar thickness. The petals from the same group were laid out to form a single layer.

Sixteen symmetrically spaced U-shaped grooves were cut along the petal and polished. Gluing was done in two steps. First, the grooves were filled with BC-600 epoxy, and the 65 cm long fibers were inserted. In the second step, the glue was applied over the fibers to fill any remaining gaps.

The scintillator is etched in a process that results in the formation of a micropore reflector deposit over the surface. Long term effect of Pb diffusion in the chemical reflector is unknown so Tyvek sheets were used to separate the scintillator and lead. The Tyvek also works as a reflector over the fibers.

The most critical point in the collar assembly is the insertion of the fibers in the connector. Before gluing all fibers were visually inspected and then bent over a cylinder with diameter of 5 cm to expose cracks. The failure rate (a fiber is broken) is below 0.5%. If Bicron fiber was bent with a radius of less than 3 cm, the crazing of the cladding was observed to develop in the curved part for some fibers. This process takes place in a hour and continues over 24–48 hrs. After that stabilization is observed (no additional crazing after 48 hours). The fibers were routed to a connector with a bending radius of 4 cm or larger. Even so some fibers show crazing which is not harmful as long as the number of such fibers is less than 1%. Then the fibers have been glued in the connector, the ends were cut and polished. A view of the assembled collar detector is shown in Fig. 2.

Figure 2: The collar detector before installation in the set–up. After installation the fibers have been shielded by protective cover.

2.3 Cosmic test

The detector was tested with cosmic rays. The trigger counters were placed above and below each sector. Though the area of the trigger counters is larger than that of a sector, the 50 cm separation selects minimum ionizing particles (MIP) with incident angles close to normal. A MIP deposits about 25 MeV of visible energy in the detector. A phototube is attached to the fiber connector through a silicone cookie. All sectors were measured with the same photomultiplier EMI-9954 which has a photocathode sensitivity extended in the green light region.

The average number of detected photoelectrons (p.e.) is calculated by dividing the MIP peak position by the single electron peak position. An attenuator was used to scale the large MIP signal to the single electron amplitude. The cosmic test results are presented in Fig. 3. Average light yield is about 43 p.e./MeV, where MeV is visible energy. Deviation from this value in different sectors is ± 3 p.e., this is within the accuracy of the single electron peak calibration.

3 Sandwich veto detector for KOPIO experiment

3.1 General description

One of the most important parts of the BNL experiment KOPIO is the determination that nothing other than single π^0 was emitted in the decay $K_L^0 \to \pi^0 \nu \bar{\nu}$, i.e. a high
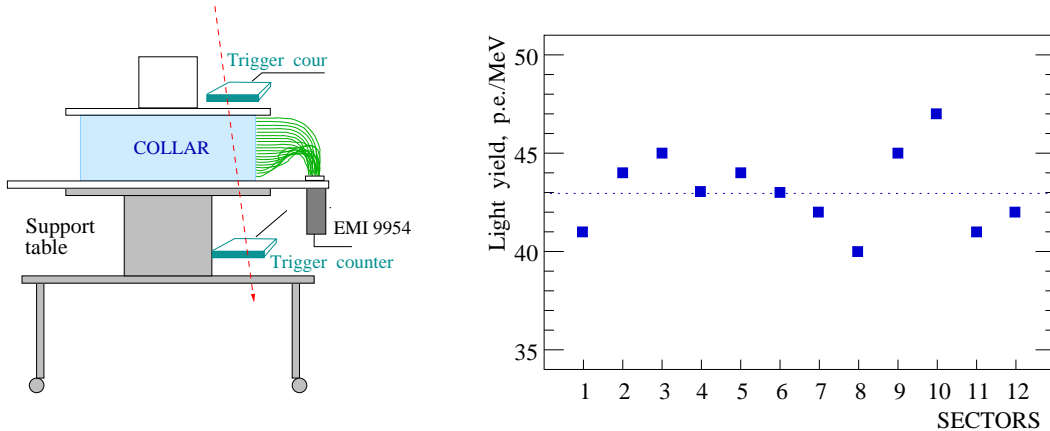
Figure 3: Light yield of the collar detector for each sector. Test bench is also shown.

efficiency veto of any extra particles. It requires an extremely high photon detection efficiency of better than 0.9996 per photon, without excessive loss from random vetoes. High light yield over all detector volume and good timing are needed to satisfy these requirements.

Lead–plastic scintillator sandwich detector is being considered for the barrel photon veto in KOPIO. To read light from the scintillators, an embedded WLS fiber readout will be used. Similar detectors were designed for BNL experiment E787 [5] (without WLS fibers) and KEK experiment E391 [6]. Thickness of the lead sheets is considered to be 0.5–1.0 mm, and the thickness of extruded polystyrene scintillator slabs is 7 mm. WLS fibers are glued in the grooves which run along the scintillator slabs with spacing of 10 mm. The schematic view of the barrel veto is shown in Fig. 4.

3.2   Sandwich module design

The results of tests of single extruded counters and a sandwich module prototype are reported in Ref. [7]. The main results for extruded counters with WLS fiber readout are summarized in Table 1.

Extruded polystyrene scintillator with WLS fiber readout produces 0.8 of light yield of BC404 scintillator. Single–clad (s.c.) and multi–clad (m.c.) fibers provide practically the same time resolution though in the tested configuration the light yield for m.c. fibers was 20–24% higher than that for s.c. ones.

A schematic view of a sandwich element (module) which is used to build roof and floor parts of the barrel is shown in Fig. 5. The number of lead–plastic layers in a single module is 15. The width is 130 mm, spacing between grooves is 10 mm,
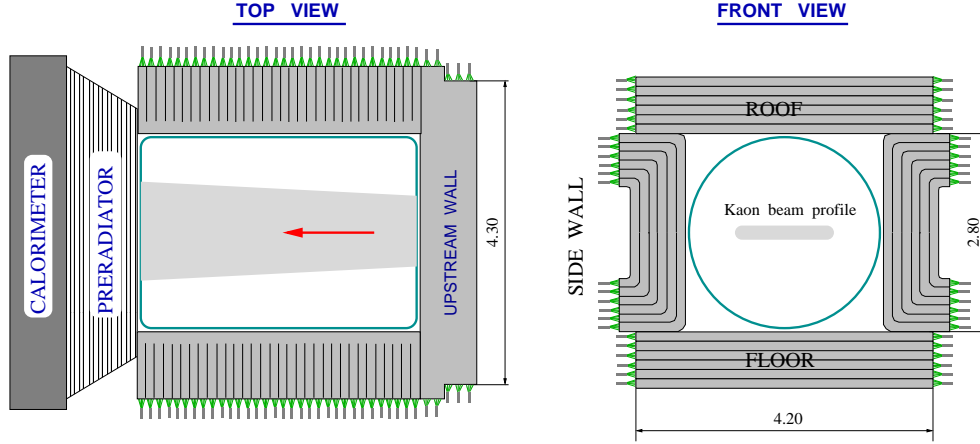
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Figure 4: The schematic view of the barrel veto detector in the KOPIO.

Table 1: Parameters of extruded polystyrene counters with 4.3 m long WLS fiber readout. Fibers: multi–clad BCF99-29AA and single–clad BCF92 of 1 mm diameter. A counter made of BC404 scintillator is also shown for comparison.

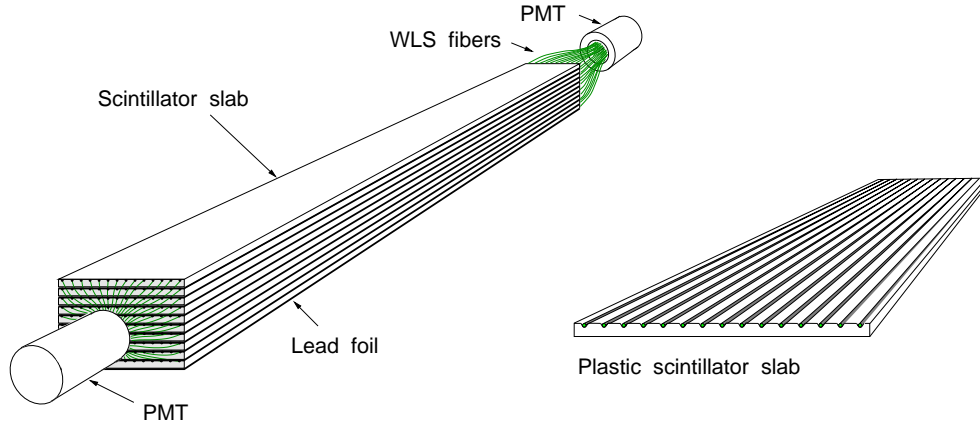| Counter thickness mm	Spacing mm	Fiber type	Light yield p.e./MIP	σ_t ns
7	19	multi–clad	11.2	
7	10	multi–clad	19.6	0.85
7	10	single–clad	14.4	0.87
7	7	multi–clad	26.2	0.71
7	7	single–clad	20.8	0.76
3	10	multi–clad	8.5	0.92
7 (BC404)	7	multi–clad	32	0.65

Figure 5: The schematic view of a sandwich module.

groove depth is 1.5–2.0 mm. Sandwich module is 4.2 m long without extending fibers. A phototube views a bundle of 195 WLS fibers at each end providing a both–side readout. A chemical etched reflector [7] is used to cover the scintillator slabs. The scintillator and lead are glued together in a monolithic block using an elastic polyurethane glue with high viscosity. The glue does not soak in the micropore chemical reflector. After gluing the lead plates with scintillator covered by the reflector we found the light output reduction of about 6%, but then no degradation in the light yield was observed for two months. To test the mechanical properties, a 4 m long dumb module (no fibers) had been assembled (see Fig. 6). 10 layers of scintillator and lead were coupled together only by glue. An additional layer of 0.1 mm stainless steel foil was also glued at the first layer of the plastic. The module sag under own weight was measured to be 4 cm after two weeks of test. This value is close to the expected sag if the module would be a solid polystyrene.

Unique feature of the veto side wall is the bent sandwich modules assembled of bent scintillator slabs as shown in Fig. 7. Bending with 10 cm radius can be done heating the scintillator slabs with fibers while the optical glue has not hardened yet. This technique was successfully tested.

The sandwich prototype module was made with a length of 1 m while the length of the WLS fibers was 4.5 m, i.e. close to length in the real detector. Single–clad BCF-92 fibers were glued with 10 mm spacing. Light yield was measured to be 122 p.e. for MIP, and time resolution was 360 ps (rms). Light yield nonuniformity along the module was measured in 10 cm steps. As shown in Fig. 8, the summed light yield from both ends was stable with deviation ±1% from the average over 90 cm length.

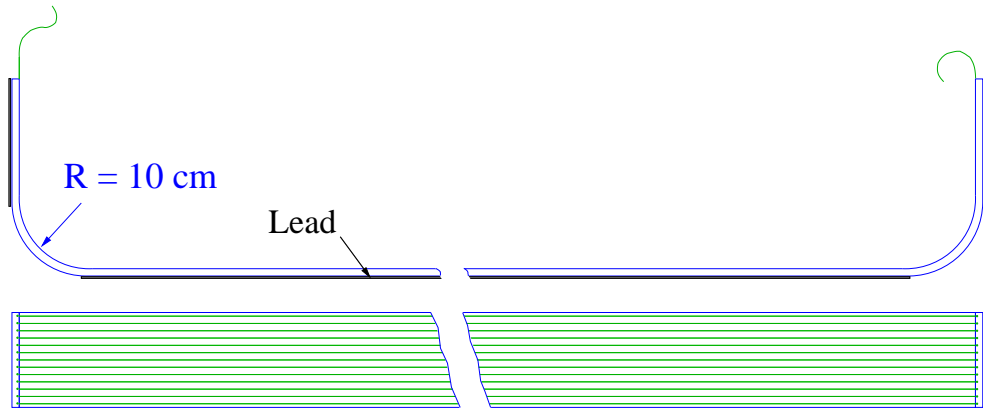Figure 6: Photo of the 4 m long glued module under mechanical test.

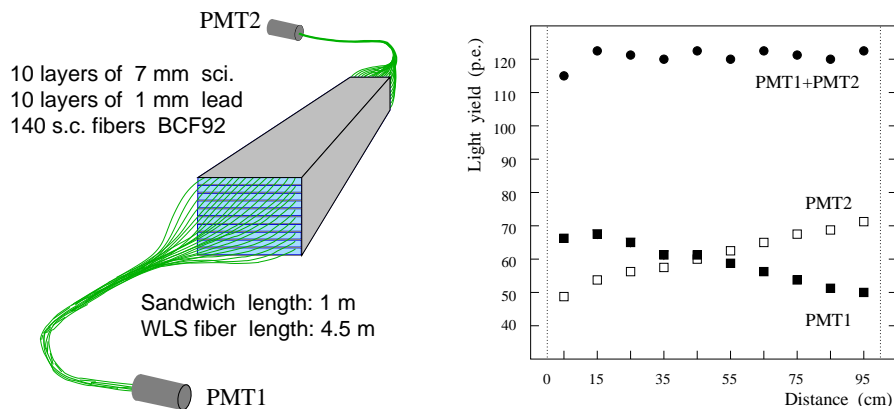Figure 7: The view of a single layer for the side wall.

Figure 8: Light yield of the sandwich module prototype at cosmic ray test.

3.3   Evaluation of sandwich veto performance

The expected performance of the barrel veto is summarized in Table 2. Visible

Table 2: Expected barrel veto performance.

Parameter	Value	Note
Integral inefficiency	$< 4 \times 10^{-4}$	Based on tests and E787 results
$\sigma_E/\sqrt{E(GeV)}$, %	3.6	Sampling fluctuations from GEANT
$\sigma_t/\sqrt{E(GeV)}$, ps	63	Stochastic term from prototype test
Position resolution, cm	3.8	Veto segmentation and timing
Angular resolution		
for 100 MeV photon, mrad	250	GEANT simulation

energy fraction for 1 mm lead and 7 mm scintillator is about 0.39. From test results we evaluate the photoyield to be 4.0 p.e. per MeV of the energy deposited in both active (scintillator) and passive (lead) layers. It means we can collect 400 p.e. for a typical 100 MeV photon. Extrapolating the parameters obtained for the prototype module, the time resolution of the veto detector is estimated to be close to 200 ps (rms) for a 100 MeV photon. Direct extrapolation for higher energies gives 63 ps/$\sqrt{E_\gamma[GeV]}$. However, at 1 GeV the time resolution includes not only stochastic term but also the systematic constant term, which is difficult to estimate.

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Since the light propagation velocity in the fibers was measured to be 17 cm/ns, the accuracy of a localization of an electromagnetic shower could be about 3.4 cm (rms) along the fibers for a 100 MeV photon. The resolution in the other direction is defined by the width of the modules. For a 130 mm width we have σ_x=3.8 cm.

We are able to recover the shower direction measuring the center-of-gravity at each level and drawing the line through these centers by χ^2 method. This method gives the systematic shift which was corrected. We simulated the photons irradiated from the center of the decay region under angles in uniform populated range from 45 to 135°. Angular resolution of 244 mrad (E_γ=100 MeV) for a typical angle of 70° leads to the measurement of the K_L^0 decay position with an accuracy of about 40 cm.

4   Conclusion

Photon veto detectors for BNL experiment E949 were manufactured and tested with cosmic rays. The detectors consist of 25 layers of 5 mm thick scintillator BC404 and 24 layers of 2 mm lead absorber. Readout is implemented with multi–clad WLS fibers (BCF 99-29AA) of 30-60 cm length. The average yield was measured with cosmic rays to be about 43 p.e./MeV.

A lead–plastic scintillator sandwich veto system is designed for BNL experiment KOPIO. The barrel veto features high light output and readout segmentation over its thickness. To read light from the scintillators, an embedded wavelength–shifting fiber readout technique will be used. A prototype photon veto module consisting of 10 layers of 7 mm thick extruded plastic slabs interleaved with 1 mm lead sheets was tested. Single–clad BCF–92 fibers of 4.5 m length spaced at 10 mm were used for the readout. The module yielded 122 p.e. per MIP and time resolution of 360 ps.

References

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