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The R&D study for the KLOD experiment at IHEP (Protvino) U-70 proton synchrotron

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The project *KLOD* has been recently started to carry out an experiment dedicated mainly to observation and study of extremely rare decay $K_L^0 \to \pi^0 \nu\tilde{\nu}$ at *IHEP* (Protvino) *U-70* proton synchrotron. The *R&D* study for the most crucial parts of the experimental setup, namely the barrel *Main Veto* and the *In-Beam-Veto* calorimeter, has been considered as the main current task. The prototypes of these devices have been manufactured and tested. The results of these studies including preliminary data from the first test beam are presented. The main emphasis is put on the capability of the proposed *In-Beam-Veto* calorimeter to satisfy harsh experimental requirements: high efficient gamma detection in presence of 300 MHz neutron flux. A general status of the *KLOD* project is also given.

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1. Introduction

Being the rare *FCNC* and purely *CP*-violating process the decay $K_L^0 \to \pi^0 \nu \tilde{\nu}$ [1] has been widely recognized as a “golden mode” which experimental detection will allow one to obtain the valuable information about *CKM*-matrix parameters and will be a probe of the existence of “new physics” beyond the *SM*.

Recently a working groups from three scientific centers of Russian Federation – *IHEP* (Protvino), *JINR* (Dubna) and *INR* (Moscow) – established a collaboration, *KLOD*, with the aim to carry out an experiment for searching the decay $K_L^0 \to \pi^0 \nu \tilde{\nu}$ at *IHEP U-70* proton accelerator. The *KLOD* Proposal has been published elsewhere [2] and briefly reported at the *KAON07* Conference [3]. The Scientific Committees of *IHEP*, *JINR* and *INR* have clearly recognized the scientific importance of this experiment and approved the *R&D* phase with the aim to prepare the *Technical Design Report*. The talk given at *KAON09* is dedicated to outline our efforts in developing of two most crucial parts of the experimental setup, the barrel *Main Veto* and the *In-Beam-Veto* calorimeter.

2. Experimental Setup Overview

The strategy of proposed experiment is similar to one considered in *KAMI* (*FNAL*) [4], *E391A* (*KEK*) [5] and *KOTO* (*J-Parc*) [6] projects assuming a “narrow beam” approach and the searching of $K_L^0 \to \pi^0 \nu \tilde{\nu}$ signal by signature of $\pi^0 (\pi^0 \to \gamma\gamma)$ + “nothing”.

Proton energy	60 GeV
#Protons/spill	10^{13}
Duration cycle/(spill)	8/(3) s
K_L^0 **extraction angle**	35 mrad
K_L^0 **momentum** average/(in peak)	10/(6.5) GeV/c
Beam profile	4 mrad, ∅
Spatial beam angle	12.6 μstr
K_L^0 **/spill** (@setup)	5.4×10^7
Effective decay region	10 m
Decay probability in fiducial volume	4.8%
Beam time	10 days
Sensitivity	2.6×10^{-11}
# signal events (@SM)	1
Signal/Background	3

Table 1.

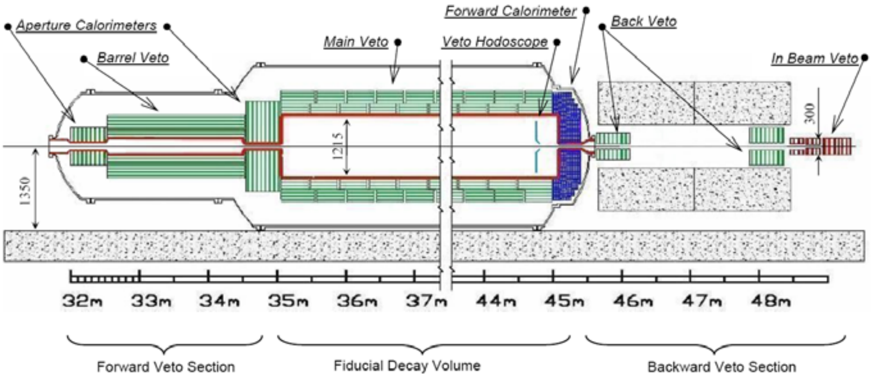

Fig. 1. Schematic layout of the KLOD setup.

Fig. 1 shows the general layout of the *KLOD* experimental setup along with some basic geometrical dimensions. The presented scale of distances has the origin at the target position. The main parameters of planned experiment are listed in the Table 1.

3. Main Veto

High efficient veto-system surrounding decay volume is one of the most critical detectors. Being the largest device the *Main Veto* dominates in total cost estimation and the choice of a sampling structure seems to be natural. In ideal case detector should provide γ detection inefficiency on the level ~10^{-6} up to the smallest energy range, tens of MeV. That is in principle possible for the γ energies above 1 GeV and requires calorimeter depth to be more than 18 X_0 to avoid *punch-through* effect. For the smaller energy the abilities are limited by increased cross sections of photo-nuclear reactions and so called sampling effect which starts to be dominant below 100 MeV and may cause few percent inefficiency for tens MeV γ's [7]. To reduce influences of the latest effects it is important to use the finest calorimeter structure decreasing detection threshold below 1 MeV.

We consider widely known "shashlyk"-type module as a basic veto cell. Its design is well developed at *IHEP* workshop allowing mass scale production of the finest calorimeter structure. The baseline module construction contains 300 pair layers of (300 μm *Pb* + 1mm Scint. plate) giving 15.9 X_0 in the elementary cell with dimensions of (100×100×560) mm^3 [8]. Basing on this design several modified to our needs modules have been produced and tested. The specific features of the manufactured modules which have not been implemented in the experimental practice so far are listed below:

- stair-like shape allows one to avoid any possible gaps at the *Main Veto* by neighboring modules stacking. The light collection from scintillating plates is organized by means of mirrored and looped *WLS* fibers as Fig. 2 shows;
- to provide the needed calorimeter depth (18 X_0) the sampling fraction has been hardened by doubling lead thickness at the last third of the module. Such a solution may cause a nonlinearity of the calorimeter response at high energy γ detection what seems to be not significant for the veto-system.

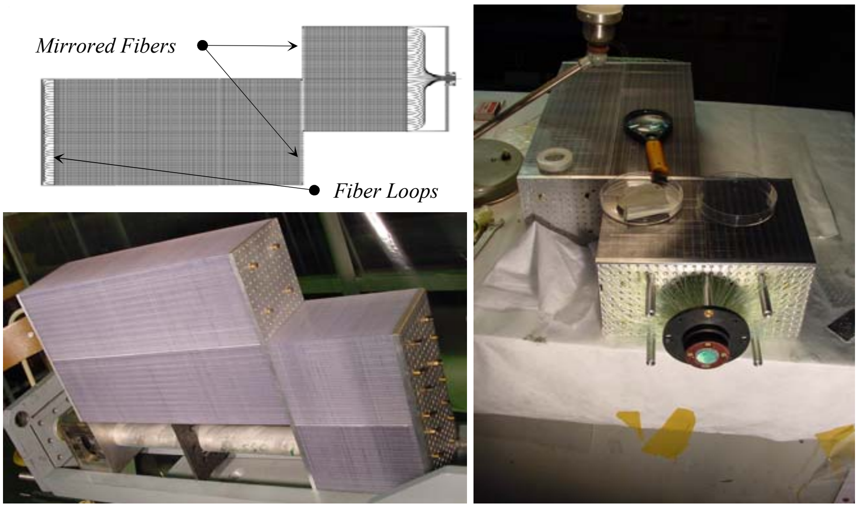

Fig. 2. Manufactured modules of the Main Veto system.

Manufactured modules have been tested at the secondary beams of the *U-70* accelerating complex. The consequences of the implemented construction changes have been also the subjects of performed measurements. The main results of our studies are:

- the veto-module allows one to firmly detect *m.i.p.* giving ≈3.5 photoelectrons per single scintillating plate[1];
- light yield has been measured to be ≈20 000 visible part of the spectrum photons per 1 GeV γ-shower;
- recalculation to the "visible" (deposited in scintillator) energy gives ≈10 photoelectrons per 1 MeV;

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[1] at ordinary bi-alkaline photocathode.

- photo-statistics is not significant factor to contribute to the energy resolution measured to be 1.5% for 8 GeV/c e^+. This value well agrees with reported for given structure parameterization $\sigma_E/E \approx 3\%/\sqrt{E} + 1\%$ [8];
- response nonlinearity for 8 GeV/c e^+ has been measured to be ≈3% with respect to the *m.i.p.* signal. This is due to the implemented sampling change at the end of the module;
- achieved working parameters allow one to set unprecedentedly low γ-detection threshold of ~100 keV (1 photoelectron).

One of the important prototyping goals was also to demonstrate the manufacturing ability of self-supporting modules of such type and mass scale production technology development.

4. In-Beam-Veto

In-Beam-Veto is small but important detector working in a very hard environment. About 18% of $K_L^0 \to \pi^0\pi^0$ decays in *Fiducial Volume* have at least 1 γ passing through the hole at *ECal*. Even in case of *In-Beam-Veto* positioning in 3 m downstairs from *ECal* still ≈2% of these decays will give 2 γ's (from one π^0) hitting this device. Such topology should be suppressed by factor 10^6 (inefficiency of $\sim 10^{-3}$ for single γ). Fortunately in this case γ-spectrum is rather hard (Fig. 3) what gives a hope to achieve the goal.

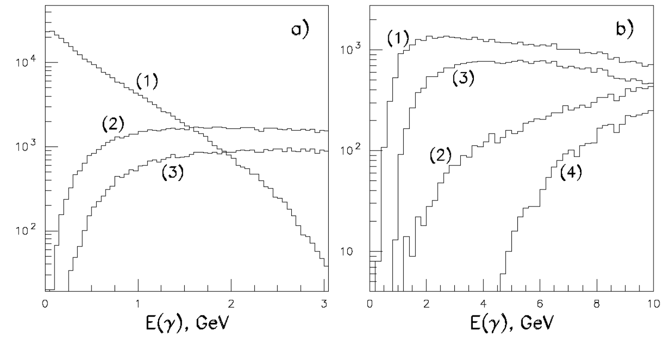

Fig. 3. a) γ-spectra from decay $K_L^0 \to \pi^0\pi^0$ hitting Main Veto(1), the hole in FCal (2) and In-Beam-Veto (3) at the condition of "2 γ's hit Fcal";
b) γ-spectra from decay $K_L^0 \to \pi^0\pi^0$ hitting In-Beam-Veto at the condition of "2 γ's hit Fcal + 2 γ's hit In-Beam-Veto" (1) and sum energy of γ's at In-Beam-Veto in this case (2). (3-4) – the same but at the extra condition of "2 γ's belong to one π^0".

From other side huge neutron flux (~300 MHz) reduces γ-detection efficiency causing also "over-veto" effect. We intend to use "spaghetti"-like structure equipped both scintillator and pure acrylic fibers ("dual"-readout calorimeter). Clear fibers are only sensitive to electromagnetic shower component giving *e/h* ration for hadron showers of ~5 [9]. Because of that the ration of Cherenkov light to scintillating one and its behavior in longitudinal and transverse directions are very different for γ's and hadrons induced showers. This feature which has been demonstrated by beam test studies [10] allows one to identify γ's in presence of superimposed neutron showers.

4.1 In-Beam-Veto Monte-Carlo

A Monte-Carlo simulation study has been performed for the calorimeter structure corresponded to 200 identical slices arranged across the beam line. Each slice contains 0.3 mm *Pb* plate, layer of scintillating fibers ∅1 mm arranged in a ribbon-like structure and identical

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layer of transparent acrylic ∅1 mm fibers. All fibers are grouping to organize the segmentations across and along the beam separately for each type of the fibers.

The responses of such a calorimeter to γ and n have been modeled in the energy range of (0.25 – 20) GeV. Energy resolution for γ's has been found to be ~5.5%/√*E* at scintillating light and ~7.6%/√*E* at Cherenkov one. These values well agree with the experimental data reported by a number of the authors for the similar calorimetric structures (single light type readout scheme) [11, 12].

For γ's at the full energy range studied the ratio of scintillating and Cherenkov signals has been found to be $R_0 = Ch/Scint \approx 0.075$ with proper Gaussian shape of $\sigma_R/R_0 \approx 8\%/\sqrt{E}$. Dramatic differences in the behavior of *R*-parameter for neutrons are caused by suppressed hadron component of the showers in the case of Cherenkov signals detections (Fig. 4).

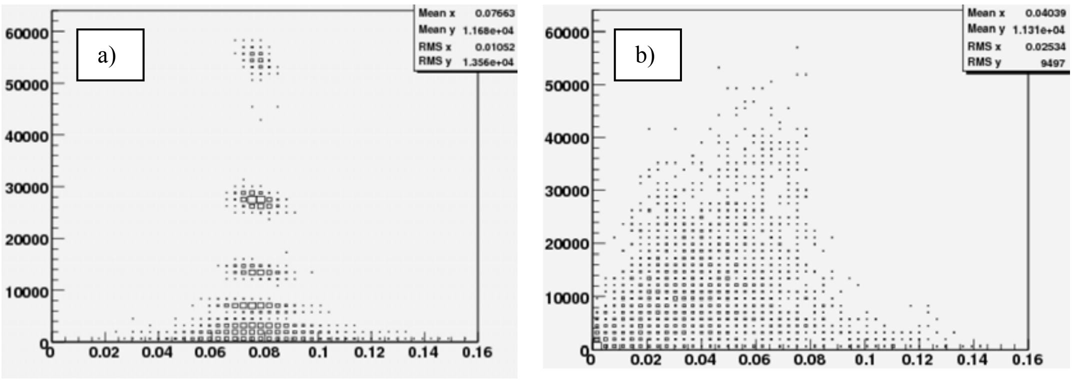

Fig. 4. Correlation between R-parameter(horizontal axis) and registered scintillating signal (vertical axis, relative units). (a) – for 8, 4, 2, 1, 0.25 GeV γ's; (b) – for neutrons with uniform (0.5 – 10) GeV/c spectrum.

The simplest selection criteria for γ-like showers, namely *R*-parameter lies in the range of $R_0 \pm 3\sigma_R(E_{Scint})$, suppress neutron component of the beam (n misidentified as a γ) by two order of magnitude, i.e. up to the level of ≈3 MHz. Even assuming to work with time window of 10 *ns* it will give 2% acceptance lost due to *"over-veto"* effect. Table 2 represents detection inefficiencies for single γ's achieved at such algorithm as well as the same ones obtained at superposition of given γ-shower and n-shower simulated according to the know beam spectrum.

E_γ, GeV	0.25	0.5	1	2	4	8
Nonefficiency	1.3×10^{-2}	3.5×10^{-3}	10^{-3}	6×10^{-4}	5×10^{-4}	5×10^{-4}
Nonefficiency in presens of *n* (beam spectrum)	3.5×10^{-2}	1.1×10^{-2}	3.5×10^{-3}	10^{-3}	6×10^{-4}	6×10^{-4}

Table 2.

The results of these brief studies are quite promising. One may expect much better detector performances using available information about transversal and longitudinal distributions of the Cherenkov and scintillating lights in the showers.

4.2 In-Beam-Veto Prototyping

On the base of the Monte-Carlo results *In-Beam-Veto* calorimeter prototype has been designed and manufactured. Produced calorimeter structure is similar to one described in the Monte-Carlo section and constitutes 100 identical slices of (0.3 mm *Pb* + 1 mm acrylic fibers + 1.5 mm scintillator) arranged across the beam line. To provide the segmentation the acrylic fibers, 17 – across the beam and 20 – along the beam, are grouped together giving a light spot of ~∅20 mm on the attached photodetector. For simplicity reason the layers of scintillating fibers have been replaced by 1.5 mm thick scintillating bars with dimensions across the beam of 17 mm. Scintillating light is collected by mean of single *WLS* fiber embedded inside the bar

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body. *WLS* fibers from 20 scintillating bars located along the beam are joined together and attached to separate photodetector. This structure together with *Pb* sheets forms the elementary detecting cell with dual readout (Fig. 5a) with dimensions of $(17 \times 220 \times \approx 60)$ mm^3.

In-Beam-Veto calorimeter prototype contains 25 elementary cells grouped in the matrix (5×5) with full dimensions (in terms of electromagnetic shower developing) of $(1R_M \times 2R_M \times 7.5X_0)$.

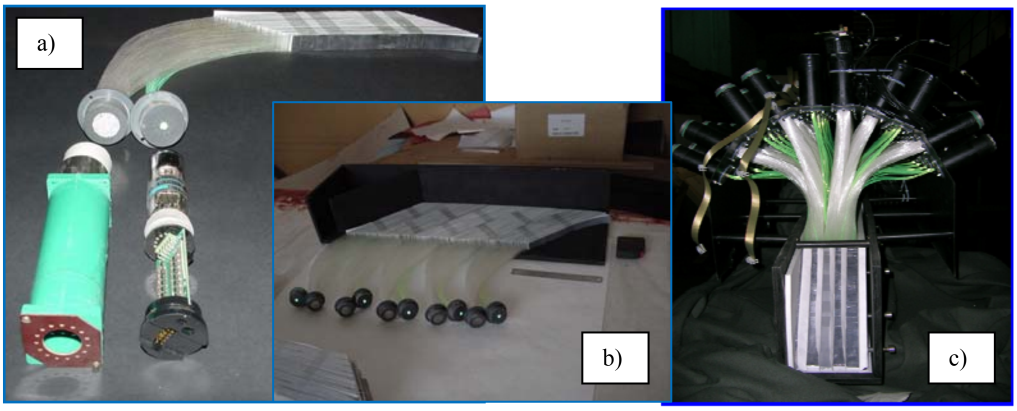

Fig. 5. In-Beam-Veto calorimeter prototype.

In-Beam-Veto calorimeter prototype has been preliminary tested at the secondary beams of the *U-70* accelerating complex. The purpose of these studies was to measure the basis characteristics of the devise like light yields, uniformity, angular dependence etc. The main results of our preliminary tests are:

- nonuniformity of the device response to the *m.i.p.* signal has been measured to be better than ±5% in the both transversal to the beam line directions;
- Cherenkov light yield from single detecting cell (20 acrylic layers) corresponds to ≈10 photoelectrons from *m.i.p.* signal at incident angle of 45^{o};
- scintillating light yield with consequent *WLS* readout exceeds Cherenkov one by factor of ≈10;
- expected from Monte-Carlo studies the angular dependence for *m.i.p.* signals has been measured with the maximum around 45^{o}. The width of the measured distribution corresponds to the numeric aperture of the acrylic fibers used;
- the absence of angular dependence for scintillating light has been measured as expected.

The results of these preliminary tests shell allow us to tune Monte-Carlo modeling parameters to the real data, to develop additional criteria for *n*'s suppression and perhaps to make the changes in the prototype construction for the final beam tests. For the final prove of the proposed device capabilities to satisfy harsh experimental requirements we intend to have dedicated beam run at the secondary positive beam with well know and on-line monitored particle composition, (e^+, p, K^+, π^+).

5. Conclusion

We present the results of *R&D* work for two crucial parts of the *KLOD* experimental setup. The report doesn't cover all efforts of the *KLOD* collaboration towards preparation of the *Technical Design Report* for future experiment. The authors are grateful to all members of the Collaboration for the valuable help and many useful discussions.

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