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A proposal to measure the rare $K_L^0 \to \pi^0 \nu \tilde{\nu}$ decay at IHEP (Protvino) 70 GeV proton accelerator

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The study of an opportunity and perspectives to create at *IHEP U-70* accelerator a high intensity K_L^0–meson beam has been performed to carry out an experiment for searching the rare decay $K_L^0 \to \pi^0 \nu \tilde{\nu}$. All major aspects related to this experiment are presented.

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1. Introduction

The decays $K_L^0 \to \pi^0 \nu\tilde{\nu}$ and $K^+ \to \pi^+ \nu\tilde{\nu}$ being the rare *FCNC* processes can be evaluated in framework of Standard Model (*SM*) with very high precision and experimentally measured branching ratios will give valuable information on *CKM* matrix parameters. Furthermore the decay $K_L^0 \to \pi^0 \nu\tilde{\nu}$ is a purely *CP*-violating process [1] and practically free from virtual *c*-quark contribution so its branching ratio can be calculated with unprecedented accuracy, ~ (1÷2)%. Using presently adopted values of *CKM* parameters, the branching ratio is equal to be $(2.8\pm0.4)\times10^{-11}$ [2] and even small deviation of measured value from theoretically predicted one will give a direct indication the existence of “new physics”.

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 talk given at the *KAON-07* Conference is based on the published Proposal of the experiment [3] where all major related aspects are presented, here just a summary of our studies are reported[1].

2. Experimental methods

Search of $K_L^0 \to \pi^0 \nu\tilde{\nu}$ signal is planned by signature of $\pi^0(\pi^0 \to \gamma\gamma)$ + “nothing”, thus the basic condition for search is the requirement of presence only 2 γ and absence of any other registered particles. Except $K_L^0 \to \gamma\gamma$ all K_L^0 decays have at least 2 charge particles or 4 γ in the final states. So because of background decays contain at least 2 additional particles the inefficiency of the veto-system should be not worse than square root of desirable level of background suppression. The most danger backgrounds are K_L^0 decays to $2\pi^0$, $3\pi^0$ and 2γ. Other serious background sources are the interactions of halo and core beam particles with material of setup. As a result either single π^0 or Λ hyperon with subsequent decay $\Lambda \to \pi^0 n$ can be produced.

So the main *Fiducial Decay Volume* of proposed setup must be inside high vacuum and be surrounded by high efficient *Main Veto* (Fig. 1). The distant wall is represented by forward electromagnetic calorimeter (*ECal*) for γ’s from $K_L^0 \to \pi^0 \nu\tilde{\nu}$ registration with a *Veto Hodoscope* in front of it for charged K_L^0 decay modes suppression. Overall vacuum volume contains also *Forward Veto Section* (a “double decay chamber” concept) what is necessary for effective suppression of backgrounds from K_L^0 (Λ) decays on a way from the target to the entrance of setup. To suppress background from interaction of beam and halo particles with residual gas inside the setup we consider a double vacuum system. Internal vacuum zone separated by thin membrane (red contour in Fig. 1) may be pumped out up to a level of $\sim10^{-7}$ torr. Non-decayed K_L^0 leaves decay region through beam hole at *ECal*. At the end the special

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[1] More detail drawings, figures, discussions etc. can be found at the Conference report slides (http://www.lnf.infn.it/conference/kaon07/) and at the reference [3].

In Beam Veto detector with ability of efficient registration of γ's from background decays at presence of high flux of beam core particles is installed. Fig. 1 also shows some basic geometrical dimensions, the presented scale of distances has the origin at the target position.

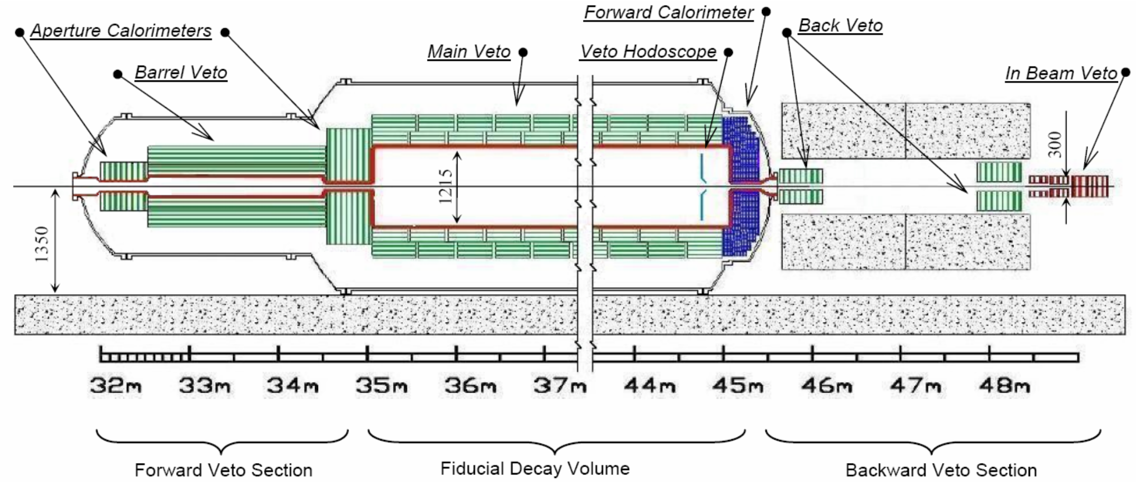

Fig. 1. Schematic layout of the setup.

Strategy of measurements is to the registration of events with 2 neutral clusters in calorimeter without signal from veto system. The reconstruction of two clusters into π^0 mass with assumption of infinite narrowness of the beam allows one to calculate decay vertex along the beam axis and P_T of π^0. In contrary to another multi-body K_L^0 decays π^0 P_T spectrum of $K_L^0 \to \pi^0 \nu\tilde{\nu}$ is more hard due to *V-A* interaction. So the cutting on P_T is the strongest factor in background suppression.

2.1 Neutral beam

The neutral beam requirements coming from proposed strategy of measurements are:

- a narrow beam (R < 5cm at least) and well collimated;
- well P_T balanced;
- intensity of ~10^8 K_L^0/cycle at mean energy of ~10 GeV;
- small contamination of other undesired neutral particles (especially neutrons/K_L^0 ratio < 10).

In the Proposal the possibility of construction of neutral beam at *IHEP* with requirement parameters on the base of available for use magnets and its placing taking into account existed beam channel system is shown. The corresponding beam channel scheme is designed and an evaluation of main beam parameters is performed. Outline design of beam channel zone is completed and corresponding engineering specifications on carrying out of installation work in the experimental hall are prepared. The detail calculations of beam channel optimization are published elsewhere [4].

The values presented in Table 1 have been obtained with an assumption to have 10^{13} 60 GeV protons on target (*pot*). Recently developed at *U-70* stochastic regime of slow beam extraction [5] provides 2×10^{13} *pot* during 3 s spill (flat top) at 8.5 s full cycle. Further intensity increasing is considered with the aim to reach of ~5×10^{13} *pot.* Additional bonus feature automatically realized at stochastic regime is the beam micro-bunching structure which is

200 MHz at present (with a possibility for adjustment) and bunch width of σ≈200 ps. This property gives an additional tool to suppress different backgrounds.

Intensity @ 10^{13} *pot*			**Ratio**		
K_L	n	γ	n/K_L	γ/K_L	γ/n
5.4×10^7	5.2×10^8	7.4×10^8	10	14	1.4

Table 1.

2.2 Detectors

In this section we present and motivate the main futures of the basic elements of the setup – *ECal*, *Main Veto* and *In Beam Veto* detectors.

For forward *ECal* we consider "spaghetti"-structure with scintillator fibers positioned across the beam and *Pb*/fibers ratio similar to the *JETSET* [6] and *KLOE* [7] electromagnetic calorimeters. Very dense structure (X_0≈13 mm) having small R_M allows one to have a fine granularity by grouping the fibers in 3 directions (*X*, *U*, *W*). Demonstrate moderate energy resolution of ~5%/√*E* is adequate to our goal since the beam itself is important source of an uncertainty. For instance the vertex reconstruction along the beam (σ_Z≈15 cm) is defined by *ECal* σ_E, at the same time the reconstructed P_T of π^0 (σ≈6 MeV/c) completely dominated by beam angular spread. The ability of proposed *ECal* to measure the angles of γ's is an important background suppression tool. Having 3-4 times longitudinally segmented device one can achieve 20mrad/√*E* and further improvement is possible by optimizing depth of each segment and providing some reasonable gaps between them along the beam.

Being the largest device the *Main Veto* dominates in total cost estimation and the choice of a sampling structure seems to be natural. 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 structure, (300μm *Pb* + 1mm Scint. plate). Such a sampling allows one to reduce detection threshold up to the smallest values giving ≈18 $ph.e^-$ per 1 MeV of "visible" energy (30000 photons per 1 GeV γ-shower) and ≈5.5 $ph.e^-$ per scintillator plate for *m.i.p.* at ordinary bi-alkaline photocathode [8].

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 ~10^{-3} for single γ). Fortunately in this case γ-spectrum is rather hard. 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 acryl 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 chernkov light to scintillator 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. It's needless to say that this devise should not be used in any trigger chain and caused by its huge counting rate losses have to be eliminated at the off-line level.

3. Experiment performances

Background and sensitivity estimations have been done using independently generated beam particles and parameterized detectors responses as well as veto γ-inefficiency function on energy. 1 MeV threshold of veto visible energy has been assumed although the *Main Veto* structure allows one to do better. The applied analysis cuts reduce the K_L^0 decays backgrounds to ≈0.3 events for 1 *SM* signal decay observation keeping $K_L^0 \to \pi^0\nu\tilde{\nu}$ acceptance on the level of (15÷18)%. The major source of backgrounds (≈80%) is $K_L^0 \to \pi^0\pi^0$ decay with losses of different kinds. Acceptance lost is estimated to be of ~10% with dominated fraction coming from *In Beam Veto* detector ("over-veto" effect). In the *Fiducial Volume* 4.8% K_L^0's decay. Thus, having the beam with intensity of $\mathbf{10^8}$ $\{5.4\times10^7\}$ K_L^0/spill, for 10 days of data taking (~ 10^4 spills/day) the sensitivity of experiment can be calculated as:

$10\times(10^4)\times(\mathbf{10^8}\{5.4\times10^7\})\times(4.8\times10^{-2})\times(\mathbf{18}\{15\}\times10^{-2})\times Br(2.8\times10^{-11}) \approx \mathbf{2.4}\{1.1\}$events.

3.1 Comparison with other experiments

Table 2 shows the parameters of running and planned (both at present and in the past) experiments on given subjects. After closing *KOPIO* (*BNL)* [11] and *KAMI* (*FNAL*) [12] projects the parameters of proposed apparatus can be compared with the only dedicated experiment *E391A* (*KEK*) [13] which will also finish soon. The last 2 months of data taking has been carried out at the end of 2005. The sensitivity is limited by intensity of existing 12 GeV accelerator and in ideal case its capability might allow one to reach the level of 10^{-10}. Recently the authors have announced the new upper limit as 2.1×10^{-7} (90% *C.L.*) [14]. Data processing continues and the analysis hopefully will reach the level of Grossman-Nir limit [15].

The actual goal of *E391A* was to show the reliability of the method and understand the background sources. This is an initial step to a high beam intensity experiment with sensitivity level of ~10^{-13} at proton accelerator *J-Parc*. But already now it is clear that moving *E391A* equipments to the new machine as was intended at the beginning doesn't allow one to achieve the goal. The global modification or completely new setup will be needed. The authors proposed the step by step approach [16]. The goal of Step-1 is to open decay mode with observation of ~3.5 *SM* events. It will require 3 years taking into account a sharing with other experiments target, non optimal extraction angle, low energy K_L^0 beam etc. On this stage the *E391A* setup with some modifications will be used. In the next Step-2 it is proposed the construction of a new optimized neutral beam line using higher energy beam and construction of a new apparatus. Additional 3 years of data taking will allow one to make detail study of $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay by collecting ~100 events. Taking into account high priority of neutrino program the results of even Step-1 can be expected not earlier of 2013.

Using the measurement strategy similar to *KAMI* and *E391A* experiments the proposed setup solves the problems with independent hardware. Offered new detectors possess greater opportunities and are more adapted for achievement of the experimental goal. Our experiment has the following features and advantages.

- Higher proton beam energy gives higher K_L^0 yield, allows increasing the extraction angle that improves K_L^0/neutron ratio.

- Higher K_L^0 momentum decreases the inefficiency of veto-system for soft γ's. Moreover at low energy for keeping acceptance the setup should be located near target that deteriorates the background conditions (accidentals). From other point of view higher energy results in increasing size and cost of setup.
- *ECal* ability to measure the incident angle of γ's helps to suppress the backgrounds. Its small R_M, fine granularity and universal segmentations reduce acceptance lost and backgrounds caused by superimposed clusters allowing easy recognize single electromagnetic shower.
- Main Veto fine sampling structure greatly improves system inefficiency for soft γ's. Veto organization in independent cells reduces "over-veto" effect due to different kind of accidentals and back-splashes from *ECal*.

Our studies show that with respect to the *J-Parc* Step-2 experiment we are compatible in terms of sensitivity but somewhat worth in signal/background ratio. The latest fact is mainly because of having so high primary beam intensity the Step-2 may allow to constrict beam size up to the smallest value still having similar to us K_L^0 beam intensity.

	KOPIO	***KAMI***	***E391A***	***J-Parc* (1)**	***J-Parc* (2)**
Proton energy	24 GeV	120 GeV	12 GeV	30 GeV	30 GeV
#Protons/spill	10^{14}	3×10^{13}	2.5×10^{12}	2×10^{14}	3×10^{14}
Duration cycle/ (spill)	5.3/(3) s	3/(1) s	4/(2) s	3.3/(0.7) s	3.3/(0.7) s
K_L^0 **extraxtion angle**	$40^o \div 45^o$	15 mrad	4^o	16^o	5^o
K_L^0 **momentum** average/(in peak)	920/(750) MeV/c	20/(12) GeV/c	2.6/(1.8) GeV/c	2.1/(1.3) GeV/c	5.2/(−) GeV/c
Beam profile	5.2mrad×96mrad	−	4 mrad, ∅	−	−
Spatial beam angle	500 μstr	0.41 μstr	12.6 μstr	9 μstr	2 μstr
K_L^0**/spill** (@setup)	2.6×10^8	6.2×10^7	3.3×10^5	8.1×10^6	4.4×10^7
Effective decay region	3 m	65 m	2 m	2 m	11 m
Decay probability in fiducial volume	≈16 (8) % (×1 decay/spill)	15 %	2.7 %	3.6 %	6 %
Beam time	3×10^7s	2×10^7s	6 months	3×10^7s	3×10^7s
Sensitivity	6×10^{-13}	−	$\sim10^{-9}$	8×10^{-12}	3×10^{-13}
# signal events (@SM)	96	88		3.5	133
Signal/Background	2	4.6		1.4	4.8

Table 2[2].

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