STUDY OF ULTRARARE DECAYS $K^0 \to \pi^0\nu\nu$(BAR) (Search of $K^0 \to \pi^0\nu\nu$(bar) decay at IHEP, project KLOD)

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Motivation of Experiment

The main goal of the presented project consists in the search and measurement of the branching ratio of $K_L^0 \to \pi^0\nu\tilde{\nu}$ decays. The experimental setup is optimized for the main purpose but opens some additional opportunities for researches of neutral modes of K_L^0-decays. The $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay is CP-violation decay [1]. In the frame of Standard Model (SM) the branching ratio of $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay is proportional to $\mathrm{Im}\,(V_{td}\ V_{ts})$, which represents the height of the Unitarity Triangl [e2] (Fig. 1).

The measurement of this height allows to determine the quark mixing matrix parameter η, which is responsible for CP-violation [3, 4]. The theoretical ambiguities in calculations of branching ratio of $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay are very small, $\sim 1 \div 2\%$. Using the current values of the Cabibo-Kaboyashi-Maskawa (CixKM) matr parameters, the branching ratio is equal to $(2.8 \pm 0.4) \times 10^{-11}$ [5], and even small deviation of the measured value from the theoretically predicted one will give a direct indication for the existence of “New Physics”.

The most strict upper limit of branching ratio derived from isotopic invariance is the model-independent theoretical limit $\mathrm{Br}(K_L^0 \to$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx$$

$$\approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4),$$

$$\lambda = \sin(\theta_c) = 0.22 \pm 0.002, \quad \text{“}\eta\text{”}(\mathrm{Im}(V_{td}))$$

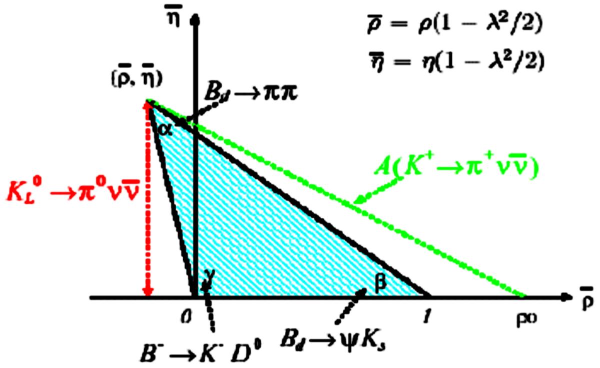

Fig. 1: The Cabibo-Kaboyashi-Maskawa (CKM) matrix and Unitarity Triangl

$\pi^0\nu\tilde\nu) < 4.37$ Br$(K^+ \to \pi^+\nu\tilde\nu)$, the so-called Grossman-Nir limit (GN) [6]. The decay $K^+ \to \pi^+\nu\tilde\nu$ was observed in experiments BNL E-787 (2 events) and E-949 (1 event). Common analysis of the data from these experiments results in the branching ratio to be in a range of $0.27\times10^{-10} <$ Br$(K^+ \to \pi^+\nu\tilde\nu) < 3.84\times10^{-10}$ (90% C.L.) [7]. The model-independent GN upper limit for $K_L^0 \to \pi^0\nu\tilde\nu$ decay is Br$(K_L^0 \to \pi^0\nu\tilde\nu|_{\rm GN} < 1.68\times10^{-9}$ (90% C.L.) and is about 300 times more sensitive than current direct measurements.

Experimental methods

The experimental setup us shown on Fig. 2.

Experimental difficulties in searches of extremely rare decays are not only achievement of sufficient efficiency of registration, but also

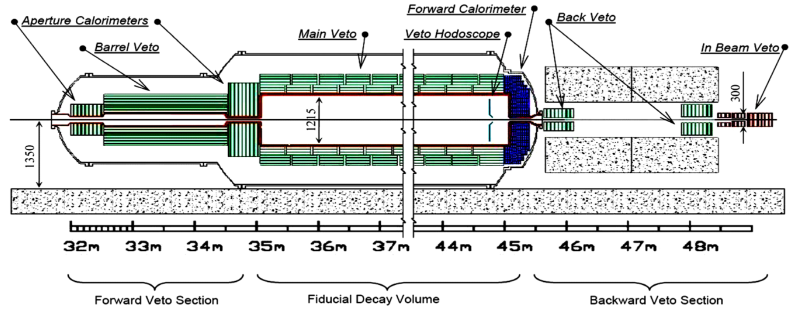

Fig. 2: The KLOD setup

control and understanding of systematic errors. The $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay is to be identified by the signature of $\pi^0(\pi^0 \to \gamma\gamma)$ + "nothing", where gammas are measured by the electromagnetic calorimeter and "nothing" is the absence of the signal in the veto-system. The sought-for decay contains only 2 gammas with the effective mass of π^0 in the final state. At the same time, having considered all decay modes of K_L^0 listed in PDG [8], one can see that 34% of K_L^0 decays have π^0 in the final state. On the other hand, all decays, except $K_L^0 \to \gamma\gamma$, have at least 2 charged particles or 4 gammas in the final state. Thus, the basic condition for the search is the requirement of presence of only 2 gammas and absence of any other registered particles. The most dangerous backgrounds are decays of K_L^0 to $2\pi^0$, $3\pi^0$ or 2γ.

The K_L^0-mesons basically decay to multi-particle final states, which results in small momenta of decay products in the K_L^0 rest system. On the contrary, a spectrum of π^0 momenta in the $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay is harder due to V-A interaction. Since the momentum in the rest system corresponds to the transverse momentum $\mathbf{P}_T$ in the laboratory system, the signal/background ratio can be improved by selection of π^0 with high $\mathbf{P}_T$. Serious background sources, which are not connected with decays, are interactions of halo and core beam particles with the material of the setup. As a result, either a single π^0 or a Λ hyperon with subsequent decay $\Lambda \to \pi^0 n$ can be produced.

Thus, the decay region of the proposed setup must be in a high vacuum and be surrounded by a highly efficient veto system. The distant wall is an electromagnetic calorimeter with a good energy and position resolution. Non-decayed K_L^0 leave the decay region through the beam hole at the center of the calorimeter. A special veto detector able to efficiently detect gammas from background decays in the presence of a large flow of beam core particles is installed at the end.

The measurement strategy is to record events with 2 neutral clusters in the calorimeter without a signal from the veto system. The reconstruction of two clusters into the π^0 mass on the assumption of the infinitely narrow beam allows one to calculate the decay vertex along the beam axis and $\mathbf{P}_T$ of π^0, the cutoff of which is the strongest factor in background suppression. One more important factor of background suppression is the requirement that the decay vertex be inside the fiducial volume.

Requirements to the neutral beam following from the proposed measurement strategy are rather severe:

- the beam must be narrow ($R < 5$ cm) and well collimated;
- the beam must have small angle deviation, that is be well balanced in transverse momentum $\mathbf{P}_T$;
- the beam must have high intensity ($\sim 10^8$ K_L^0/cycle) at the mean K_L^0 energy ~ 10 GeV;
- the beam must have small contamination by other undesired neutral particles. Especially, the neutron/K_L^0 ratio should be as small as possible.

The full version of the proposal shows the possibility of constructing a neutral beam at IHEP (Protvino) on the basis of the existing magnets and accommodating it into the existing beam channel system. The beam channel providing a well-collimated highly intense beam is designed and the calculation of the main parameters of K_L^0 and other components of the beam is presented.

The geometry of the detector (Figure 1) is dictated by the requirement of air-tightness for good efficiency of gamma registration [9].

Comparison with Other Experiments

Now only one experiment on registration of the$K_L^0 \to \pi^0\nu\tilde{\nu}$ decay is under way. The best upper limit of 5.7×10^{-7} (90% C.L.) (as of the

Table 1: Particle fluxes per spill

	K_L	n	γ
Without Pb	7.7×10^{7}	8.3×10^{8}	3.1×10^{10}
With Pb	5.4×10^{7}	5.2×10^{8}	7.4×10^{8}
	n/K_L	γ/K_L	γ/n
Without Pb	11	402	37
With Pb	10	14	1.4

beginning of 2006) was obtained by the KTeV-E799 experiment [10] through observing the Dalitz-decay $\pi^0 \to e^+e^-\gamma$. An advantage of this method is a possibility of measuring the decay vertex, which does not require a narrow beam. The disadvantages are a small probability of the Dalitz-decay and the background from K_{e3}-decays ($K_L^0 \to \pi^\pm e^\mp \gamma\nu$) due to misidentification of $\pi^\pm$ as $e^\pm$. Table 1 shows the parameters of the running and planned experiments on the given subjects. After closure of the KOPIO (BNL) [i] and KAMI (FNAL) [11] projects the parameters of the KLOD setup can be compared only with the running E-391A (KEK) experiment [12] which will also finish soon. The last two-month data-taking run (RUN-III) was carried out at the end of 2005. The sensitivity is limited by the intensity of the 12 GeV proton accelerator and might ideally reach the level of 10^{-10}. Recently the authors have announced a new upper limit 2.1×10^{-7} (90% CL) [13] based on $\sim 10\%$ RUN-I statistics. Data processing continues and the analysis of the full data set will probably allow the level of the Grossman-Nir limit to be reached.

The goal of the E391a experiment was to show the reliability of the method and to understand the background sources. This is the first step for the high beam intensity experiment with a sensitivity level of $\sim 10^{-13}$ at the proton accelerator J-Park [14]. But now it is clear that moving the E391a setup to a new accelerator, as was initially intended, does not solve this problem. The global modification or a completely new setup will be required.

Recently the proposal of the experiment has been published [15]. They proposed the step-by-step approach. The goal of the first step is to observe the decay (~ 3.5 events at the level of SM). In view of target share with other experiments, a non-optimal extraction angle and a low-energy K_L^0 beam, it will require three years of data taking. At this stage the E391a setup with some modifications will be used.

For example, it is considered to replace the CsI calorimeter with its big cells and inadequate radiation length by a more suitable CsI calorimeter from the KTeV experiment.

At the next (main) step it is proposed to construct a new optimized neutral beam line, to use a higher-energy beam, and to construct a new setup. Three more years of data taking will allow a detailed study of the $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay by collecting ~ 100 events with a good S/N ratio. Considering the delay in the construction of the J-Park and high priority of the neutrino program, the results of the first step can be expected not earlier than 2013 [16].

Our experiment will have the following features and advantages:

1. The primary proton beam energy as high as 60–70 GeV provides a higher K_L^0 yield and allows a larger extraction angle of the secondary beam, which improves the K_L^0/neutron ratio.

2. A higher energy of the K_L^0 beam (the mean energy of the neutral beam is considered to be ~ 10 GeV) decreases the inefficiency of the veto-system for soft gammas from background decays. Moreover, to retain acceptance at low energy, the setup should be located near the target, which deteriorates the background conditions. On the other hand, higher energy results in increasing size and cost of the setup.

3. The ability of the calorimeter to measure the incident angle of gammas helps to suppress backgrounds.

4. A high visible ratio of deposited energy in the veto detectors due to thin converter layers allows a decrease in the veto threshold to 1 MeV.

5. The veto system of independent cells can be used not only for background suppression but also for gamma measurements, which may increase acceptance for $K_L^0 \to \pi^0\nu\tilde{\nu}$. In addition, calibration of the main detectors is simplified and their inefficiency can be monitored using the real events.

It is worth mentioning that the proposed setup is generally a set of calorimeters. The collaborating institutes have rich experience in designing, constructing and operating such detectors in home and foreign experiments.

Estimation of Background Suppression and Sensitivity of Experiment

Characteristics of the complete experimental setup were also studied independently using GEANT-3 and GEANT-4. The results were compared and verified. The beam profile and the spectra, obtained from the beam line simulation, and the inefficiency functions of detectors were used in the simulation.

The following cuts were used for estimation of the contribution from the main background K_L^0-decays:

- The reconstructed energy of each gamma is larger than 0.15 GeV.
- The reconstructed energy of each gamma is smaller than 6 GeV.
- The reconstructed transverse momentum of π^0 is larger than 120 MeV/c.
- The reconstructed decay vertex must be inside the decay volume.
- The decay vertex reconstructed from the clusters using gamma angles must agree within ± 0.5 m with the decay vertex reconstructed from the cluster on the assumption of the π^0 mass.
- The center of gravity of 2 clusters in the calorimeter must be at a distance more than 20 cm from the beam axis.
- The distance between the gamma clusters must be larger than 15 cm.

Table 2 shows the contribution of the most essential background decays. The estimation was done by generating the number of events for the given decay 10 times (100 times for $K_L^0 \to 2\pi^0$ decay) larger than required for observation of one $K_L^0 \to \pi^0\nu\tilde{\nu}$ event with the given acceptance. No events of any background decay (except $K_L^0 \to 2\pi^0$) were observed in the simulation. The limit for $K_L^0 \to \pi^+e^-\nu$ was obtained from the simulation of $K_L^0 \to \pi^-e^+\nu$ with allowance for the difference in registration inefficiency between $\pi^{\pm}$ and $e^{\pm}$. The major part of $K_L^0 \to 2\pi^0$ backgrounds comes from events with 2 gammas in the beam veto.

Table 2

Background source	Number of backgrounds normalized to SES (single event sensitivity) at SM level
K_L^0 decays, yielding at least one gamma. Caused by inefficiency for gammas	0.26 $(\pi^0\pi^0)$ < 0.1 $(\gamma\gamma)$ < 0.1 $(\pi^0\pi^0\pi^0)$
K_L^0 decays, yielding charged particles. Caused by inefficienc y for charged particles	< 0.1 $(\pi^- e^+ \nu)$ < 0.01 $(\pi^+ e^- \nu)$

The acceptance for the $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay with the above cuts was estimated to be $\sim 18\%$. In the decay region 4.8% of K_L^0 decays occurred. Thus, with the beam of intensity 10^8 $\{5.4\times10^7\}$ K_L^0/spill, the sensitivity of the experiment for 10 days of data taking ($\sim 10^4$ spills/day) can be calculated as:

$$1\times(10^4)\times(10^8\{5.4\times10^7\})\times(4.8\times10^{-2})\times(18\times10^{-2})\times\mathrm{Br}(2.8\times10^{-11})\approx$$

2.4{1.1} events.

Setup Construction Stages

A beam with the required characteristics is the basic condition for the success of the experiment. Therefore, realization of the project must begin with design and construction of the beam line with detailed simulation and optimization of all its elements. Under favorable conditions this work can be completed within 1-1.5 years. By that time the equipment for measurement of beam characteristics and their comparison with the design parameters should be prepared.

Most detectors of the setup are well-studied calorimetric structures and do not demand detailed researches of their prototypes. In particular, for making a decision on creation of the step veto-system of the main decay volume only one counter should be assembled for optimization of manufacturing technology and for demonstration of a possibility of creating self-supported modules. The only exception is the beam veto and, probably, the forward electromagnetic calorimeter. If they are similar in design, it is possible to create a common prototype which will also be necessary for studying beam characteristics. This means that it should be made simultaneously with the beam line, whose operation should comply with the accelerator beam time schedule.

Mass production of all detectors should start 0.5-1 year after accomplishment of the beam line construction. This delay is assumed to be used for beam survey. Also, detailed simulation carried out in parallel allows us to simplify the design of the detectors before their production.

The total time from the beam line designing to the beginning of the experiment is expected to be 4-4.5 years. Two years of data taking should allow measuring or, at least, observing $K_L^0 \to \pi^0 \nu \tilde{\nu}$ decay.

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