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ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ЭКСПЕРИМЕНТ

SEARCH FOR THE $K_L^0 \to \pi^0\nu\tilde{\nu}$ DECAY AT THE IHEP U-70 ACCELERATOR: THE KLOD PROJECT

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The rare decay $K_L^0 \to \pi^0\nu\tilde{\nu}$ branching ratio measurement is one of the clearest Standard Model test. Calculations based on the SM predict $\mathrm{Br}(K_L^0 \to \pi^0\nu\bar{\nu}) \approx 2.8{\cdot}10^{-11}$, but the most accurate experimental value $\mathrm{Br}(K_L^0 \to \pi^0\nu\bar{\nu}) < 6.7{\cdot}10^{-8}$ (90% C.L.). We present design of a new experimental setup KLOD (U-70 accelerator, IHEP, Protvino) for $K_L^0 \to \pi^0\nu\tilde{\nu}$ branching ratio measurement. Sensitivity of the KLOD experiment will be enough for registration of 2.4 events $K_L^0 \to \pi^0\nu\tilde{\nu}$ for every 10 days of the data taking (according to SM predictions).

Измерение относительной вероятности редкого распада $K_L^0 \to \pi^0\nu\tilde{\nu}$ является одним из наиболее ясных тестов стандартной модели. Расчеты, основанные на положениях СМ, предсказывают $\mathrm{Br}(K_L^0 \to \pi^0\nu\bar{\nu}) \approx 2{,}8 \cdot 10^{-11}$, а наиболее точное экспериментальное значение: $\mathrm{Br}(K_L^0 \to \pi^0\nu\bar{\nu}) < 6{,}7 \cdot 10^{-8}$ (90 % C.L.). В настоящей работе представлены результаты расчета экспериментальной установки KLOD (для ускорителя У-70, ИФВЭ, Протвино) по измерению относительной вероятности распада $K_L^0 \to \pi^0\nu\tilde{\nu}$. Чувствительности эксперимента KLOD будет достаточно для регистрации 2,4 события (согласно предсказаниям СМ) $K_L^0 \to \pi^0\nu\tilde{\nu}$ за каждые 10 сут. экспозиции на пучке.

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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 research of neutral modes of K_L^0 decays.

The $K_L^0 \to \pi^0\nu\tilde{\nu}$ decay is CP-violation decay [1]. It proceeds through direct CP violation in FCNC $s \to d\nu\tilde{\nu}$ process and also through indirect CP violation due to $|K^0\rangle \leftrightarrow |\overline{K}^0\rangle$

mixing. The contribution of the direct CP-violation mechanism is dominant and the influence of the indirect one is negligible [2]. In the framework of the 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 triangle. The measurement of this height allows one 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, $\sim$ 1–2%. Using the current values of the Cabibbo–Kobayashi–Maskawa (CKM) matrix parameters, the branching ratio is equal to $(2.8 \pm 0.4) \cdot 10^{-11}$ [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 $\mathrm{Br}(K_L^0 \to \pi^0 \nu \tilde{\nu}) < 4.37\,\mathrm{Br}(K^+ \to \pi^+ \nu \tilde{\nu})$, 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 $0.27 \cdot 10^{-10} < \mathrm{Br}(K^+ \to \pi^+ \nu \tilde{\nu}) < 3.84 \cdot 10^{-10}$ (90% C.L.) [7]. The model-independent GN upper limit for $K_L^0 \to \pi^0 \nu \tilde{\nu}$ decay is $\mathrm{Br}(K_L^0 \to \pi^0 \nu \tilde{\nu})|_{\mathrm{GN}} < 1.68 \cdot 10^{-9}$ (90% C.L.) and is about 40 times more sensitive than current direct measurements.

EXPERIMENTAL METHODS

Experimental difficulties in searches of extremely rare decays are not only achievement of sufficient efficiency of registration, but also 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. Because background decays contain at least 2 additional particles, the efficiency of the veto system should be better than the square root of the desirable level of the background suppression. 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 multiparticle 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 P_T in the laboratory system, the signal/background ratio can be improved by selection of π^0 with high 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 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 on 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 P_T;

• the beam must have high intensity ($\sim 10^8$ K_L^0/cycle) at the mean K_L^0 energy $\sim$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 (Table 1).

Table 1. **Particle fluxes per spill**

Beam channel	K_L	n	γ	n/K_L	γ/K_L	γ/n
Without Pb absorber	$7.7 \cdot 10^7$	$8.3 \cdot 10^8$	$3.1 \cdot 10^{10}$	11	402	37
With Pb absorber	$5.4 \cdot 10^7$	$5.2 \cdot 10^8$	$7.4 \cdot 10^8$	10	14	1.4

Outline design of the beam channel zone is performed, and the corresponding specifications for the installation work in the experimental hall of the accelerator are prepared. The detailed calculations for beam channel optimization are published [9].

The geometry of the detector (Fig. 1) is dictated by the requirement of air-tightness for good efficiency of gamma registration. The entire vacuum volume of the setup is divided into the main decay volume and its entrance part (double decay chamber concept). This configuration is necessary for effective suppression of backgrounds from K_L^0 (Λ) decays on the way from the target to the entrance of the setup. The decay volume (up to the back wall of the forward calorimeter) must be pumped out to a level of high vacuum ($\sim 10^{-7}$ Torr) for suppression of the background from interaction of K_L^0 and neutrons with residual gas in the setup.

High vacuum in the fiducial volume can be reached by creation of a double vacuum system. The main volume of the external metal casing that contains detecting elements of the setup can be pumped out to a level of $\sim 10^{-3}$–10^{-4} Torr. The decay volume itself and the adjoining area along the beam are separated from it by a thin (0.19 mm, $4 \cdot 10^{-4}\,X0$) CH_2 membrane, shown by the internal contour in the figure, and are pumped out to high vacuum.

The forward electromagnetic calorimeter, the veto system of the decay volume and the forward hodoscope veto are the elements of the main decay volume. Detectors of the entrance

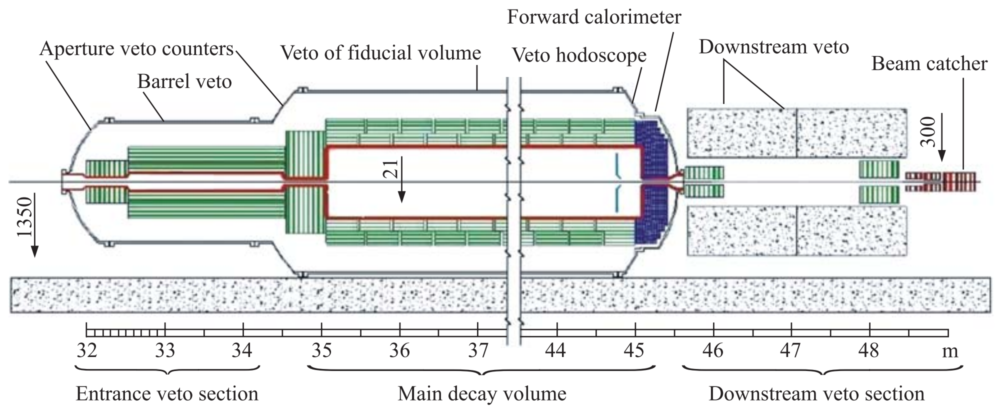

Fig. 1. Schematic layout of the setup

veto section are 2 aperture calorimeters and a forward barrel veto. The downstream veto section, which is outside the vacuum casing and consists of 2 back veto detectors and a beam veto calorimeter, closes the setup. Figure 1 shows some geometrical dimensions of the basic detectors. The presented scale of distances has the origin at the target position.

In the full version of the Project requirements on the detectors derived from their tasks are considered and motivated. Some concrete methodological studies of basic elements of the setup are also presented there.

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 $6.7 \cdot 10^{-8}$ (90% C.L.) (as of the beginning of 2009) was obtained by the E391 experiment [10, 11].

Table 2 shows the parameters of the running and planned experiments on the given subjects. After closure of the KOPIO (BNL) [12] and KAMI (FNAL) [13] projects the parameters of the KLOD setup can be compared only with the running E-391A (KEK) experiment 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}. 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.

Table 2[1]

Experiment	KOPIO	KAMI	E391A	J-Park (1)	J-Park (2)
Proton energy, GeV	24	120	12	30	30
#Protons/spill	10^{14}	$3 \cdot 10^{13}$	$2.5 \cdot 10^{12}$	$2 \cdot 10^{14}$	$3 \cdot 10^{14}$
Duration cycle/ (spill), s	5.3/(3)	3/(1)	4/(2)	3.3/(0.7)	3.3/(0.7)
K_L^0 beam extraction angle	(40–45)°	15 mrad	4°	16°	5°
K_L^0 beam 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	5.2×96 mrad	—	4 mrad, ∅	—	—
Spatial beam angle, μsr	500	0.41	12.6	9	2
K_L^0/ spill (@setup)	$2.6 \cdot 10^8$	$6.2 \cdot 10^7$	$3.3 \cdot 10^5$	$8.1 \cdot 10^6$	$4.4 \cdot 10^7$
Effective decay region, m	3	65	2	2	11
Decay probability in fiducial volume, %	≈ 16 (8) (×1 decay/ bunch)	15	2.7	3.6	6
Beam time	$3{\cdot}10^7$ s	$2{\cdot}10^7$ s	6 months	$3{\cdot}10^7$ s	$3{\cdot}10^7$ s
Sensitivity	$6 \cdot 10^{-13}$	—	$\sim 10^{-9}$	$8{\cdot}10^{-12}$	$3{\cdot}10^{-13}$
#signal events (@SM)	96	88	Under determination	3.5	133
S/N	2	4.6	Under determination	1.4	4.8

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.

With the strategy of measurements similar to that in the E391a experiment, the proposed setup solves the problem with independent hardware. The proposed new detectors possess

[1]The data presented in the table were taken from the original proposals without recalculations and tracking of changes in values.

greater potentialities and are better adapted to achieve the goal of the experiment. Our experiment will have the following features and advantages:

• 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.

• 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.

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

• 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.

• 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 of designing, constructing and operating such detectors in home and foreign experiments.

ESTIMATION OF BACKGROUND SUPPRESSION AND SENSITIVITY OF EXPERIMENT

Full simulation of all background decays has not been done yet because it required huge CPU power and time. The detector parameters, such as the energy, the coordinate and angular resolution of the calorimeter, and the inefficiency of registration of γ's in a wide energy range by the veto were studied using the GEANT-3 and GEANT-4 packages. The data obtained were then used as parameterized response functions of the detectors.

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:

1. The reconstructed energy of each gamma is larger than 0.15 GeV.
2. The reconstructed energy of each gamma is smaller than 6 GeV.
3. The reconstructed transverse momentum of π^0 is larger than 120 MeV/c.
4. The reconstructed decay vertex must be inside the decay volume.
5. 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.
6. The center of gravity of 2 clusters in the calorimeter must be at a distance more than 20 cm from the beam axis.
7. The distance between the gamma clusters must be larger than 15 cm.

Table 3 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 3

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^0decays, yielding charged particles. Caused by inefficiency 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 $\{15\}$%. In the decay region 4.8% of K_L^0 decays occurred. Thus, with the beam of intensity 10^8 $\{5.4 \cdot 10^7\}K_L^0$/spill, the sensitivity of the experiment for 10 days of data taking ($\sim 10^4$ spills/day) can be calculated as

$$10 \times (104) \times (10^8\{5.4 \cdot 10^7\}) \times (4.8 \cdot 10^{-2})(18\{15\} \cdot 10^{-2})\,\mathrm{Br}(2.8 \cdot 10^{-11}) \approx 2.4\{1.1\} \text{ events.}$$

SETUP CONSTRUCTION STAGES

A beam with the required characteristics (and better whenever possible) 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 yr. 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 research 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 yr (depending on accessible beam time) 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 yr. Two years of data taking should allow measuring or, at least, observing $K_L^0 \to \pi^0 \nu \tilde{\nu}$ decay.

CONCLUSION

The presented briefly summarized results of our studies show an opportunity and perspectives to create at IHEP U-70 accelerator a high-intensity K_L^0-meson beam to carry out an experiment for searching the rare decay $K_L^0 \to \pi^0 \nu \tilde{\nu}$.

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