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DIRECT CP AND T VIOLATION IN KAON DECAYS

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The recent experimental results concerning direct CP violation in the decays of neutral kaons and the search for T violation in the decays of charged kaons are reviewed.

Представлены новые экспериментальные результаты прямого нарушения CP-инвариантности в распадах нейтральных каонов и поиска нарушения T-инвариантности в распадах заряженных каонов.

INTRODUCTION

Since the discovery of CP violation in neutral kaon decays in 1964 [1] its origin is still a mystery and one of the most outstanding issues in particle physics. It is being intensively studied in both kaon and B sectors by existing experiments and new ones specifically constructed for this purpose. In this talk, I would like to outline the status and prospects for the study of CP violation in the kaon sector.

The mass eigenstates of neutral kaons consist of $|K_S\rangle \sim (|K_1\rangle + \varepsilon|K_2\rangle)/\sqrt{2}$ and $|K_L\rangle \sim (|K_2\rangle + \varepsilon|K_1\rangle)/\sqrt{2}$. The $K_L \to \pi\pi$ decay is dominated by $\varepsilon|K_1\rangle$ (CP $= +1$) which is caused by the mixing between K^0 and $\bar{K}^0$ and is called indirect CP violation. If the K_2 (CP $= -1$) state decays into $\pi\pi$ (CP $= +1$), CP is violated in the decay itself and this process is called direct CP violation and parametrized by ε'.

The standard mechanism to incorporate CP violation in the Standard Model is the CKM complex matrix $V_{\rm CKM}$ for 3 families of quarks [2]:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{\rm CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \qquad (1)$$

The CKM matrix can be expressed in terms of 4 parameters (Wolfenstein parameterization) λ, A, ρ, η, where η represents the only CP-violating parameter:

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \qquad (2)$$

The unitarity of the CKM matrix leads to the relationships between the elements:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0. \qquad (3)$$

As a result of the unitarity of the CKM matrix the quantities $V_{ub}^*/A\lambda^3 = \rho + i\eta$, $V_{td}/A\lambda^3 = 1 - \rho - i\eta$ and 1 form a triangle in the (ρ, η) plane, i.e., the unitarity triangle (see Fig. 1).

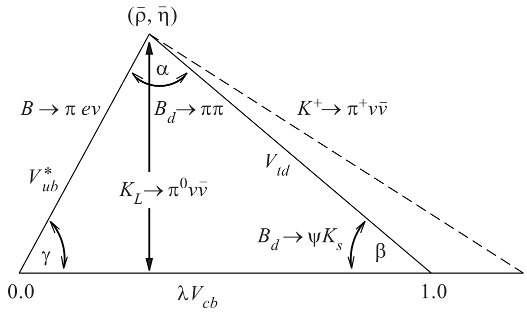

Fig. 1. $K \to \pi\nu\bar\nu$ and the unitarity triangle

In the SM, a single parameter η is the only source of CP violation which makes the predictions for CP-violation phenomena quite constrained. The CKM matrix generates CP-violating effects in $\Delta S = 2$, $K^0 - \bar{K}^0$ transitions through the box diagram whose imaginary part provides explanation of the indirect CP violation ε and direct CP violation ($\Delta S = 1$ decay amplitude) can be generated through the penguin diagrams. The study of rare flavour-changing neutral current processes $K \to \pi\nu\bar\nu$ can shed further light on CP violation in the SM. The most interesting is the $K_L \to \pi^0\nu\bar\nu$ which proceeds in the SM entirely through a CP-violating amplitude which originates from the box and weak penguin diagrams with top quarks running in the loop. This process is the best probe of η.

1. THE PARAMETER ε'/ε

The information about the parameter ε'/ε is derived from the measurement of the double ratio of decay rates

$$1 - 6\mathrm{Re}\,(\varepsilon'/\varepsilon) = \frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{\Gamma(K_L^0 \to \pi^0\pi^0)}{\Gamma(K_S^0 \to \pi^0\pi^0)}\frac{\Gamma(K_S^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \pi^+\pi^-)}. \quad (4)$$

The history of the ε'/ε measurements is shown in the Table.

The ε'/ε measurements

$\mathrm{Re}\,(\varepsilon'/\varepsilon)\cdot 10^{-4}$	Experiment	Year	Ref.	Comments
32 ± 30	E731A	1987	[3]	First run of E731
33 ± 11	NA31	1986	[4]	
-4 ± 15	E731	1990	[5]	result based on 20 % statistics
7.4 ± 5.9	E731	1992	[6]	
23 ± 6.5	NA31	1993	[7]	
28.0 ± 4.1	KTeV	1999	[8]	
18.5 ± 7.3	NA48	1999	[9]	
12.2 ± 4.9	NA48	2000	[10]	preliminary, based on data-98

The two last experiments (KTeV and NA48) settled the long-standing issue of the value of direct CP violation in kaon decays. However, a clear determination of the actual value of $\mathrm{Re}\,(\varepsilon'/\varepsilon)$ must still be obtained after the analysis of full statistics and a detailed study of systematics. The Standard Model theoretical predictions have been rather controversial because several groups have obtained different results (for a review see [11]). The accuracy of the calculations is determined by large hadronic uncertainties in $K \to \pi\pi$ that makes the reliable extraction of the SM parameters very difficult. However, some models which predict a substantially smaller value of $\mathrm{Re}\,(\varepsilon'/\varepsilon)$ than the SM predicts (superweak model) are consequently excluded.

2. SUPPRESSED DECAYS

The interest in these decays is driven mainly by their potential to elucidate flavor physics, in particular the question of CP violation.

2.1. $K \to \pi\nu\bar{\nu}$. The most interesting of these processes are the «golden» decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$. These decays are uniquely sensitive to $|V_{td}|$ and to the CKM CP-violation parameter η, respectively. They are strongly GIM-suppressed and their leading contributions arise from loops involving weak bosons and heavy quarks. The connection between the rates of these processes and the fundamental parameters of the SM is extremely well determined because the matrix element connecting the short-distance interaction to the initial and final state hadrons is measured by the rate of the K_{e3} decay [12].

The decay $K^+ \to \pi^+\nu\bar{\nu}$ is sensitive primarily to the matrix element V_{td} with a small charm correction. The Standard Model predictions [13] for the $K \to \pi\nu\bar{\nu}$ branching ratios look as follows:

$$B(K^+ \to \pi^+\nu\bar{\nu}) = \frac{r_{K^+}\alpha^2 B(K^+ \to \pi^0 e^+\nu)}{V_{us}^2 2\pi^2 \sin^4\theta_W} \sum_{l=e,\mu,\tau} |V_{cs}^* V_{cd} X_{NL}^l + V_{ts}^* V_{td} X(x_t)|^2. \quad (5)$$

Here, $r_{K^+} = 0.901$ is an isospin-breaking correction, X_{NL}^l is a charm function calculated in [13]. The SM prediction based on the current data for the CKM matrix elements gives $B(K^+ \to \pi^+\nu\bar{\nu}) = (8.2 \pm 3.2) \cdot 10^{-11}$.

The branching ratio of the $K_L^0 \to \pi^0\nu\bar{\nu}$ decay can be written as

$$B(K_L^0 \to \pi^0\nu\bar{\nu}) = r_{IB} B(K^+ \to \pi^0 e^+\bar{\nu}) \frac{\tau(K_L)}{\tau(K^+)} \frac{3\alpha^2}{2\pi^2 \sin^4\,\theta_W} \eta^2 A^4 \lambda^8 X^2(x_t), \quad (6)$$

where

$$X(x) = \eta_X \frac{x}{8}\Big[\frac{x+2}{x-1} + \frac{3x-6}{(x-1)^2}\ln x\Big]. \quad (7)$$

Here $\eta_X = 0.985$, $x_t = m_t^2/M_W^2$, and λ, A, ρ, η are the usual Wolfenstein parameters. The coefficient $r_{IB} = 0.944$ summarizes the leading isospin-breaking corrections in relating $K_L^0 \to \pi^0\nu\bar{\nu}$ to $K^+ \to \pi^0 e^+\bar{\nu}$. As a consequence $B(K_L^0 \to \pi^0\nu\bar{\nu}) \sim \eta^2$. Using current values of SM parameters, the branching ratio for $K_L^0 \to \pi^0\nu\bar{\nu}$ is expected to be in the range of about $(2.8 \pm 1.7) \cdot 10^{-11}$. The unitarity relation

$$1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \equiv \bar{\rho} + i\bar{\eta} \quad (8)$$

determines a triangle in the $(\bar{\rho}, \bar{\eta})$ plane as shown in Fig. 1, where the potential of $K \to \pi\nu\bar{\nu}$ is illustrated and the relations to quantities measured in B decay is shown. Here, $\bar{\rho} \simeq \rho(1-\lambda^2/2)$

and $\bar{\eta} \simeq \eta(1-\lambda^2/2)$. A clean measure of its height is provided by the $K_L^0 \to \pi^0\nu\bar{\nu}$ branching ratio itself and $B(K_L^0 \to \pi^0\nu\bar{\nu})$ plus $B(K^+ \to \pi^+\nu\bar{\nu})$ determine the unitarity triangle completely. An accuracy of ± 10 % in the branching ratio measurements provides a 5 % accuracy in η determination. Such a precise determination of the CKM parameters in $K \to \pi\nu\bar{\nu}$ decays is comparable to what can be achieved by CP-violation studies at the B factories [14]. Moreover, any additional to B decays and independent measurement of CKM parameters would test the Standard Model and any significant deviations would point to new physics [15]. These decays are suppressed down to the level of few$\times 10^{-11}$ and therefore they are also quite sensitive to physics beyond the SM. This has been emphasized lately by theorists attempting to explain the large value of ε'/ε. Effects that are relatively small and difficult to discern in ε'/ε can become completely unmistakable in $K \to \pi\nu\bar{\nu}$ [16, 17]. With two unobservable particles in the final state, these decays present very difficult experimental challenges, but their potential is so great that they are being quite actively pursued.

2.1.1. $K^+ \to \pi^+\nu\bar{\nu}$. For many years AGS E787 has been on the trail of $K^+ \to \pi^+\nu\bar{\nu}$. The main elements of the E787 detector are a solenoidal spectrometer situated at the end of a very intense low-energy separated beam, an active target, a cylindrical drift chamber, an array of scintillators and photon detectors [18]. Definitive recognition of the $K^+ \to \pi^+\nu\bar{\nu}$ signal requires that no other observable activity is present in the detector and all backgrounds are suppressed below the sensitivity for the signal. Charged decay products of stopped K^+ are tracked through the target, a cylindrical drift chamber and into a cylindrical array of scintillators and drift chambers («Range Stack») where they range out. Pions are identified by kinematic correlation ($\frac{dE}{dx}$/total energy/range/momentum) and by observing their $\pi^+ \to \mu^+ \to e^+$ decay chain in the stopping scintillators. Photon detectors surround the Range Stack, and the entire apparatus serves as an hermetic veto for extra tracks. These techniques have been perfected over many years and the backgrounds have been reduced to 10^{-11}/event, which is sufficient for a measurement at the SM level. The data through 1997 have been analyzed and the result is shown in Fig. 2 as a plot of pion range vs kinetic energy for candidates passing all the other cuts.

The single point falling into the signal region is the famous 1995 event [19]. Recently an analysis of a larger data set (a combination of the 1995 data with the 1996–97 data) has been published [20]. No further events were seen with a measured background of 0.08 ± 0.02, which gives a branching ratio $B(K^+ \to \pi^+\nu\bar{\nu}) = (1.5^{+3.4}_{-1.2}) \cdot 10^{-10}$. This result provides the limits on $|V_{td}|$ $0.002 < |V_{td}| < 0.04$. E787 has now finished running and collected data approximately of the sensitivity equal to the sum of all its previous runs that should allow them to reach the SM level for $K^+ \to \pi^+\nu\bar{\nu}$.

E787 has improved the sensitivity to $K^+ \to \pi^+\nu\bar{\nu}$ by a thousand-fold from the inception of the experiment, but this still does not exhaust the potential of this decay. To obtain a useful measurement of $|V_{td}|$, a more sensitive experiment will be needed. Thus a successor experiment, AGS E949, has been proposed [21].

E949 exploits the fact that the AGS is now primarily an injector for RHIC; hence it will most likely serve at most one or two proton experiments at any one time. Thus much larger proton currents can be devoted to a $K^+ \to \pi^+\nu\bar{\nu}$ experiment, and the accelerator running mode can be highly optimized for this work. This allows a large increment in sensitivity to be made with only modest hardware upgrades. In this way, a sensitivity of $\sim 10^{-11}$/event can be achieved in three years of running. In the longer term, to go beyond this level, the

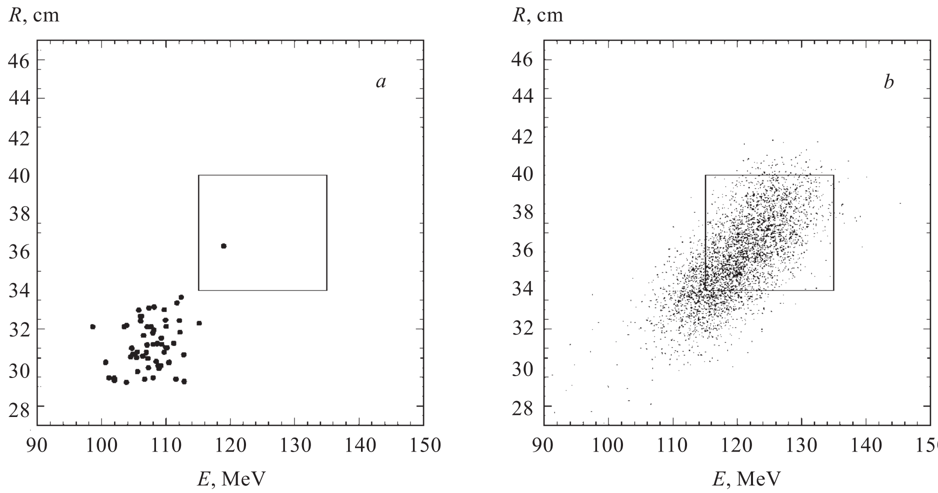

Fig. 2. Range versus kinetic energy of π^+ for $K^+ \to \pi^+\nu\bar{\nu}$ candidates from E787. The inner rectangle bounds the signal region. *a*) Experimental data. The cluster of events to the lower left is residual $K^+ \to \pi^+\pi^0$ background. *b*) Monte-Carlo simulation of $K^+ \to \pi^+\nu\bar{\nu}$ with the same cut applied

CKM experiment [22] has been proposed for the Fermilab Main Injector. This is an in-flight experiment designed to reach the 10^{-12}/event level. At this point the experimental precision will be comparable to that currently claimed by theory in the SM.

2.1.2. $K_L^0 \to \pi^0\nu\bar{\nu}$. In the Standard Model the rare decay $K_L^0 \to \pi^0\nu\bar{\nu}$ is a uniquely sensitive probe of direct CP violation [23, 24]. There are as yet no results from dedicated experiments to measure this decay. The indirect limit on $K_L^0 \to \pi^0\nu\bar{\nu}$ is derived in a model-independent way [25] from the measurement of $K^+ \to \pi^+\nu\bar{\nu}$: $B(K_L^0 \to \pi^0\nu\bar{\nu}) < 4.4 \cdot B(K^+ \to \pi^+\nu\bar{\nu}) < 2.6 \cdot 10^{-9}$ (90 % C.L.).

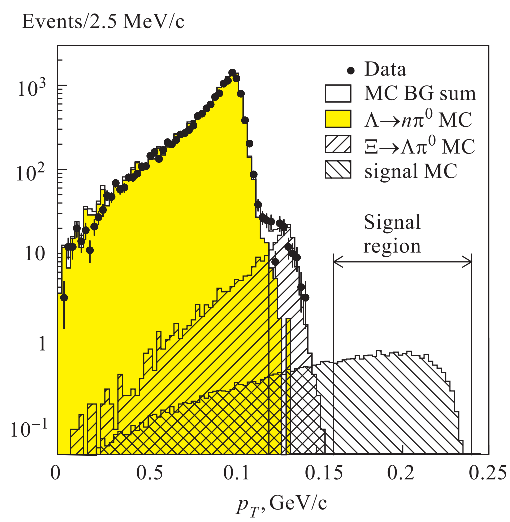

Fig. 3. The final KTeV p_T distribution. No events are observed in the signal region above 160 MeV/c

The best direct limit was recently obtained by the KTeV collaboration at FNAL [26] using a narrow «pencil» beam and the Dalitz decay mode of π^0 ($\pi^0 \to e^+e^-\gamma$). The basic principle of this experiment is the reconstruction of the decay vertex position of π^0s and selection of events with high π^0 momentum transverse to the K_L^0 beam direction (p_T) to suppress backgrounds. No signal events were observed and a 90 % C.L. upper limit $B(K_L^0 \to \pi^0\nu\bar{\nu}) < 5.9 \cdot 10^{-7}$ was obtained. The p_T distribution of the π^0 ($\pi^0 \to e^+e^-\gamma$) events which passed all the other cuts is shown in Fig. 3. Ultimately, this experiment is expected to reach the $\sim 10^{-8}$/event level of sensitivity, with a residual background of ~ 3 events.

The ongoing KLOE experiment at DAΦNE, designed to measure ε'/ε, should be able to achieve a sensitivity of 10^{-9} to $B(K_L^0 \to \pi^0\nu\bar{\nu})$ [27]. However, dedicated experiments will be needed for the measurement of $K_L^0 \to \pi^0\nu\bar{\nu}$ at the Standard Model level and beyond. Three such experiments have been proposed at FNAL, KEK and BNL. To observe and measure $K_L^0 \to \pi^0\nu\bar{\nu}$ with reasonable accuracy, they plan to detect the π^0 through its $\pi^0 \to 2\gamma$ decay.

The KAMI approach [28] exploits a high-energy pencil K_L^0 beam. The longitudinal coordinate of the vertex is determined through the reconstruction of the π^0 invariant mass and then p_T is extracted. An extremely good photon veto system with $\sim 10^{-6}$/photon inefficiency for high energies and better than 10^{-2}/photon for low energies is needed in this experiment. The first stage of this experiment is designed to collect about 30 $K_L^0 \to \pi^0\nu\bar{\nu}$ events per year with a signal/background ratio of ~ 2. In the second stage the production target will be moved closer to the apparatus, allowing an increase in the signal/background ratio and the accumulation of about 120 events per year.

An experiment that utilizes a similar approach with an optimization for lower kaon energies is under preparation at KEK [29]. The main features of this experiment are a very narrow pencil beam, an efficient photon veto system and a CsI (pure) electromagnetic calorimeter. The acceptance to $K_L^0 \to \pi^0\nu\bar{\nu}$ is designed to be about 7 %. Unfortunately, the available intensity of the 12 GeV KEK PS limits the sensitivity of this experiment to $\sim 10^{-10}$/event, i.e., by about a factor of 3 less than the $B(K_L^0 \to \pi^0\nu\bar{\nu})$ predicted by the Standard Model.

An alternative approach was taken in designing the E926 experiment at the AGS [30]. An 800 MeV/c K_L^0 beam can be obtained at 45° using a 24 GeV/c primary proton beam. Microbunching ($\sigma \sim 200$ ps) the AGS proton beam on extraction makes it possible to measure the momentum of K_L^0 by time of flight. The decay vertex and K_L^0 direction are determined by measuring both the directions and energies of the π^0 photons. This allows one to work in the K_L^0 center-of-mass system where π^0s from $K_L^0 \to \pi^0\pi^0$ have a unique energy and can be kinematically rejected without an excessive loss in acceptance. This full kinematic reconstruction of π^0s reduces the requirement on photon detection efficiency and makes it possible to suppress those kinematic configurations of $K_L^0 \to \pi^0\pi^0$ events with missing low-energy photons. This approach allows the experiment to be done using a relatively compact detector with low background from π^0s produced by low-energy beam neutrons and very suppressed background from hyperon decay.

A schematic view of the E926 detector is shown in Fig. 4. A decay region 3.5 m long, where about 16 % of the K_L^0s decay, is surrounded by efficient veto counters, and a photon detector consisting of a preshower and a calorimeter in succession. A detector designed to veto photons traveling down the calorimeter beam hole is located behind the calorimeter. The beam region is evacuated to a level of 10^{-7} Torr to suppress neutron-induced π^0 production. In the forward detection region the photon detector consists of two parts: a 2 X_0 fine-grained preradiator in which the photons are converted and the first e^+/e^- pair is tracked, and an 18 X_0 calorimeter in which the remaining energy of the electromagnetic shower is measured. The preradiator must provide an accurate measurement of the photon positions ($\sigma \sim 200\,\mu$m (rms)) and directions ($\sigma \sim 25$ mr) in order to allow reconstruction of the K_L^0 decay vertex while also contributing to the requirement of sufficient energy resolution. Located 15 m downstream of the calorimeter, a beam hole photon detector («beam catcher») is designed to veto decay photons whose trajectories are directly in the beam. A lead/lucite detector, consisting of 50 layers of 1 mm lead and 5 mm lucite, is currently being considered, as a

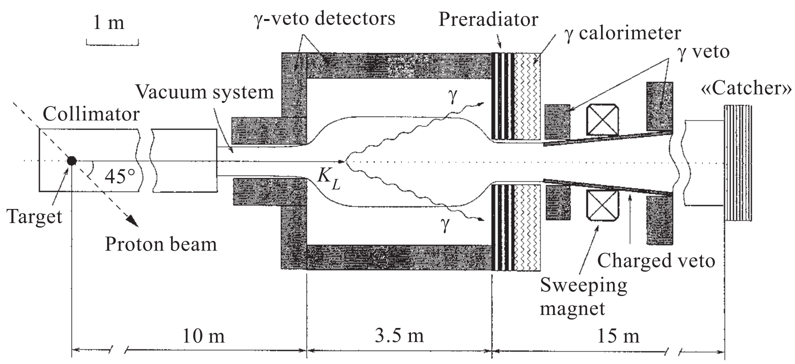

Fig. 4. Schematic view of the KOPIO experiment

lead/aerogel device. The barrel veto detector will consist of lead-plastic scintillator sandwich counters with a thickness of 18 X_0 ($\sim$ 80 layers of 1 mm lead and 5–7 mm plastic scintillator).

The estimated acceptance of the detector for $K_L^0 \to \pi^0\nu\bar{\nu}$ is approximately 1 % [30]. This includes the solid angle, photon conversion and reconstruction factors and phase space acceptance in addition to cuts on missing energy and mass and on photon energy sharing applied to suppress the major $K_L^0 \to \pi^0\pi^0$ backgrounds. Assuming the Standard Model central value for the $K_L^0 \to \pi^0\nu\bar{\nu}$ branching ratio, the expected number of detected $K_L^0 \to \pi^0\nu\bar{\nu}$ events to be accumulated after 9,000 hours of beam at 10^{14} protons/spill is about 65. The single event sensitivity of the experiment would be approximately $6 \cdot 10^{-13}$. The backgrounds which include other kaon decays, among which $K_L^0 \to \pi^0\pi^0$ dominates, neutron production of π^0s and $\Lambda \to n\pi^0$, are estimated to be suppressed to about 50 % of the level of the expected signal.

2.2. $K_L^0 \to \pi^0 e^+ e^-$. Since the golden decays are technically so difficult, it is interesting to look into other decays which are easier to measure than $K \to \pi\nu\bar{\nu}$ and which could give equivalent information. Two decays closely related to $K_L^0 \to \pi^0\nu\bar{\nu}$ are currently being actively studied: $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0\mu^+\mu^-$. In principle one can measure η with these decays. However they also receive a contribution from indirect CP violation and there is also a CP-conserving contribution from an intermediate $\pi^0\gamma\gamma$ state which in principle can be determined by studying the decay $K_L^0 \to \pi^0\gamma\gamma$. The SM direct CP-violating contribution to $B(K_L^0 \to \pi^0 e^+ e^-) \approx (5 \pm 2) \cdot 10^{-12}$ [31].

The size of indirect CP-violating contribution is proportional to the rate for $K_S^0 \to \pi^0 e^+ e^-$, which has never been observed and $B(K_L^0 \to \pi^0 e^+ e^-)|_{\text{indir}} \sim (1-5) \cdot 10^{-12}$, i.e., not necessarily smaller than the direct CP-violating component. A CP-conserving contribution from an intermediate $\pi^0\gamma^*\gamma^*$ state can be estimated from measurements of the decay $K_L^0 \to \pi^0\gamma\gamma$. There is a recent measurement of $K_L^0 \to \pi^0\gamma\gamma$ by the KTeV group [32]. Their results, $B(K_L^0 \to \pi^0\gamma\gamma) = (1.68 \pm 0.07 \pm 0.08) \cdot 10^{-6}$ and effective vector coupling $a_V = -0.72 \pm 0.05 \pm 0.06$, lead to a prediction of $B(K_L^0 \to \pi^0 e^+ e^-)|_{\text{absorptive}} \approx 1.3 \cdot 10^{-12}$. The dispersive part is somewhat more problematical. It is thought that the total contribution is in the neighborhood of $2 \cdot 10^{-12}$. Again this is not at all negligible compared to the expected direct CP-violating component. An irreducible background arises from the process

$K_L^0 \to e^+e^-\gamma\gamma$ when $m_{\gamma\gamma}$ happens to be near m_{π^0} [33]. Although the probability of this happening is small, since the total rate of $K_L^0 \to e^+e^-\gamma\gamma$ is four orders of magnitude larger than that of $K_L^0 \to \pi^0 e^+e^-$, the former process is a serious limitation on the exploitation of the latter.

The KTeV experiment has announced results for both $K_L^0 \to \pi^0 e^+e^-$ and $K_L^0 \to \pi^0\mu^+\mu^-$ [34]. The extracted 90 % C.L. upper limits are $5.1 \cdot 10^{-10}$ for $K_L^0 \to \pi^0 e^+e^-$ and $3.4 \cdot 10^{-10}$ for $K_L^0 \to \pi^0\mu^+\mu^-$. There is still more than an order of magnitude to go to see $K_L^0 \to \pi^0 e^+e^-$ at the SM level. With background already evident, this will not be easy. However in some supersymmetric extensions of the SM [35] the $B(K_L^0 \to \pi^0 e^+e^-)$ can be as high as 10^{-10} so that it is certainly worthwhile to pursue it vigorously in the near term.

3. T VIOLATION IN K^+ DECAYS

The transverse muon polarization (P_T) in the decays $K^+ \to \pi^0\mu^+\nu$ ($K_{\mu3}$) and $K^+ \to \mu^+\nu\gamma$ ($K_{\mu2\gamma}$) provides a good opportunity for detecting CP violation beyond the SM. This polarization vanishes in the SM, but it can be as large as 10^{-3} in models with multi-Higgs bosons, leptoquarks, left-right symmetry or SUSY [36, 37]. Measurement of a non-zero transverse muon polarization in these decays would be a clear indication of physics beyond the SM and provide insight into the origin of CP violation, since any spurious effect from final state electromagnetic interactions is known to be small [38]. Until recently the best measurement of transverse muon polarization was obtained in Ref. 40: $P_T = (-3.1 \pm 5.3) \cdot 10^{-3}$ for $K_{\mu3}$ and T-violating physics parameter $\mathrm{Im}\,(\xi) = (-1.6 \pm 2.5) \cdot 10^{-2}$, where $\xi(q^2)$ is defined as the ratio of two form factors, $f_+(q^2)$ and $f_-(q^2)$ in the $K_{\mu3}$ decay matrix element [39]. No measurements of P_T in $K_{\mu2\gamma}$ have been done yet.

A new dedicated experiment (E246 at KEK), which uses a stopped K^+ beam, published its first result in 1999. In this experiment, P_T is measured as the azimuthal polarization of the muon emitted in the direction normal to the kaon beam for those $K_{\mu3}$ events in which π^0 is tagged to be either in the forward or backward direction relative to the beam. This method provides nearly total coverage of the decay kinematics for the isotropic decay of kaons at rest, separates events with forward- and backward-going pions, which have opposite signs of P_T, and cancels out most of spurious instrumental sources of false polarization, which are likely independent of the π^0 direction. The set-up is shown in Fig. 5. A 660 MeV/c kaon beam is stopped in a scintillating fiber target. The $K_{\mu3}$ events are identified by analyzing the μ^+s with a 12-gap superconducting toroidal spectrometer and measuring the π^0s in a CsI(Tl) photon detector. The muons leaving the spectrometer are stopped in a polarimeter (Fig. 5*c*) in which the decay positron asymmetry is measured in order to obtain P_T. The result is based on about $3.9 \cdot 10^6$ good $K_{\mu3}$ events which have been analyzed from the data collected in 1996 and 1997 [41]. The result is consistent with non-T-violation: $P_T = (-4.2 \pm 4.9(\mathrm{stat.}) \pm 0.9(\mathrm{sys.})) \cdot 10^{-3}$ which gives $\mathrm{Im}\,(\xi) = (-1.3 \pm 1.6(\mathrm{stat.}) \pm 0.3(\mathrm{sys.})) \cdot 10^{-2}$. Further improvement of the statistical error to about $\delta\,\mathrm{Im}\,(\xi) \sim 0.01$ is expected from the data accumulated in 1998, and after an additional run in 1999–2000 $\delta\,\mathrm{Im}\,(\xi) \sim (6-7) \cdot 10^{-3}$ should be obtained. An important feature of this experiment is that the detector systematics are to first order independent of the characteristics of the kaon beam. The major limitation of the experiment is the low acceptance of the detector to $K_{\mu3}$ events which is about $(0.7-0.8) \cdot 10^{-5}$ per incident kaon. The sensitivity of E246 is basically limited by this factor.

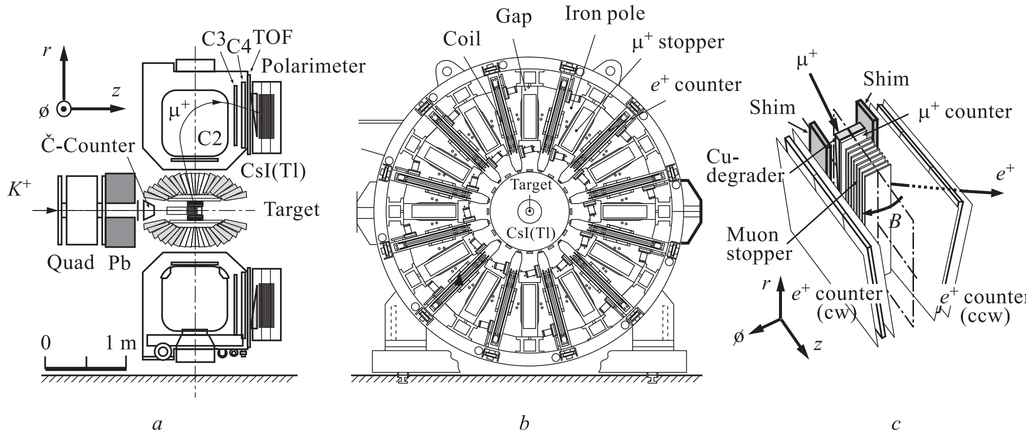

Fig. 5. The layout of the KEK E246 detector: *a*) side view, *b*) end view and *c*) one sector of the polarimeter

A planned E923 experiment at BNL [42] uses in-flight K^+ decays. A cylindrical active polarimeter around the kaon beam and an electromagnetic calorimeter will be used to reconstruct $K_{\mu 3}$ decays and suppress background. The detector acceptance to $K_{\mu 3}$ events is about $2.5 \cdot 10^{-5}$ per 2 GeV/c kaon. The advantage of the in-flight experiment is thus relatively high detector acceptance. The statistical sensitivity (1 σ level) to P_T in this experiment will be about $1.3 \cdot 10^{-4}$, which corresponds to $\delta\,\mathrm{Im}\,(\xi) = 7 \cdot 10^{-4}$. In this experiment a sensitivity of $\leq 10^{-3}$ can be also obtained for P_T in the $K_{\mu 2\gamma}$ decay.

A new approach to measure the T-odd polarization in the two decays $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu\gamma$ with a statistical sensitivity to P_T at the 1 σ level of better than 10^{-4} has recently been proposed [43]. The basic principles can be briefly formulated as follows: (a) a high resolution measurement of π^0 from the $K_{\mu 3}$ decay of stopped K^+s; (b) an active muon polarimeter which also provides the muon momentum measurement, and the photon detection; (c) a highly efficient photon veto covering nearly 4π solid angle. This experiment can be done at the low-energy separated kaon beam at JHF [44].

CONCLUSION

The intensive study of the CP and T violation in kaon physics is now providing a lot of interesting results; however a fundamental explanation of the origin of CP violation still awaits.

An improvement of the measurement accuracy of the non-vanishing value of Re$\,(\varepsilon'/\varepsilon)$ to the level of 10^{-4} is needed and this is expected in the near future. The $K \to \pi\pi$ decays will be extensively exploited because of their ability to construct the very clean «alternative» unitarity triangle to that obtained from B decays. The comparison of the two triangles, K and B, provides a powerful tool to probe for new physics effects beyond the SM. The new physics might have additional sources of CP violation. Many of these, in contrast with the CKM picture of the Standard Model, predict a non-zero dipole moment for the neutron and electron and T-odd correlations in kaon decays. In this sense to pursue the measurement of P_T to the level of 10^{-4} would be of great importance.

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