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Status of $K \rightarrow \pi\nu\bar{\nu}$ Experiments

Toshio Numao[a] *

[a]TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada

Two theoretically clean $K \rightarrow \pi\nu\bar{\nu}$ decays that are sensitive to V_{td} are discussed. The E787 group at Brookhaven National Laboratory recently reported two events at a branching ratio of $B(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$. The goal of the subsequent experiment E949 is to improve the event statistics by a factor of five, which allows a 15 % measurement of V_{td}. In the search of the CP-violating decay $K_L \rightarrow \pi^0\nu\bar{\nu}$, the KOPIO experiment, employing a low-energy micro-bunched K_L^0 beam to allow determination of the incident kaon momentum, aims to obtain about 65 events with a signal to background ratio of 2:1.

1. Introduction

Among possible measurements relating to CP violation, it is generally agreed that four theoretically unambiguous "golden" processes will allow a clear perspective of CP violation in the Standard Model (SM)[1] and its extensions[2]. Two are B experiments, asymmetries in $B \rightarrow \Psi K_s$ decays and the ratio of $B_s^0 - \overline{B_s^0}$ to $B_d^0 - \overline{B_d^0}$ mixing, and two are K experiments, the branching ratios of the charged and neutral $K \rightarrow \pi\nu\bar{\nu}$ decays.

Because of the GIM mechanism, the lowest order diagrams of these kaon decays come from second order weak interactions with a u-type quark in the loop diagrams, in which the top-quark contributions dominate. This makes these decay modes very sensitive to V_{td}, the least constrained coupling-constant of the top and down quarks in the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

The SM calculation of the branching ratio $B(K^+ \rightarrow \pi^+\nu\bar{\nu})$ based on the current phenomenology gives a prediction of $(0.8 \pm 0.3) \times 10^{-10}$[1], where the hadronic matrix elements are extracted from the isospin-symmetric decay $K^+ \rightarrow \pi^0 e^+\nu$. Theoretical uncertainties in the calculation due to long distance contributions and other effects are small. The contribution from the intermediate charm quark is about 30 % and is well calculated. The total theoretical uncertainty is only 7%.

The decay $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ proceeds by similar diagrams with a "spectator" d quark instead of a u quark. This decay mode is CP-violating since the final state $\pi^0\nu\bar{\nu}$ is a nearly pure CP-even state in the SM. The contribution from CP mixing in K_L^0 is expected to be around 10^{-15}[3]. Therefore, the $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay mode is completely dominated by "direct" CP violation. The process is free from long-range contributions and is sufficiently clean for the study of the origin of CP violation. The theoretical uncertainty in $B(K_L^0 \rightarrow \pi^0\nu\bar{\nu})$ is only ~ 1 %, excluding uncertainties in the CKM matrix elements. Conversely, the observation of this decay mode uniquely determines $Im(V_{td})$ or η in the Wolfenstein parametrization. This process is expected to occur at $B(K_L^0 \rightarrow \pi^0\nu\bar{\nu}) \sim (2.6 \pm 1.2) \times 10^{-11}$ [1].

One of the unitarity conditions of the CKM matrix, $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ with the approximation $V_{ud} \sim V_{tb} \sim 1$, leads to a unitarity triangle in the complex plane with V_{td} and V_{ub}^* as two sides of the triangle. The height of the triangle $Im(V_{td})$ or the area of the triangle is an indication of CP violation due to the CKM phase. The branching ratio of the decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ is roughly proportional to $|V_{td}|^2$ and that of $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ to $Im^2(V_{td})$. These measurements alone can determine the unitarity triangle independently from the B sector.

Since decays $K \rightarrow \pi\nu\bar{\nu}$ are generally expected to be less sensitive to the contributions from Supersymmetry and other extensions of the SM[2],

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the K decays provide a normalization to the SM, and when combined with the measurements from B decays they provide excellent tests of the SM.

Moreover, the decay $K_L^0 \to \pi^0 \nu\bar{\nu}$ provides direct measure of Jarlskog invariant[4], twice the area of any unitarity triangles for three generations, and a 10 % measurement of this decay mode is expected to be the best experimental source of this invariant[1].

The goal of the $K \to \pi\nu\bar{\nu}$ experiments at Brookhaven National Laboratory (BNL) is to determine $|V_{td}|$ and $Im(V_{td})$ with a 10–15 % accuracy, which corresponds to a single event sensitivity of $10^{-11} - 10^{-12}$. While the decay $K^+ \to \pi^+\nu\bar{\nu}$ has already been observed [5] and further data taking is in progress[6], the present upper limit of the decay $K_L^0 \to \pi^0\nu\bar{\nu}$ is still 5.7×10^{-7}[7], four orders of magnitude higher than the SM prediction.

2. $K^+ \to \pi^+\nu\bar{\nu}$ Experiments

The signature of $K^+ \to \pi^+\nu\bar{\nu}$ decay at rest is a single π^+ ($P \leq 227$MeV/c) without any other activity in the detector. The primary area of search is between the two 2-body decay peaks of $K^+ \to \pi^+\pi^0$ at $P_\pi = 205$ MeV/c and $K^+ \to \mu^+\nu$ at $P_\mu = 236$ MeV/c. The major background sources are these two decays, and π^+'s in the beam or produced by the beam. To attack the $K^+ \to \pi^+\pi^0$ background, it is crucial to have good kinematical resolutions and efficient photon detection (π^0 detection inefficiency of $\bar{\epsilon}_{\pi^0} \sim 10^{-6}$), and excellent particle identification capability between a pion and a muon, for the $K^+ \to \mu^+\nu$ background.

The E787 experiment at BNL is designed to effectively distinguish these backgrounds from the signal. Kaons of about 700 MeV/c at a rate of $(4 - 7) \times 10^6$ per 1.6-s spill with a K/π ratio of 4 are detected and identified by a Čerenkov counter and hodoscopes, degraded by BeO and stopped in an active target, primarily consisting of 413 5-mm square scintillating fibers. The momentum (P), kinetic energy (E) and range (R) of decay products are measured using the target, a central drift chamber, 21 layers of 1.9-cm thick plastic scintillator (Range Stack) and two layers of straw chambers, all contained in a 1-T magnetic field. Consistency of the pulse shape of the K decay product in the Range Stack scintillator with the $\pi^+ \to \mu^+ \to e^+$ decay sequence is observed by 500-MHz transient digitizers for particle identification. Photons are detected by a 4π-sr calorimeter consisting of a 14-radiation-length-thick lead/scintillator barrel detector, 13.4-radiation-length-thick end caps of undoped CsI crystals, and a 3.5-radiation-length-thick lead-glass Čerenkov counter which also works as an active beam degrader.

In the data analysis, background studies are done first, using data simultaneously taken with looser trigger conditions to reflect in the estimates the actual data-taking condition, including possible detector problems. In order to avoid a possible human bias, the signal region is kept untouched until the background estimation as well as the optimization of the acceptance has been done. In the background study, after applying all the final cuts except two orthogonal (uncorrelated) cut groups to be studied—e.g. the kinematical cuts and those related to the observation of the decay sequence $\pi^+ \to \mu^+ \to e^+$ in the stopping counter for the estimation of the $K^+ \to \mu^+\nu$ background—the remaining data sample is used to obtain the suppression factor for each cut group. The background estimate is obtained by the product of the number of the remaining events and the two suppression factors. The correlation between the two cut groups is studied by varying the cuts being studied or by enhancing certain types of background events. The total background for the entire 1995–1998 exposure with the final analysis cuts was estimated to be 0.15 ± 0.05 events. The correlation effect, though small, was included in the error. The estimate was limited by the statistics of the data for the background study.

The acceptances for $K^+ \to \pi^+\nu\bar{\nu}$, 0.20-0.21 ($\pm 0.01$) %, were calculated based on data and Monte Carlo calculations. The largest uncertainty came from the uncertainty in pion-nucleus interaction. The measurement of the branching ratio for $K^+ \to \pi^+\pi^0$ within a few % of Ref.[8] confirmed the acceptance calculation.

After the completion of the background studies, the signal region was inspected. Two clean events were found that correspond to a branching ratio $1.57^{+1.75}_{-0.82} \times 10^{-10}$.

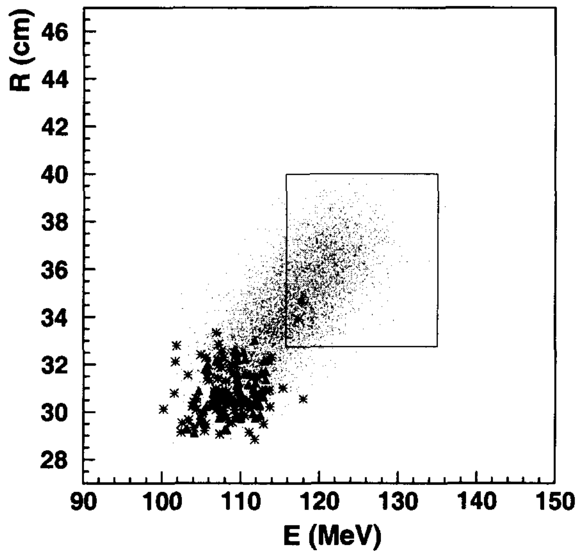

Figure 1. Range *vs* Energy plot of E787 data. Two events survived the analysis cuts indicated by the box. The small dots show the MC distribution of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events.

Although it has a potential of providing a higher acceptance owing to less nuclear interaction and more phase space, the region below the $K^+ \rightarrow \pi^+\pi^0$ peak was considered to be the second-class search-region because π^+ interactions in the target cause a low energy tail, resulting in a higher background level. Also, due to the correlation between the low energy tail (scattered events) and the inefficient regions of photon detection, the background originating from the $\pi^+\pi^0$ mode is not suppressed as desired; when the π^+ is emitted toward the beam direction (but scattered into the acceptance region) the pair of photons from the π^0 decay tend to go to the direction where photon detection is the weakest. We observed one event, which is consistent with the expected background of 0.7 mostly coming from the decay $K^+ \rightarrow \pi^+\pi^0$. A 90-% c.l. upper limit was set 4.1×10^{-9} [9] assuming the SM spectrum (this region is sensitive to the presence of scalar interactions). The goal of the new experiment E949 at BNL[6] is to improve the sensitivity nearly by an order of magnitude. Since the AGS in the RHIC era will be used for two hours a day to feed heavy ions into the RHIC ring, the remaining 22 hours can be used for the high energy program. The operation is expected to provide a stabler, longer running period. The photon veto capability has been improved with additional lead/scintillator layers in the barrel region and a larger active degrader in the beam region. For the study of the region below the $K^+ \rightarrow \pi^+\pi^0$ peak, the additional photon veto capability, especially in the beam direction, may suppress the background by more than an order of magnitude (to less than the signal level), doubling the phase space in the search.

3. $K^0_L \rightarrow \pi^0\nu\bar{\nu}$ Experiment

The decay $K^0_L \rightarrow \pi^0\nu\bar{\nu}$ is also a three-body decay, but involves only neutral particles. The signature of this decay in flight is two photons from the π^0 decay and no other activity in the detector. In this decay mode, available kinematical parameters are very limited. Relatively easy ones to measure are the positions and energies of γ-rays. Since the three-body decay does not have definite signature, it is important to have as many kinematical constraints as possible to identify the signal from the background. A further experimental challenge arises from the high probability of π^0 emission in comparison with the expected decay probability for $K^0_L \rightarrow \pi^0\nu\bar{\nu}$ which is ten orders of magnitude smaller; the major decay modes of K^0_L are $\pi^0\pi\pi$ and $\pi^\pm\ell^\mp\nu$. Suppression of most backgrounds is achieved by high-efficiency hermetic photon and charged-particle detector systems surrounding the decay volume, and kinematical constraints.

The BNL experiment E926[10] attempts to measure the additional kinematic values: the directions of γ-rays and the momentum of the K^0_L. Measurements of γ-ray directions allow full reconstruction of the π^0 kinematics without the assumption of the π^0 mass, providing more constraints with redundancy, which is necessary to suppress the background to the level well below the signal. The time-of-flight (TOF) of a K^0_L be-

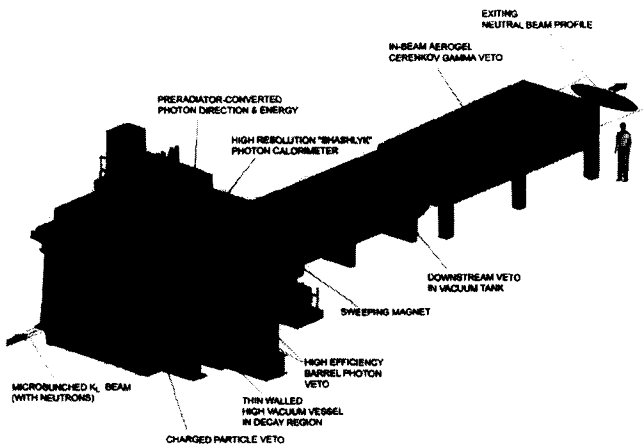

Figure 2. Cutway view of KOPIO detector.

tween the production target and the decay vertex can be measured for low momentum K_L^0's when the incident proton beam is bunched. This measurement allows the calculation of missing mass, and kinematical reconstruction in the center of mass system, which is effective to eliminate backgrounds from two-body decays.

A low energy K_L^0 beam with an average momentum around 650 MeV/c will be produced by irradiating a target with a 24-GeV proton beam from the AGS and extracted at $\sim 45^o$ with respect to the incident beam. The proton beam is bunched to form a $\leq$200 ps wide bucket at a rate of 25 MHz. About 16 % of K_L^0's decay in the 4-m long decay volume, which is evacuated to a level of 10^{-7} Torr to suppress the background from neutron-induced π^0 production. The decay region is surrounded by a charged particle veto system and a photon veto system of 18-radiation-length-thick lead/scintillator sandwiches in the barrel region. The two photons from the π^0 decay are converted into electron-positron pairs of in a 2-radiation-length pre-radiator next to the vacuum region for the measurement of the directions of the γ-rays. The pre-radiator consists of sandwiches of 1-cm thick scintillator, a copper plate as an electrical ground and radiator, and a tracking chamber. This is followed by an 18-radiation-length Shashlyk-type lead/scintillator calorimeter for the measurement of γ-ray energies and for vetoing additional photons.

The estimates of the sensitivity for $K_L^0 \to \pi^0 \nu\bar{\nu}$ are tightly coupled to the cuts required for background suppression, particularly for the $K_L^0 \to \pi^0\pi^0$ and $K_L^0 \to \pi^0\pi^+\pi^-$ backgrounds. An acceptance of $\sim$ 1.5 % for the case S/N=2 comes from the combination of factors; 0.58 for the fiducial region and usable kaon momentum region, 0.33 for the solid angle, 0.5 for the efficiency of the pre-radiator, and the remaining factor for the π^0 mass cut and other cuts to reduce backgrounds. Assuming three years of running with kaon decays at 14 MHz, the expected number of events is 65.

Conclusion

Studies of rare kaon decays have contributed to the discoveries of several symmetry violations. The decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$ are expected to "complete" the measurement of the CKM matrix in the next decade independently from the B-decay system, and to elucidate the origin of CP violation.

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