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Measurement of $K^+ \to \pi^0\mu^+\nu\gamma$ decay using stopped kaons

KEK-E470 Collaboration

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Abstract

The $K^+ \to \pi^0\mu^+\nu\gamma$ ($K_{\mu3\gamma}$) decay has been measured with stopped positive kaons at the KEK 12 GeV proton synchrotron. A $K_{\mu3\gamma}$ sample containing 125 events was obtained. The partial branching ratio $Br(K_{\mu3\gamma}, E_\gamma > 30\ \text{MeV}, \theta_{\mu^+\gamma} > 20^\circ)$ was found to be $[2.4 \pm 0.5(\text{stat}) \pm 0.6(\text{syst})] \times 10^{-5}$, which is in good agreement with theoretical predictions.

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Semi-leptonic radiative decays of K-mesons, $K \to \pi l\nu\gamma$ ($K_{l3\gamma}$), offer a good testing ground of hadron structure models making use of low-energy effective Lagrangians inspired by chiral perturbation theory (ChPT). It is expected that branching ratio measurements and decay spectra with a single pion in the final state provide simple but good constraints on the models. The radiative decays of mesons usually consist of an internal bremsstrahlung (IB) process and a hadron-structure-dependent direct emission (DE) process. While the IB process is dominant in the decays with electrons in the final state such as $K \to \pi e\nu\gamma$ ($K_{e3\gamma}$) decays, one expects a significant DE contribution when there is a muon in the final state, $K \to \pi\mu\nu\gamma$ ($K_{\mu3\gamma}$), because of the larger lepton mass. The relative size of the DE effects can be calculated in strong interaction models. Following the early estimates [1–3], based on current algebra, calculations in the framework of the ChPT theory have been done [4].

$K_{l3\gamma}$ branching ratios of neutral kaons with electrons and muons in the final state have been reported in the literature with branching fractions of $K^0_{e3\gamma}$ and $K^0_{\mu3\gamma}$ of 3.5×10^{-3} and 5.5×10^{-4}, respectively [5]. For the charged kaons, a $K^+_{e3\gamma}$ decay branching ratio of 2.65×10^{-4} has been measured [5], and results of the first measurement of the $K^-_{\mu3\gamma}$ decay using an in-flight K^- beam has recently been reported [6]. In this Letter, we

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present a new measurement of the $K^+ \to \pi^0\mu^+\nu\gamma$ ($K^+_{\mu3\gamma}$) decay using a stopped K^+ beam along with detailed Monte Carlo simulations, which enabled us to determine the $K^+_{\mu3\gamma}$ branching ratio.

The experiment was performed at the KEK 12 GeV proton synchrotron. The detector was basically the E246 setup [7], which had the 12-sector toroidal spectrometer and the ancillary detector assemblies such as the photon calorimeter and the particle tracking system. Since the system was built primarily for the purpose of a high precision test of time-reversal invariance in the $K^+ \to \pi^0\mu^+\nu$ ($K_{\mu3}$) decay [7], an elaborate simulation program based on GEANT3 [8] has been developed. Details of the setup are well documented in Ref. [9]. In addition to the T-violation search, spectroscopic studies for various decay channels have also been successfully performed using the same detector system [10–12].

A separated 660 MeV/c K^+ beam was stopped in an active target system. The $K_{\mu3\gamma}$ events were identified by analyzing the μ^+ momentum with the spectrometer and detecting three photons in the CsI(Tl) calorimeter. The momentum vectors of the charged particles were determined by reconstructing their trajectories in the spectrometer using multi-wire proportional chambers (MWPCs). The μ^+s were selected by determining the squared mass (M^2_{TOF}) from a time-of-flight measurement. The photon energy and hit position were obtained, respectively, by summing the energy deposits and taking the energy-weighted centroid of the CsI(Tl) crystals sharing a shower. The analysis procedures of the present work for the charged particle tracking, TOF measurement, and photon energy and hit position determinations are the same as those of the previous $K_{\pi2\gamma}$ study (see Ref. [11] for details).

Specific cuts for the $K_{\mu3\gamma}$ selection are described below. The charged particle momentum corrected for the energy loss in the target (P_{μ^+}) was imposed to be $P_{\mu^+} < 170$ MeV/c. Events from π^+ decays in-flight and scattering of the charged particle from the magnet pole faces were eliminated by requiring the particle track to be consistent with the hit position in the ring counters surrounding the active target system [9]. The selection criterion for muons was $8000 < M^2_{\mathrm{TOF}} < 14500$ MeV$^2/c^4$, as shown in Fig. 1. Events with three photon clusters in the calorimeter were selected: two as coming from $\pi^0 \to \gamma_1\gamma_2$ and one being a radiative photon (γ_3). Since there are three possible combinations to form a π^0 from three photons, a quantity Q^2 was introduced to find the correct pairing,

$$Q^2 = (M_{\pi^0} - M)^2/\sigma_M^2 + \left(\cos\theta^{\mathrm{MEA}}_{\mu^+\gamma_3} - \cos\theta^{\mathrm{CAL}}_{\mu^+\gamma_3} - \alpha\right)^2/\sigma_\alpha^2, \tag{1}$$

where M_{π^0} is the invariant mass of the selected pair and $\theta_{\mu^+\gamma_3}$ is the opening angle between the μ^+ and γ_3. The superscripts MEA and CAL stand for the measured angle and the angle calculated from other observables by assuming the $K_{\mu3\gamma}$ kinematics. The pair with the minimum Q^2 ($= Q^2_{\mathrm{min}}$) among the three possible combinations was adopted as the correct pairing. The σ (σ_M, σ_α) and offset values (M, α) in each terms are $\sigma_M = 10.92$ MeV/c^2, $\sigma_\alpha = 0.273$, $M = 118.3$ MeV/c^2, and $\alpha = 0.265$. The choice of the parameters were determined to

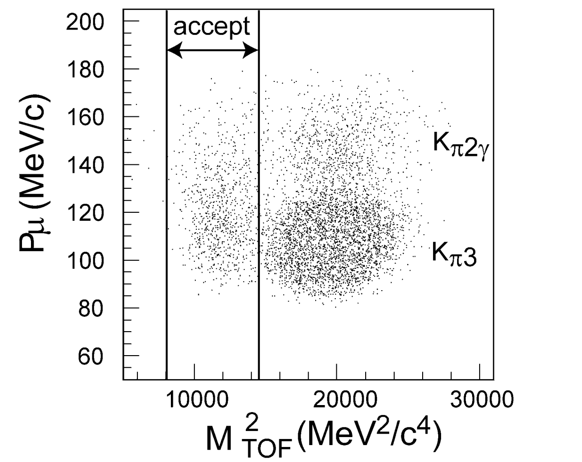

Fig. 1. Correlation plot of M^2_{TOF} and P_μ. The $K_{\pi3}$ and $K_{\pi2\gamma}$ events which were used to calculate the $K_{\mu3\gamma}$ branching ratio and the background fractions are also seen.

obtain the highest probability for the correct pairing by using the simulation data. The correct pairing probability was estimated to be 69% from the Monte Carlo simulation. Further, since most of background events do not satisfy the $K_{\mu3\gamma}$ kinematics, the cut of $Q^2_{\mathrm{min}} < 1.5$ reduced the background contaminations. An additional cut condition, $\cos[\theta_{\gamma\gamma}]_{\mathrm{min}} < 0.45$, was applied to reject events with a photon split into multiple clusters, where $[\theta_{\gamma\gamma}]_{\mathrm{min}}$ is the minimum opening angle of photons among the three combinations. The above conditions were sufficient to select $K_{\mu3\gamma}$ events. From this analysis, a sample with 565 events was extracted. The spectra are shown in Fig. 2. The black (solid) histograms are the data comprising of the $K_{\mu3\gamma}$ events and the background events to be discussed below.

There are three major background components, $K^+ \to \pi^+\pi^0\pi^0$ ($K_{\pi3}$), $K^+ \to \pi^+\pi^0\gamma$ ($K_{\pi2\gamma}$), and $K_{\mu3}$. The former two could imitate $K_{\mu3\gamma}$ if the pion decays in flight and the three photons hit the calorimeter. Also, $K_{\mu3}$ with an accidental photon could contribute to $K_{\mu3\gamma}$. The $K_{\pi3}$ and $K_{\pi2\gamma}$ contaminations were estimated using a Monte Carlo simulation. The simulation data were analyzed in the same manner as the experimental data, yielding surviving background fractions. In order to determine these fractions, the results of careful evaluations, carried out in the previous $K_{\pi2\gamma}$ study [11], were used. These $K_{\pi3}$ and $K_{\pi2\gamma}$ events can be seen in the P_μ–M^2_{TOF} scatter plot in Fig. 1. The numbers of the $K_{\pi3}$ and $K_{\pi2\gamma}$ events were calculated from those of the experimental $K_{\pi3}$ and $K_{\pi2\gamma}$ events by using acceptance ratios as

$$Y\left(K^{\mathrm{BG}}_{\pi3}\right) = \frac{\Omega(K^{\mathrm{BG}}_{\pi3})}{\Omega(K^{\mathrm{NM}}_{\pi3})} Y\left(K^{\mathrm{NM}}_{\pi3}\right), \tag{2a}$$

$$Y\left(K^{\mathrm{BG}}_{\pi2\gamma}\right) = \frac{\Omega(K^{\mathrm{BG}}_{\pi2\gamma})}{\Omega(K^{\mathrm{NM}}_{\pi2\gamma})} Y\left(K^{\mathrm{NM}}_{\pi2\gamma}\right), \tag{2b}$$

where $Y(X)$ is the yield of decay channel X and $\Omega(X)$ is the detector acceptance determined by the simulation. BG and NM stand for the selection conditions of the present background evaluation and the previous normal $K_{\pi2\gamma}$ study [11], respectively. Potential systematic errors from the uncertainty of