Measurement of $K^+ \to \pi^+\pi^0\gamma$ from BNL E787

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Abstract

We have performed a new measurement of the $K^+ \to \pi^+\pi^0\gamma$ decay with the E787 apparatus and have observed 20k signal events. The best fit to the decay spectrum gives a branching ratio for direct emission of $(4.72 \pm 0.77) \times 10^{-6}$ in the π^+ kinetic energy region of 55 to 90 MeV, with 15% systematic uncertainty, and requires no interference with inner bremsstrahlung.

1 Introduction

The primary motivation for studying the radiative decay $K^+ \to \pi^+\pi^0\gamma$ is to understand the direct emission (DE) component of the decay, where the γ is emitted directly due to the low energy hadronic interaction of the mesons [1]. The inner bremsstrahlung (IB) component, which is a QED radiative correction to $K^+ \to \pi^+\pi^0$ decay, dominates the process, even though it is suppressed by the $\Delta I = 1/2$ rule. The DE component consists of the magnetic and electric transitions. The magnetic transition is known to be due to the chiral anomaly in Chiral Perturbation Theory [2]. The electric transition can interfere with the IB component since their parities are the same. This interference term is designated by INT.

The variable $\mathsf{W}^2 \equiv (\mathsf{p} \cdot \mathsf{q})/\mathsf{m}^2_{\mathsf{K}^+} \times (\mathsf{p}_+ \cdot \mathsf{q})/\mathsf{m}^2_{\pi^+}$ is defined in terms of the energy-momentum four-vectors of the K^+ (p), π^+ (p_+) and γ (q). In the theoretical W spectrum of the decay normalized to the IB spectrum [1], the INT component is proportional to W^2 and the DE component is proportional to W^4. To observe the DE and INT components of the decay mode

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Experiment		Kaon	Events	Br(DE) $\times 10^{-5}$
BNL '72	[3]	$K^{\pm}$	2100	$1.56 \pm 0.35 \pm 0.5$
CERN '76	[4]	$K^{\pm}$	2461	2.3 ± 3.2
DUBNA '87	[5]	K^{-}	140	$2.05 \pm 0.46^{+0.39}_{-0.23}$
PDG '98	[6]		-	1.8 ± 0.4

Table 1: Previous measurements of the $K^+ \to \pi^+\pi^0\gamma$ decay. Br(DE) is the branching ratio for DE in the region 55 MeV $< T_{\pi^+} <$ 90 MeV.

in the data, a deviation of the measured spectrum from the IB spectrum at large W must be identified.

Table 1 lists the results of previous measurements [3] [4] [5]. In these experiments the branching ratio was measured with decays-in-flight and in the π^+ kinetic energy region 55 MeV $< T_{\pi^+} <$ 90 MeV. The theoretical prediction for the IB branching ratio, 2.61×10^{-4} [1], has been verified. The current Particle Data Group average for the DE component of the branching ratio is $(1.8 \pm 0.4) \times 10^{-5}$ [6]. In the 1980's, chiral QCD theories [7] claimed to be able to account for DE branching ratios in the region of 10^{-5}. But there presently exists no definite prediction from Chiral Perturbation Theory.

2 E787 Detector and Trigger

The new measurement reported here used the E787 apparatus [8] [9] at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory (BNL). In the 1995 data set, with which we observed the first evidence for $K^+ \to \pi^+\nu\bar{\nu}$ [10], E787 had a physics trigger called "3gamma" to detect the final state of the $K^+ \to \pi^+\pi^0(\to \gamma\gamma)\gamma$ decay and took data with it simultaneously with the $\pi^+\nu\bar{\nu}$ trigger.

In the E787 detector (Figure 1), which is a solenoidal spectrometer with a 1.0 Tesla field directed along the beam line, charged tracks emanating from stopped K^+ decays were measured. Kaons of 790 MeV/c were delivered to the experiment at a rate of 7×10^6 per 1.6-s spill of the AGS, and were detected by Čerenkov and energy loss (dE/dx) counters. Slowed by a BeO degrader, kaons stopped in the scintillating-fiber target at the center of the detector. The charged decay products passed through the drift chamber, lost energy by ionization loss and stopped in the Range Stack made of plastic scintillators and straw chambers. The output pulse-shapes of the Range Stack counters were recorded and the π^+ track was reconstructed with good timing accuracy. The hermetic calorimeters in the Barrel and

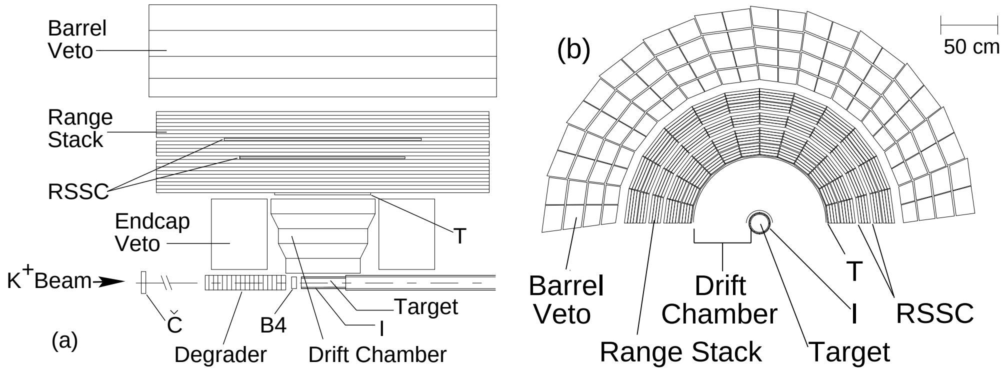

Figure 1: Schematic (a) side and (b) end views showing the upper half of the E787 detector. Č: beam Čerenkov counter; B4: energy loss counter; I and T: trigger scintillators; RSSC: straw tube tracking chambers.

Endcap detected γ's and extra particles from the K^+ decays.

The Barrel calorimeter, designed to veto any extra particles in the $K^+ \to \pi^+\nu\bar{\nu}$ analysis, detected the three γ's from the $K^+ \to \pi^+\pi^0\gamma$ decay. It consisted of 48 azimuthal sectors and 4 radial layers, made of lead/scintillator 14 radiation lengths in depth, and covered a solid angle of about 3π sr. 30% of the energy was deposited and visible in the scintillators. The Z position (along the beam line) of the Barrel hits was measured with the ADC and TDC information from phototubes on both ends of each 2-m long module.

In the "3gamma" trigger a stopped kaon decay, a charged track in the Range Stack, and no extra particle in the Range Stack and Endcap were required. The online delayed-coincidence (> 1.5 ns) of the timing between the stopping K^+ (via the Čerenkov counter) and the outgoing π^+ (via the I-counter surrounding the target) rejected pions scattered into the detector or kaons which decayed in flight. For the $K^+ \to \pi^+\pi^0\gamma$ decay a shorter range particle was required in the Range Stack, one whose kinetic energy exceeded the maximum allowed from $K_{\pi 3}$ decay and was smaller than that from $K_{\pi 2}$ decay. In addition, ≥ 3 online Barrel clusters were required. The trigger was prescaled by 5 and a total of 1.1×10^7 events (5 events per spill) was recorded.

3 Signal Selection

The energy and direction of the three γ's from the $K^+ \to \pi^+\pi^0\gamma$ decay were determined from the offline clustering in the Barrel calorimeter and the decay vertex position in the target. The π^+ momentum vector and the kinetic energy were measured with the target, drift chamber and Range Stack. These thirteen observables were available for the kinematical fit in this analysis. The range-momentum relation of the track in the Range Stack was sufficient to reject μ^+ backgrounds, so that the pulse-shape information of the decay chain $\pi^+ \to \mu^+ \to e^+$ in the stopping scintillator was not used. Any coincident signals other than the three γ's and the π^+ caused the event to be vetoed.

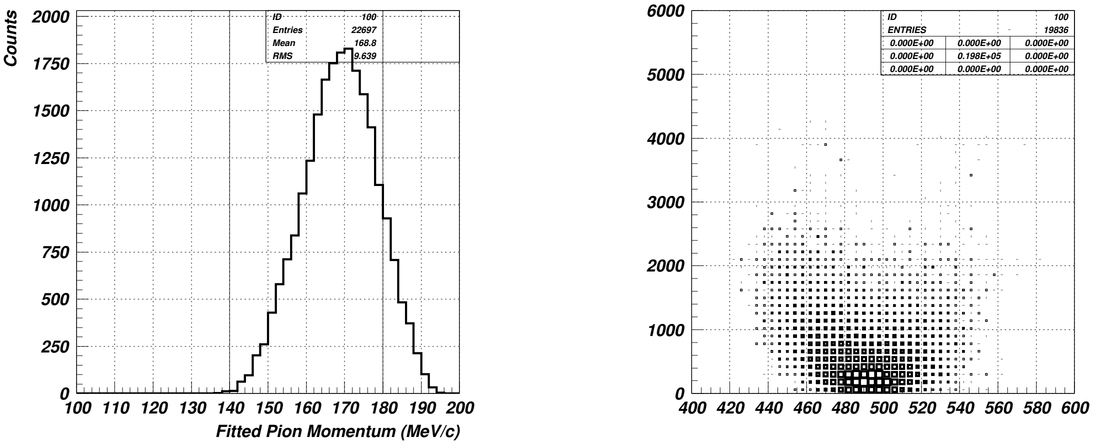

Figure 2: (left) Fitted π^+ momentum after the χ^2 probability cut; (right) Missing-momentum squared vs. total energy of the signal events.

Since the E787 detector measures stopped K^+ decays, a kinematical fit was applied to the observables with the following six constraints: energy-momentum conservation, π^+ energy and momentum consistent with m_{π^+} and invariant mass of the two γ's from π^0 equal to m_{π^0}. In order to minimize feed-down of IB events into the DE region, the following method was used to select the two γ's to be assigned to the π^0. The square of the matrix element of the IB decay was taken as a weight: the combination which maximized the product of the χ^2 probability of the kinematical fit and the IB weight was chosen. For the signal selection we required the χ^2 probability to be more than 10% and the fitted π^+ momentum (Figure 2-left) to be between 140 and 180 MeV/c; the latter condition was imposed to remove the $K_{\pi 3}$ and $K_{\pi 2}$ backgrounds as well as $K^+ \to \pi^+\pi^0\gamma$ decays outside the region 55 MeV $< T_{\pi^+} <$ 90 MeV. Figure 2-right shows missing momentum squared versus total energy of the $K^+ \to \pi^+\pi^0\gamma$ events, 19836 in total, after applying all selection cuts. The signal events are clustered at

m_{K^+} in the total energy and at small values of missing-momentum squared.

4 Spectrum Analysis

The challenge of this analysis consists in the fact that 98% of the signal events in Figure 2 are from the IB component of the $K^+ \to \pi^+\pi^0\gamma$ events. To address this, we performed the W spectrum analysis described earlier. In the stopped K^+ decays, W^2 was constructed from the opening angle between π^+ and γ ($\theta_{\pi^+\gamma}$), π^+ energy (E_{π^+}), momentum (P_{π^+}) and γ energy (E_γ) as $\mathsf{W}^2 = \mathsf{E}_\gamma^2 \times (\mathsf{E}_{\pi^+} - \mathsf{P}_{\pi^+} \times \cos\theta_{\pi^+\gamma})/(\mathsf{m}_{\mathsf{K}^+} \times \mathsf{m}_{\pi^+}^2)$ and is directly related to the observables in the E787 detector.

A Monte Carlo simulation of the IB, DE and INT spectra of the $K^+ \to \pi^+\pi^0\gamma$ decay in the E787 detector was performed by generating the IB, DE and INT decay events, respectively, with the standard matrix elements in [1] and analyzing them with the codes for real data. Thus, the effect of "incorrect pairing" of the two γ's from π^0 on the Monte Carlo spectra is taken into account. The probability of incorrect pairing with the algorithm of this analysis is estimated by the Monte Carlo to be 2.6% for IB, 20% for DE and 9% for INT.

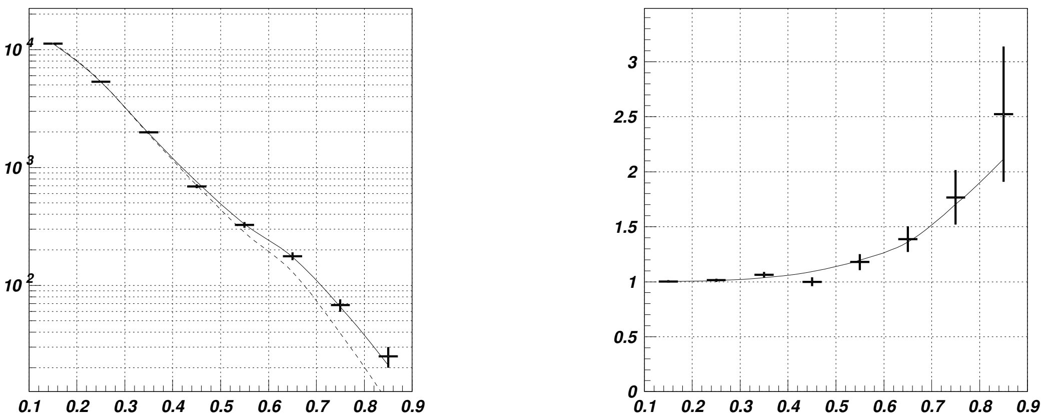

Figure 3: (left) W spectrum of the signal events and best fits to IB+DE [solid curve] and IB alone [dashed curve]; (right) W spectrum normalized to the IB spectrum.

Figure 3-left shows the W spectrum of the signal events. The solid curve is the best fit to the sum of IB and DE; the χ^2 of the fit was 7.85

for 6 degrees of freedom. The dashed curve is the best fit to IB alone. Normalized to the IB spectrum the deviation of the measured spectrum at large W is apparent (Figure 3-right). The DE component was measured to be $(1.85 \pm 0.30)\%$ of the IB component with the spectrum and, normalized to the theoretical prediction for the IB branching ratio, the branching ratio for DE is

$$(4.72 \pm 0.77) \times 10^{-6}$$

in the region 55 MeV $< T_{\pi^+} <$ 90 MeV.

Several checks to verify the result were made. The best fit to the sum of IB, DE and INT gave the INT component to be $(-0.4 \pm 1.6)\%$ of the IB component, and we concluded that no interference term is required for the fit to this spectrum. A spectrum analysis was performed on the $\cos\theta_{\pi^+\gamma}$ distribution and a consistent result was obtained. To study systematic uncertainties, we enhanced possible problems in the analysis such as Barrel calorimeter mis-calibration, π^+ momentum scale error, incorrect pairing, π^+-nuclear interaction and so on by loosening the corresponding cuts and examining the consequent changes in the result. All the changes were within 15%, no more than the statistical fluctuation due to the limited sample, and for the present we have assigned a 15% systematic uncertainty to the measurement. Background contamination in the signal sample was studied with a similar technique and was confirmed to be negligible.

The result from E787 is smaller than the results of previous measurements in Table 1. The DE decay rate in the region $\mathsf{E}_\gamma >$ 20 MeV is calculated to be 808 s^{-1} after correction for phase-space acceptance and is close to the rate of $K_L^0 \to \pi^+\pi^-\gamma$ decay, 617 s^{-1} (corresponding to the DE branching ratio $(3.19 \pm 0.16) \times 10^{-5}$ [11]).

5 Summary and Prospects

We have performed a new measurement of the $K^+ \to \pi^+\pi^0\gamma$ decay with more than eight times higher statistics than previous experiments and good kinematical constraints, using the hermetic E787 detector and stopped K^+ decays. In 1998, new E787 data with a modified "3gamma" trigger were taken to collect the $K^+ \to \pi^+\pi^0\gamma$ decays with lower π^+ energy threshold. We aim to study the direct emission and interference components as well as to search for a new decay mode $K^+ \to \pi^0\mu^+\nu\gamma$ at the 10^{-5} level.

Acknowledgments

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