NA48: Rare Decay Results

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Recent results on the kaon rare decays of the $K_S \rightarrow \gamma\gamma$, $K_{S,L} \rightarrow \pi^+\pi^-e^+e^-$, $K_S \rightarrow \pi^0e^+e^-$ measured in NA48 experiment at CERN are presented in this paper.

1 The experiment

The NA48 experiment is designed to measure direct CP violation in two-pion decays and to search for rare decays of neutral kaons using simultaneous and almost collinear $K_S$ and $K_L$ beams. The $K_L$ beam is produced by 450 GeV/c protons from SPS hitting a beryllium target at an angle of 2.4 mrad. The proton intensity is $1.5 \times 10^{12}$ per SPS pulse and these pulses are 2.4 s long with a repetition period of 14.4 s. Non-interacting protons are directed to the $K_S$ target, which is positioned $\sim 120$ m downstream of the $K_L$ beam line, to produce the $K_S$ beam. Anticounter at the end of the final collimator(AKS) defines the beginning of the fiducial volume of $\sim 40$ m long. A set of seven scintillator counters(AKL) surround the decay region and vetoes events outside the detector acceptance. The energy and the position of the electromagnetic showers of electrons and photons as the products of the kaon decays are detected in the liquid krypton calorimeter(LKR), with an energy resolution of $\sigma(E)/E \simeq 0.100/E \oplus 0.032/\sqrt{E} \oplus 0.005$ (E in GeV). The momenta of charged particles are measured in a spectrometer consisting of a dipole magnet and four drift chambers(DCH). The spectrometer has a momentum resolution of $\sigma(p)/p \simeq [0.009p \oplus 0.5]\%$ (p in GeV). A hodoscope placed in front of the calorimeter is used to measure the event time with resolution of 150 ps. An iron-scintillator hadron calorimeter(HAC)

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is used to measure the energies of the hadrons and the muons are identified by a muon veto system. The detailed description of the experiment can be found elsewhere.\textsuperscript{3}

The results presented here are based on data taken in 1998 and 1999. During two days in 1999, data was recorded with a factor $\sim 200$ higher beam intensity than the usual $K_S$ beam, resulting in $2.3 \times 10^8$ $K_S$ decays.

2 Decays of $K_S \to \gamma\gamma$

In the framework of the chiral perturbation theory (\chiPT), the contributions of one loop of charged pions and kaons to $K_S \to \gamma\gamma$ decays are finite and give an unambiguous prediction for branching ratio, $2.25 \times 10^{-6}$ with less than 10\% uncertainty\textsuperscript{4}. Thus, a precise determination of branching ratio provides a good test of \chiPT. The CERN experiment NA31\textsuperscript{4} measured a value compatible with theory: $(2.4 \pm 0.9) \times 10^{-6}$.

Two-gamma decays of short-lived kaons are reconstructed from $K_S$ high intensity data taken in 1999. $K_S \to \gamma\gamma$ candidates are selected by requiring events with $\geq 2$ clusters. The pairs of these clusters must be within $\pm 5$ ns. No other cluster with energy $> 1.5$ GeV within $\pm 3$ns around the event time must be present. The energy of each cluster must lie between $3 < E_i < 100$ GeV and the sum of cluster energies, the kaon energy, must be between 60 and 170 GeV. The center of gravity (cog) measured for two clusters $cog = \sqrt{\sum_i E_i(x_i^2 + y_i^2)/\sum_i E_i}$, must be less than 7 cm. Events with some activity in the AKS, AKL and DCH are rejected. Energy deposited in the HAC must not exceed 3 GeV in a time window of $\pm 15$ ns around the event time. After the initial event selection, the longitudinal vertex position of the event is calculated by

$$z_{\text{vertex}} = z_{\text{LKR}} - \frac{\sqrt{\sum_{i,j,i>j} E_i E_j[(x_i - x_j)^2 + (y_i - y_j)^2]}}{m_K}, \quad (1)$$

where $z_{\text{LKR}}$ is the longitudinal position of the liquid krypton calorimeter from the AKS, $x_i, y_i$ are the transverse position of the clusters at the LKR, and $m_K$ is the kaon mass. The study of $K_S \to \gamma\gamma$ is done in a limited region, $-2 < z_{\text{vertex}} < 5$ m in order to minimize the main source of background which is $K_S \to \pi^0\pi^0$. After the above cuts, 450 $K \to \gamma\gamma$ events are obtained. The $z_{\text{vertex}}$ distribution of those events are shown in Figure 1(left).

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**Figure 1:** (left) The $z_{\text{vertex}}$ distribution for data and MC. The open circles represent $K_S \to \pi^0\pi^0$ events while closed squares show $K \to \gamma\gamma$. The solid line shows the $\gamma\gamma$ background from MC simulated $K_S \to \pi^0\pi^0$ decays. The peak at $z = -1250$ cm is due to $\eta$ mesons produced in the AKS. (right) The $z_{\text{vertex}}$ distribution obtained from maximum likelihood method for fitted $K_S \to \gamma\gamma$ events (dotted area) and $K_L \to \gamma\gamma$ component (hatched area). The dots show the data and the arrows show the fitted region.
The main background to $K_S \rightarrow \gamma \gamma$ decays are $K_S \rightarrow \pi^0\pi^0$ decays where two photons are not detected. The maximum invariant mass of the $\gamma\gamma$ from $\pi^0\pi^0$ events is 458 MeV resulting in a 9 m shift in the $z_{\text{vertex}}$. This background is minimized by requiring the $z_{\text{vertex}}$ cut described above. $10^8 K_S \rightarrow \pi^0\pi^0$ events are simulated to estimate this contribution. A second background to $K_S \rightarrow \gamma\gamma$ decays arises from $K_L \rightarrow \gamma\gamma$ decays because of the $K_L$ flux produced at the target. This background is estimated by measuring $K_L$ flux from $K_S \rightarrow \pi^0\pi^0$ decays. The remaining background originated from $\Lambda \rightarrow n\pi^0$ is estimated by comparing cog distribution for those events with signal events.

Using a binned maximum likelihood method, $149 \pm 21 K_S \rightarrow \gamma\gamma$ events are estimated in the signal region and the branching ratio of $K_S \rightarrow \gamma\gamma$ is measured to be

$$BR(K_S \rightarrow \gamma\gamma) = (2.58 \pm 0.36(\text{stat}) \pm 0.22(\text{sys})) \times 10^{-6}. \quad (2)$$

The result of the likelihood method is shown in Figure 1(right). The main systematic error sources are due to uncertainty of $BR(K_L \rightarrow \gamma\gamma)(5\%)$, the selection cuts (4\%), background (5\%), acceptance (2\%), and the trigger efficiency (2\%).

From this measurement, the ratio of the decay widths of $K_S \rightarrow \gamma\gamma$ to $K_L \rightarrow \gamma\gamma$ is computed to be

$$R = \frac{\Gamma(K_S \rightarrow \gamma\gamma)}{\Gamma(K_L \rightarrow \gamma\gamma)} = 2.53 \pm 0.35(\text{stat}) \pm 0.22(\text{sys}).$$

3 Decays of $K_L \rightarrow \pi^+\pi^-e^+e^-$

The study of $K_L \rightarrow \pi^+\pi^-e^+e^-$ decays provides a way to observe CP violation in the neutral kaon system. The two main contributions to this decay are the CP conserving direct emission associated with a magnetic dipole transition (M1) and the CP violating inner bremsstrahlung. The interference between these two components produces CP violating asymmetry ($A_L \sim 14\%$) in the angle $\phi$ between normals to the $\pi^+\pi^-$ and $e^+e^-$ planes in the kaon center of mass system.

The asymmetry and the branching ratio is determined from the combined data taken in 1998 and 1999. $K_L \rightarrow \pi^+\pi^-e^+e^-$ events are selected by requiring two positive and two negative intime tracks. The electron and pion identifications are based on the $E/p$ measurement, where $E$ is measured in the LKR and $p$ is measured in the spectrometer.

![Figure 2: For combined 1998 and 1999 data: (left) Measured $M_{3+\pi^+\pi^-e^+e^-}$ invariant mass for $K_L \rightarrow \pi^+\pi^-e^+e^-$, (right) After acceptance correction, the $\phi$ distribution from which asymmetry is obtained.](image)

The main background to $K_L \rightarrow \pi^+\pi^-e^+e^-$ decays is due to the $K_L \rightarrow \pi^+\pi^0\pi^0_D$, where $\pi^0_D$ decays into $e^+e^-\gamma$, with a lost $\gamma$. They are eliminated using a variable $p_0^2$, $p_0^2 = (m_K^2 - m_{\pi^0}^2 - m_{\pi^\pm}^2)^2 - 4m_{\pi^\pm}^2 m_{\pi^0}^2 - 4(p_{\perp})_{\pi^\pm} m_{\pi^0}^2 / 4(m_{\pi^\pm}^2 + (p_{\perp})_{\pi^\pm}^2)$. For $K_L \rightarrow \pi^+\pi^-\pi^0_D$ events $p_0^2$ is greater than zero. The second background source is due to the $K_L \rightarrow \pi^+\pi^-\gamma$, where $\gamma$ converts into a
$e^+e^-$ pair. The rejection is done by demanding 2 cm separation between electron tracks in the first drift chamber.

The invariant mass $m_{\pi^+\pi^-e^+e^-}$ distribution for $K_L \to \pi^+\pi^-e^+e^-$ is shown in Figure 2(left). Using KTEV results on $a_1/a_2 = -0.72 \pm 0.03$ and $g_{M1} = 1.35^{+0.20}_{-0.17}$, the preliminary measurement on branching ratio of $K_L \to \pi^+\pi^-e^+e^-$, based on 1337 reconstructed events, is $BR(K_L \to \pi^+\pi^-e^+e^-) = (3.1 \pm 0.1(stat) \pm 0.2(sys)) \times 10^{-7}$. The asymmetry is obtained from the $\phi$ distribution corrected for acceptance (Figure 2(right)). The preliminary result on the asymmetry is given by $A_L = (13.9 \pm 2.7(stat) \pm 2.0(sys))\%$ which is in good agreement with the theoretical prediction.

4 Decays of $K_S \to \pi^+\pi^-e^+e^-$

The main contribution to the $K_S \to \pi^+\pi^-e^+e^-$ decay arises from CP conserving inner bremsstrahlung and as a result no asymmetry in the $\phi$ distribution is expected.

The events selection is done in a similar way as in $K_L \to \pi^+\pi^-e^+e^-$. The main background arising from $K_L \to \pi^+\pi^-\pi^0_D$ is eliminated by requiring the event to be tagged as coming from the $K_S$ beam. The first observation of this decay is based on the data taken in 1998. Based on the 56 $K_S \to \pi^+\pi^-e^+e^-$ events, the value obtained for the branching ratio of $K_S \to \pi^+\pi^-e^+e^-$ is $BR(K_S \to \pi^+\pi^-e^+e^-) = (4.5 \pm 0.7(stat) \pm 0.4(sys)) \times 10^{-5}$. This value translates into the inner bremsstrahlung component of $K_L \to \pi^+\pi^-e^+e^-$, $BR(K_L^IB \to \pi^+\pi^-e^+e^-) = (1.4 \pm 0.2) \times 10^{-7}$.

The asymmetry, $A_S$, and branching ratio of $K_S \to \pi^+\pi^-e^+e^-$ are measured by using combined 1998 and 1999 data including the 2-day $K_S$ high intensity data. Figure 3 shows the invariant mass $M_{\pi^+\pi^-e^+e^-}$ and $\phi$ distributions for these data. Based on 921 $K_S \to \pi^+\pi^-e^+e^-$ events, the preliminary result for the asymmetry is given by $A_S = (-0.2 \pm 3.4(stat) \pm 1.4(sys))\%$ which is consistent with zero. The value obtained for the branching ratio is $BR(K_S \to \pi^+\pi^-e^+e^-) = (4.3 \pm 0.2(stat) \pm 0.3(sys)) \times 10^{-5}$, and the inner bremsstrahlung component of $K_L \to \pi^+\pi^-e^+e^-$, $BR(K_L^IB \to \pi^+\pi^-e^+e^-) = (1.3 \pm 0.1) \times 10^{-7}$.

![Figure 3: For combined 1998 and 1999 data: (left) Measured $M_{\pi^+\pi^-e^+e^-}$ invariant mass for $K_S \to \pi^+\pi^-e^+e^-$, (right) After acceptance correction, the $\phi$ distribution from which asymmetry is obtained.](image)

5 Decays of $K_S \to \pi^0e^+e^-$

The study of $K_S \to \pi^0e^+e^-$ decay is important to improve the limit on the indirect CP violating term in $K_L \to \pi^0e^+e^-$. The branching ratio is given by: $BR(K_S \to \pi^0e^+e^-) \sim 5.2 \times 10^{-9}a_S^2$ where $a_S$ is the strength of the indirect CP violating component in $K_L \to \pi^0e^+e^-$. The present limit on the branching ratio comes from the NA31 experiment, $BR(K_S \to \pi^0e^+e^-) < 1.1 \times 10^{-6}$ at 90% confidence level. A more precise measurement of branching ratio of $K_S \to \pi^0e^+e^-$ will provide better limits on the indirect CP violating contribution in $K_L \to \pi^0e^+e^-$. 
The $K_S \rightarrow \pi^0 e^+e^-$ search is based on the $K_S$ high intensity data taken in 1999. The events are selected by requiring at least four cluster in the LKR, two tracks and one vertex. Then the group of four clusters has to pass additional kinematic cuts such as the invariant mass of $\gamma \gamma$ must be within 2.5 MeV with respect to the nominal $\pi^0$ mass, and the invariant mass of $ee\gamma\gamma$ must lie within 10 MeV with respect to nominal kaon mass.

The main background $K_S \rightarrow \pi^0 e^+e^-$ comes from $K_S \rightarrow \pi^0 D\pi^0 D$, where both $\pi^0 D$ decays into $e^+e^-\gamma$, and one electron and one positron are lost. This background is rejected by requiring invariant mass difference $|m_{ee} - m_{\pi^0}|$ to be greater than 30 MeV. Another source of background arises from $K_S \rightarrow \pi^0\pi^0 D$, where $\pi^0 D$ decays into $e^+e^-\gamma$ with a lost $\gamma$. Due to the origin of the electrons, their invariant mass cannot exceed pion mass. The remaining background in $K_S \rightarrow \pi^0 e^+e^-$ are negligible.

Figure 4 shows the invariant mass distribution of $e^+e^-$ pair for events passing the above cuts. The events below $m_{ee} < 165$ MeV is in good agreement with the background $K_S \rightarrow \pi^0 \pi^0 D$ events. No events are observed $m_{ee}$ above 165 MeV. Using $K_S \rightarrow \pi^0 \pi^0 D$ as a normalization channel, at 90% confidence level upper limit on the branching ratio is obtained,

$$BR(K_S \rightarrow \pi^0 e^+e^-) < 1.4 \times 10^{-7}.$$  \hfill (3)

![Figure 4: Invariant mass distribution of $e^+e^-$ for data (dots) and for $\pi^0\pi^0_D$ monte-carlo events (solid line). The expected distribution for $K_S \rightarrow \pi^0 e^+e^-$ events is shown by the shaded area.](image)

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