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Measurement of structure dependent radiative $K^+ \to e^+\nu\gamma$ decays using stopped positive kaons at J-PARC

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The J-PARC E36 experiment aims at searching for a lepton universality violation by precisely measuring the ratio of the branching ratio of the $K^+ \to e^+\nu(\gamma)$ ($K_{e2(\gamma)}$) to $K^+ \to \mu^+\nu$ ($K_{\mu 2}$) decays. The E36 experiment was performed in 2015 at J-PARC using a stopped K^+ method in conjunction with a 12-sector iron-core superconducting toroidal spectrometer. Charged particle momenta were calculated by reconstructing the tracks in the spectrometer. Particle discrimination between e^+ and μ^+ was carried out using an aerogel Cherenkov counter and a lead-glass Cherenkov counter, as well as by measuring the time-of-flight between TOF counters. The peak structure due to the $K_{e2(\gamma)}$ decays was successfully observed in the e^+ momentum spectrum. The structure-dependent radiative $K^+ \to e^+\nu\gamma$ ($K^{\mathrm{SD}}_{e2\gamma}$) events were selected by requiring photon hits in the CsI(Tl) calorimeter or the GSC counter. The experimental spectra were reproduced by the Monte Carlo simulation, which indicates a correct understanding of the detector acceptance. The $Br(K^{\mathrm{SD}}_{e2\gamma})$ value relative to $Br(K_{e2(\gamma)})$ was obtained by calculating the ratio of the $K^{\mathrm{SD}}_{e2\gamma}$ and $K_{e2(\gamma)}$ yields corrected for their detector acceptances. The $Br(K^{\mathrm{SD}}_{e2\gamma})/Br(K_{e2(\gamma)})$ value was obtained to be $1.22 \pm 0.07_{stat} \pm 0.04_{syst}$ in the CsI(Tl) analysis and $1.22 \pm 0.13_{stat} \pm 0.08_{syst}$ in the GSC analysis.

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1. Introduction

High precision electroweak tests represent a powerful method to check the Standard Model (SM) and to obtain indirect hints of new physics beyond the SM. The $K^+ \to l^+\nu$ (K_{l2}), which is the simplest leptonic decay among the K^+ decay channels, is one of the best decay channels to perform these tests. Lepton universality, which can be expressed as the same coupling constants for the three lepton generations, is a basic assumption in the SM, lepton universality violation hence would indicate the existence of new physics beyond the SM. Although the K_{l2} decay width is described using the K_{l2} hadronic decay constant, it can be canceled out by forming the ratio of the electronic (K_{e2}) and muonic ($K_{\mu 2}$) decay channels with radiative correction (δ_r) as,

$$R_K^{\mathrm{SM}} = \frac{\Gamma(K^+ \to e^+\nu(\gamma))}{\Gamma(K^+ \to \mu^+\nu(\gamma))} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta_r) \tag{1}$$

under the assumption of μ-e universality. The factor $(m_e/m_\mu)^2$ arises from the helicity suppression effect of K_{e2} decay due to the $V - A$ structure of the charged weak current, and it enhances the sensitivity to effects beyond the SM. As a result, the SM prediction of R_K^{SM} is determined to be $(2.477 \pm 0.001) \times 10^{-5}$ with high accuracy and this makes it possible to search for new physics effects by an accurate R_K measurement [1].

Recently, the NA62 [2] and KLOE [3] groups reported the experimental results of the R_K measurement. In the NA62 measurement, an in-flight kaon beam with particle momentum of 75 GeV/c, was used and $K_{\mu 2}$ and structure-dependent radiative $K^+ \to e^+\nu\gamma$ ($K_{e2\gamma}^{\mathrm{SD}}$) decays were the main background sources in the K_{e2} sample. The treatment of these backgrounds was one of the most difficult points to determine the R_K value in the NA62 experiment. Since low energy kaons from $\phi \to K^+K^-$ were used in the KLOE experiment, the kinematical resolution of K_{l2} decays was very good. The NA62 and KLOE results were obtained to be $(2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$ and $(2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$, respectively. The combined value was determined by calculating the error-weighted average as, $R_K = (2.488 \pm 0.009) \times 10^{-5}$, which is consistent with the SM within the experimental uncertainty. Since this uncertainty is about 10 times larger than the theoretical one, there is still room for further improvement of the R_K determination.

2. The J-PARC E36 experiment

The E36 experiment was performed in 2015 at J-PARC employing a stopped K^+ beam in conjunction with a 12-sector iron-core superconducting toroidal spectrometer [4]. Schematic cross sectional side and end views of the detector setup are shown in Fig. 1. The K_{e2} (P_{e^+}=247 MeV/c) and $K_{\mu 2}$ (P_{μ^+}=236 MeV/c) events were accepted by analyzing the charged particle momentum using this toroidal spectrometer. Details of the detector configuration are well documented in Ref. [4]. In order to compare the experimental R_K with the SM prediction, the internal bremsstrahlung (IB) process in the radiative $K^+ \to e^+\nu\gamma$ decay has to be included in the K_{e2} sample ($K_{e2(\gamma)}$). On the other hand, the structure-dependent (SD) radiative $K^+ \to l^+\nu\gamma$ decays [3] are backgrounds and have to be subtracted from the observed $K_{e2(\gamma)}$ events in the analysis.

A separated 760-MeV/c beam was transported using the J-PARC K1.1BR beamline. The beam was slowed down by a BeO degrader and stopped in an active fiber target. Charged particles from

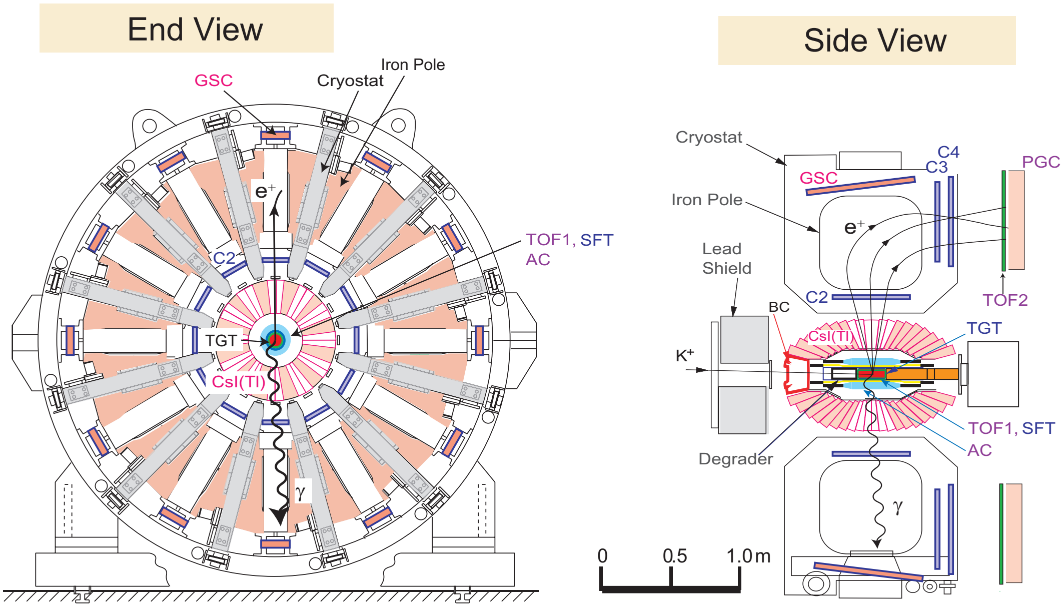

Figure 1: Schematic cross sectional side view (right) and end view (left) of the E36 detector configuration. Charged particles from TGT were momentum-analyzed by reconstructing the particle trajectory using three MWPCs, C2, C3, and C4, as well as by TGT and SFT. Particle identification was carried out using AC, PGC and by measuring the time-of-flight between the TOF1 and TOF2 counters. The photon energy and hit position were measured by the CsI(Tl) calorimeter.

the target were tracked using a spiral-fiber tracker (SFT) [5] surrounding the K^+ target and three multi-wire proportional chambers (C2, C3, C4) in each spectrometer sector. The C2 and C3/C4 chambers were placed at the entrance and exit of the magnet gaps, respectively. The K_{e2} and $K_{\mu2}$, and their radiative decays were collected with a central magnetic field of the spectrometer, B=1.5 T. Particle identification for e^+ and μ^+ was carried out using an aerogel Cherenkov counter [6] and a lead-glass Cherenkov counter [7], and by measuring the time-of-flight between the TOF1 and TOF2 plastic scintillation counters. The CsI(Tl) calorimeter, an assembly of 768 CsI(Tl) crystals, covered 70% of the total solid angle [8]. There were 12 holes for the outgoing charged particles to enter the spectrometer, and thus all of the radiated photons from K^+ decays at rest cannot be detected by the calorimeter. Some photons passed through the holes of the CsI(Tl) calorimeter, and some of these escaping photons entered the GSC counters which were set in each sector at the outer radius of the magnet pole, as shown in Fig. 1. There were four layers, and the size of each layer was 900 mm $\times$ 196 mm and the thickness was 3.7 mm (10 mm) for Pb (plastic) corresponding to 2.7 radiation lengths. The radiative photons from $K_{e2\gamma}^{\mathrm{SD}}$ were measured by the CsI(Tl) calorimeter or the GSC counters, as shown in Fig. 1.

3. Data analysis

The $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$ ratio can be obtained by calculating the ratio of the accepted K_{e2} and $K_{\mu2}$ event numbers (N) corrected for the detector acceptance as,

$$R_K = \Gamma(K_{e2(\gamma)})/\Gamma(K_{\mu2(\gamma)}) = N(K_{e2(\gamma)})/N(K_{\mu2(\gamma)}) \cdot \Omega(K_{\mu2(\gamma)})/\Omega(K_{e2(\gamma)}), \qquad (2)$$

where Ω is the detector acceptance calculated by Monte Carlo simulation. The charged particle momentum in the spectrometer gap was calculated by reconstructing the track using the active target, SFT, C2, C3, and C4. Then, the original momentum was determined by correcting for the energy loss in the target, as shown in Fig. 2 (a). Monochromatic peaks due to the $K_{\mu 2}$ and $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$) decays are clearly seen in the figure. Next, choosing e^+ particles using the three PID detectors, the peak structure due to the genuine K_{e2} decays are successfully observed in the e^+ momentum spectrum, as shown in Fig. 2 (b). The black dots are the experimental data which include the $K_{e2\gamma}^{\rm SD}$ and $K_{\mu 2}$ backgrounds as well as the $K_{e2(r)}$ events.

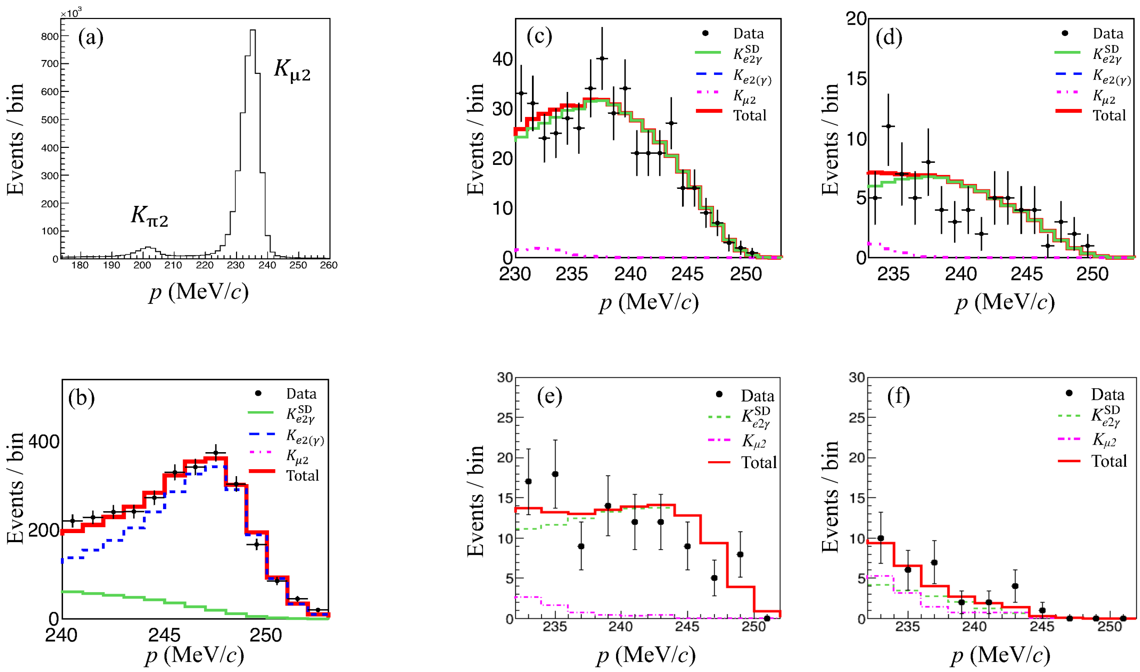

Figure 2: (a) is the momentum spectrum corrected for the energy loss in TGT before imposing the positron selection PID. The peak structures due to the predominant $K_{\mu 2}$ and $K_{\pi 2}$ decays are seen at 236 MeV/c and 205 MeV/c, respectively. The e^+ momentum spectra (b) without CsI(Tl) constraints, with requiring (c) one photon cluster and (d) two photon clusters in the CsI(Tl) calorimeter, and (e) $e-\gamma$ sector difference =6 and (f) $e-\gamma$ sector difference =5 in GSC. The dots (black) are the experimental data. The solid (green), dashed (blue), and dashed-dotted (magenta) lines are the $K_{e2\gamma}^{\rm SD}$, $K_{e2(\gamma)}$, and $K_{\mu 2}$ decays, respectively, determined by simulation calculations. The thick-red lines are the fitted result obtained by adding all the decay contributions.

Since the SD radiative $K_{e2\gamma}^{\rm SD}$ process is a serious background for the R_K measurement, the characteristics of this decay channel have to be well understood for the background subtraction. In order to study the $K_{e2\gamma}^{\rm SD}$ decay, events with one cluster and two cluster (photon+accidental) in the CsI(Tl) calorimeter generated by a radiative photon were selected to pick up these events from the above accepted e^+ events. The squared missing mass ($M^2_{\rm miss}$) defined as, $M^2_{\rm miss} = (M_K - E_{e^+} - E_\gamma)^2 - (\vec{P}_{e^+} + \vec{P}_\gamma)^2$, where E and $\vec{P}$ are the energy and momentum vector, respectively, was required to be $-8000 < M^2_{\rm miss} < 5000$ (MeV/c^2)^2 to remove accidental backgrounds in the CsI(Tl) calorimeter. The experimental $K_{e2\gamma}^{\rm SD}$ events were successfully extracted, as shown in Fig. 2 (c) and (d) for 1-cluster and 2-cluster events, respectively, indicated by the dots. Also, by requiring the GSC hits, the $K_{e2\gamma}^{\rm SD}$ events were observed, as shown in Fig. 2 (d) and (e). The e^+ momentum spectra were obtained by selecting events with the spectrometer sector difference of the accepted e^+ and radiative photon (diff) for (d) 6 = 180° and (e) 5 = 150°.

The current Monte Carlo (MC) simulation was based on a GEANT4 code. The $K_{e2\gamma}$ data were generated according to the matrix elements given in Ref. [9] and the form factors obtained by the KLOE group [3] was adopted. The blue, green, and magenta histograms in Fig. 2 are the MC simulations of $K_{e2(\gamma)}$, $K_{e2\gamma}^{\mathrm{SD}}$ and $K_{\mu 2}$ decays, respectively, and the red ones are the fitted result obtained by adding all the decay contributions. The experimental data are in good agreement with the MC simulation. Comparing the experimental data with the simulation, the $K_{e2\gamma}^{\mathrm{SD}}$ branching ratio relative to the K_{e2} decay, the $Br(K_{e2\gamma}^{\mathrm{SD}})/Br(K_{e2})$, was determined to be $1.22 \pm 0.07_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$ and $1.22 \pm 0.13_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}$ in the CsI(Tl) and GSC analyses, respectively, although the IB radiative correction was not applied yet.

4. Summary

The J-PARC E36 experiment is aiming at searching for a lepton universality violation by precisely measuring the ratio of the decay widths of the $K^+ \to e^+\nu(\gamma)$ and $K^+ \to \mu^+\nu$ decays. The E36 experiment was performed at J-PARC employing a stopped K^+ beam in conjunction with a 12-sector iron-core superconducting toroidal spectrometer. Particle discrimination between e^+ and μ^+ was carried out using an aerogel Cherenkov counter and a lead-glass Cherenkov counter, as well as by measuring the time-of-flight between the TOF1 and TOF2 scintillating counters. The peak structure due to the $K_{e2(\gamma)}$ decays was successfully observed in the e^+ momentum spectrum. Also, the SD radiative $K_{e2\gamma}^{\mathrm{SD}}$ events were selected by requiring photon hits in the CsI(Tl) calorimeter or the GSC counters. The experimental spectra were reproduced by the Monte Carlo simulation, which indicates a correct understanding of the experimental conditions. The $K_{e2\gamma}^{\mathrm{SD}}$ branching ratio relative to the K_{e2} decay was determined by comparing the experimental spectra with the simulation.

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