TESTS OF CHPT WITH K_{e4}^{+-} AND K_{e4}^{00} DECAYS AT THE NA48/2 EXPERIMENT AT CERN

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The NA48/2 experiment has collected the largest samples to date of semi-leptonic charged kaon decays in the K_{e4}^{+-} ($K^\pm \rightarrow \pi^+\pi^-e^\pm\nu$) and K_{e4}^{00} ($K^\pm \rightarrow \pi^0\pi^0e^\pm\nu$) modes. From 1.1 million K_{e4}^{+-} decays, form factors in the S- and P-wave have been extensively studied. Branching ratio and form factors have been measured at unprecedented precision. From ~ 66000 K_{e4}^{00} decays, preliminary values of the Branching ratio and form factor have been obtained at a percent level precision. The comparison of Branching ratio and form factor values in both K_{e4} modes sheds new light on isospin symmetry breaking effects. Form factor measurements are major inputs to the study of low energy QCD and are powerful tests of Chiral Perturbation Theory predictions.

1. NA48/2 beam and detector

Two simultaneous $K^\pm$ beams were produced by 400 GeV/c protons from the CERN SPS impinging on a beryllium target. Opposite charge particles with a central momentum of (60 ± 3) GeV/c were selected and focused ~ 200 m downstream at the first spectrometer chamber. A magnetic spectrometer (a dipole magnet surrounded by four drift chambers) measured the momentum (p) of charged decay products with a relative precision of $\sim 1\%$ for 10 GeV/c momentum tracks. It was followed by a scintillator hodoscope consisting of two planes segmented into horizontal and vertical strips achieving a very good ~ 150 ps time resolution. A liquid krypton calorimeter (LKr), $27 X_0$ thick, was used to measure electromagnetic energy deposits and to identify electrons through their E/p ratio (the energy and transverse position resolutions were $\sim 1\%$ and ~ 1.5 mm (resp.) for 10 GeV

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showers). A two-level trigger logic selected and flagged events with a high efficiency for both K_{e4} topologies. A more detailed detector description is available in Ref. 1.

2. The K_{e4} decay formalism

Four-body final state decays are described by five kinematic variables, namely for K_{e4} decays, the Cabibbo-Maksymowicz variables:² two invariant masses $S_\pi = M_{\pi\pi}^2$ and $S_e = M_{e\nu}^2$ and three angles ϑ_π , ϑ_e and φ . The hadronic current is described by form factors which can be developed in a partial wave expansion as suggested in Ref. 3. Limiting the expansion to S- and P-waves and considering a unique phase δ_p for all P-wave form factors, two axial (F , G) and one vector (H) complex form factors contribute to the transition amplitude: $F = F_s e^{i\delta_s} + F_p e^{i\delta_p} \cos\theta_\pi$, $G = G_p e^{i\delta_p}$, $H = H_p e^{i\delta_p}$. From the differential rate study in the 5-dimensional space, four real form factors (F_s , F_p , G_p and H_p) and a single phase difference ($\delta = \delta_s - \delta_p$) are then measured, together with their energy variation with S_π and S_e . In the neutral pion mode K_{e4}^{00} , the variables ϑ_π and φ are irrelevant and the form factors reduce to the single F_s value due to Bose statistics.

3. Event reconstruction, analysis procedure and results

Event reconstruction and selection follow similar strategy for both signal modes: the K_{e4}^{+-} (K_{e4}^{00}) candidates are reconstructed from three charged tracks (one track and four photons forming two π^0 s) pointing to the same decay vertex. The abundant $K_{3\pi}$ decay modes ($K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ and $K^\pm \rightarrow \pi^0\pi^0\pi^\pm$) are used as normalization modes. They are recorded concurrently using the same trigger logic and the same reconstruction as the signal events. Kinematic separation of signal and normalization candidates is obtained by requiring (or not) missing mass and missing transverse momentum in the $K_{3\pi}$ hypothesis. Extra requirements of electron identification ($0.9 < E/p < 1.1$ and properties of LKr associated shower consistent with the electron hypothesis) ensure a low background contamination of order $\sim 1\%$ relative. The remaining background is mainly due to $K_{3\pi}$ decays with a $\pi^\pm$ faking an electron response in LKr or followed by the rare $\pi \rightarrow e\nu$ decay. Accidental coincidence with another track/photon is one order of magnitude lower. Control data samples are used to measure most background contributions. The four decay modes geometrical acceptances are obtained from a MC simulation including detector geometry, detailed material description and local imperfections. They are typically $\sim 18 - 20\%$ in the K_{e4}^{+-} and $K_{3\pi}^{+-}$ modes and 2% (4%) in the K_{e4}^{00} ($K_{3\pi}^{00}$) modes.

Form factors values are obtained by fitting the differential distributions of simulated signal candidates to those of data in small multi-dimensional boxes in the kinematical space. Branching ratios (BR) are obtained as:

$$\text{BR}(K_{e4}) = (N_s - N_b)/N_n \cdot (A_n \varepsilon_n)/(A_s \varepsilon_s) \cdot \text{BR}(K_{3\pi}),$$

where N_s is the number of signal candidates ($1.1 \cdot 10^6$ K_{e4}^{+-} , $6.6 \cdot 10^4$ K_{e4}^{00}), N_b the background contribution (10552 for K_{e4}^{+-} , 708 for K_{e4}^{00}) and N_n the number

Fig. 1. Relative F_s^2/f_s^2 form factor measurements function of q^2 in the K_{e4}^{+-} (Left) and the K_{e4}^{00} (Right) mode. By construction $F_s^2/f_s^2(q^2 = 0) = 1$. Red lines are degree-2 polynomial fits to the data (stat. errors only) for $q^2 > 0$ while the blue line is the extrapolation to negative values.

of normalization events ($19 \cdot 10^8 K_{3\pi}^{+-}$, $94 \cdot 10^6 K_{3\pi}^{00}$). $A_s(A_n)$ are the geometrical acceptances described above and $\varepsilon_s(\varepsilon_n)$ are the trigger efficiencies, well above 95% and similar for signal and normalization modes. $\text{BR}(K_{3\pi})$ are the normalization Branching ratios. The K_{e4}^{+-} BR and form factor measurements are already been published in Ref. 4 while the corresponding K_{e4}^{00} measurements are still preliminary.

Branching ratios, inclusive of $K_{e4}(\gamma)$ decays, are obtained at improved precision with respect to current world average:⁵

$$\text{BR}(K_{e4}^{+-}) = (4.257 \pm 0.004_{\text{stat}} \pm 0.016_{\text{syst}} \pm 0.031_{\text{ext}}) \cdot 10^{-5}, \quad \text{PDG} = (4.09 \pm 0.10) \cdot 10^{-5}$$

$$\text{BR}(K_{e4}^{00}) = (2.585 \pm 0.010_{\text{stat}} \pm 0.010_{\text{syst}} \pm 0.032_{\text{ext}}) \cdot 10^{-5}, \quad \text{PDG} = (2.2 \pm 0.4) \cdot 10^{-5}$$

Quoted systematic errors include uncertainties on acceptance, resolution, beam geometry, particle identification, trigger efficiencies and radiative corrections. External errors come from the normalization mode BR uncertainties and are now the dominant errors. The F_s form factor variations with $q^2 = (S_\pi/4m_{\pi^+}^2 - 1)$ are displayed in Fig.1. The same quadratic behavior is present in both modes for ($q^2 > 0$) and a deficit of events is observed below the $2m_{\pi^+}$ threshold ($q^2 = 0$) in the K_{e4}^{00} mode as observed in the $K_{3\pi}^{00}$ mode.⁶ It can be explained by final state charge exchange scattering ($\pi^+\pi^- \rightarrow \pi^0\pi^0$). A fit to the distribution could have been performed to measure the a_0 and a_2 scattering lengths but the sensitivity was low due to much smaller data sample.

The absolute form factors have also been obtained with the formula:

$$\begin{aligned} F_s(K_{e4}^{+-}) &= 5.705 \pm 0.003_{\text{stat}} \pm 0.017_{\text{syst}} \pm 0.031_{\text{ext}}, \\ F_s(K_{e4}^{00}) &= 6.092 \pm 0.012_{\text{stat}} \pm 0.017_{\text{syst}} \pm 0.045_{\text{ext}}. \end{aligned}$$

These two new results introduce a tension between $F_s(K_{e4}^{+-})$ and $F_s(K_{e4}^{00})$ as well as between $\text{BR}(K_{e4}^{+-})$ and $2\text{BR}(K_{e4}^{00})$. Possible isospin symmetry breaking, radiative or other effects need to be investigated.

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