Studies of the $K_{e4}$ decay at NA48/2

Michal Zamkovský on behalf of NA48/2 collaboration

Charles University in Prague

June 29, 2015
Outline

1. NA48 detectors
2. Physics motivation
3. Current experimental & theoretical situation
4. Event selection
5. Form factor measurement
6. Branching ratio measurement
7. Summary

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### Experimental setup

Detector performances and resolutions:

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Beam: simultaneous \( K^+ \) and \( K^- \) with a central momentum 60 GeV/c \( \pm 3.8\% \) (rms)

- Focused at DCH1 with \( \sim 10 \) mm transverse size
- Superimposed beam axes within 1 mm
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Mandelstam variables:

\[ s = \left( p_{\pi_1} + p_{\pi_2} \right)^2 = (k - L)^2, \]
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\[ L = p_l + p_\nu, \quad P = p_{\pi_1} + p_{\pi_2}, \quad Q = p_{\pi_1} - p_{\pi_2} \]

Kinematic constrain: \( s + t + u = m_K^2 + 2m_\pi^2 + L^2 \)

Cabibbo-Maksymowicz formulation: \( S_\pi = M_{\pi\pi}^2, \quad S_e = M_{e\nu}^2 \) and three angles: \( \theta_\pi, \theta_e, \phi \)
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Studies of the \( K_{e4} \) decay at NA48/2
Differential decay rate summed over lepton spins in Cabibbo-Maksymowicz formulation:

\[
d^5\Gamma = \frac{G_F^2|V_{us}|^2}{2(4\pi)^6 m_K^5} \rho(S_\pi, S_e) J_5(S_\pi, S_e, \cos \theta_\pi, \cos \theta_e, \phi) \\
\quad \times dS_\pi dS_e d\cos \theta_\pi d\cos \theta_e d\phi,
\]

Function \( J_5 \) depends on complex hadronic form factors:

\[
F_1 = \frac{1}{2} \lambda^{1/2}(m_K^2, S_\pi, S_e) \cdot F + \sigma(S_\pi)(PL) \cos \theta_\pi \cdot G,
\]

\[
F_2 = \sigma(S_\pi)(S_\pi S_l)^{1/2} G,
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\[
F_3 = \sigma(S_\pi)(S_\pi S_l)^{1/2} \frac{H}{m_K^2},
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F_4 = -(PL) F - S_l R - \sigma(S_\pi) \frac{1}{2} \lambda^{1/2}(m_K^2, S_\pi, S_e) \cos \theta_\pi \cdot G
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In \( K_{e4} \) decays, \( m_e \) can be neglected \( \Rightarrow \) \( F_4 \) will not contribute as is always multiplied by \( m_e^2 \).
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Partial wave expansion:

\[
\frac{F_1}{m_K^2} = \sum_{l=0}^{\infty} P_l(\cos \theta) \cdot F_{1,l} e^{i \delta_l}, \quad \frac{F_{2(3)}}{m_K^2} = \sum_{l=0}^{\infty} P'_l(\cos \theta) \cdot F_{2(3),l} e^{i \delta_l}
\]

Expression for \(F, G, H\) form factors:

\[
F = F_s e^{i \delta_{fs}} + (F_p e^{i \delta_{fp}} \cos \theta + F_d e^{i \delta_{fd}} \cos^2 \theta + \ldots),
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\[
G = G_p e^{i \delta_{gp}} + (G_d e^{i \delta_{gd}} \cos \theta + \ldots), \quad H = H_p e^{i \delta_{hp}} + (H_d e^{i \delta_{hd}} \cos \theta + \ldots)
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S-wave term (only term for \(K_{e4}^{00}\) mode) contribution:

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F_s = \left( f_s + f'_s q^2 + f''_s q^4 + f_e \left( \frac{S_e}{4m_{\pi^+}^2} \right) \right) e^{i \delta_0}, \quad q = \sqrt{\frac{S_\pi - 4m_{\pi^+}^2}{4m_{\pi^+}^2}}
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Integration of \(J_5\) over \(\cos \theta\) and \(\phi\):

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J_3 = |XF_s|^2(1 - \cos 2\theta) = 2|XF_s|^2 \sin^2 \theta_e,
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Current experimental status of $K_{e4}^{00}$

1. Measurements done by other experiments
   - 37 events from three different experiments: $\text{BR} = (2.2 \pm 0.4) \cdot 10^{-5}$
   - 214 events from KEK E470: $\text{BR} = (2.29 \pm 0.34) \cdot 10^{-5}$
     - error dominated by systematics
   - No form factor determination so far, just a relation between partial rate and a constant form factor value: $\Gamma = 0.8|V_{us} \cdot F|^2 \cdot 10^3 s^{-1}$

2. Theoretical predictions for BR
   - Isospin symmetry relates more precisely measured modes and predicts:
     $\Gamma(K_{e4}^{+-}) = 1/2\Gamma(K_{e4}^{0\pm}) + 2\Gamma(K_{e4}^{00})$
     Considering the different mean lifetimes $\tau_{K^+}, \tau_{K^0}$, this results in:
     $\text{BR}(K_{e4}^{+-}) - 2\text{BR}(K_{e4}^{00}) - \frac{1}{2} \text{BR}(K_{e4}^{0\pm}) \frac{\tau_{K^+}}{\tau_{K^0}} = (-0.772 \pm 0.801) \cdot 10^{-2}$,
     where the error is dominated by $K_{e4}^{00}$
   - $\chi$PT calculations $O(p^2, p^4, p^6)$ from Bijnens Colangelo Gasser (1994) using $K_{e4}^{+-}$ form factors from 1977 predicts:
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   - $\chi$PT calculations $O(p^2, p^4, p^6)$ from Bijnens Colangelo Gasser (1994) using $K_{e4}^{+-}$ form factors from 1977 predicts:
     $\text{BR}(K_{e4}^{00}) = (2.01 \pm 0.11) \cdot 10^{-5}$
Current experimental status of $K^{00}_{e4}$

1. Measurements done by other experiments
   - 37 events from three different experiments: $\text{BR} = (2.2 \pm 0.4) \cdot 10^{-5}$
   - 214 events from KEK E470: $\text{BR} = (2.29 \pm 0.34) \cdot 10^{-5}$
     - error dominated by systematics
   - No form factor determination so far, just a relation between partial rate and a constant form factor value: $\Gamma = 0.8 |V_{us} \cdot F|^{2} \cdot 10^{3} \text{s}^{-1}$

2. Theoretical predictions for BR
   - Isospin symmetry relates more precisely measured modes and predicts:
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     Considering the different mean lifetimes $\tau_{K^+}$, $\tau_{K^0_{L}}$, this results in:
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Michal Zamkovský on behalf of NA48/2 collaboration
Studies of the $K_{e4}$ decay at NA48/2
Current experimental status of $K_{e4}^{00}$

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1. Final state with one charged track and four photons from $\pi^0$’s pointing to the same vertex
2. Common selection for signal $K_{e4}^{00}$ and normalization $K_{3\pi}^{00}$
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4. Particle ID against background
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Studies of the $K_{e4}$ decay at NA48/2
Fit performed in 2D plane \((S_\pi, S_e)\) after background subtraction

The event density in the Dalitz plot is proportional to the S-wave axial vector form factor \(F_s^2\)

Fitting ten equal population bins for \(S_\pi\) above \(4m_{\pi^+}^2\) and two bins below

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_Fitting procedure for \(K_{e4}^{00}\)_.

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Data – Bkg

Studies of the $K_{e4}$ decay at NA48/2
Fitting procedure for $K_{e4}^{00}$

1. $F_s = \left(1 + a q^2 + b q^4 + c \left(\frac{S_e}{4 m_{\pi^+}^2}\right)\right)$ \quad $q^2 \geq 0$

2. $F_s = \left(1 + d \sqrt{|q^2/(1 + q^2)|} + c \left(\frac{S_e}{4 m_{\pi^+}^2}\right)\right)$ \quad $q^2 < 0$

3. Cusp singularity at $q^2 = (S_\pi/4 m_{\pi^+}^2 - 1) = 0$

4. Comparison of $K_{e4}^{+-}$ and $K_{e4}^{00}$ modes

Michal Zamkovský on behalf of NA48/2 collaboration

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$\left( \frac{F_s}{f_s} \right)^2 / N$

$q^2$

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Fit results for $K_{e4}^{00}$

- $a = 0.149 \pm 0.033$
- $b = -0.070 \pm 0.039$
- $c = 0.113 \pm 0.022$
- $d = -0.256 \pm 0.049$
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\( \pi^- \pi^- re-scattering \)

1. \((K^+ \rightarrow \pi^0 \pi^0 l^\pm \nu)\) decay amplitude: \(\mathcal{M} = \mathcal{M}_0 + \mathcal{M}_1\)

2. The unperturbed amplitude \(\mathcal{M}_0\) corresponds to the tree level:

\[
\mathcal{M}_0 = f_{s0} \left( 1 + a q^2 + b q^4 + c \frac{S_e}{4m_{\pi^+}^2} \right)
\]

3. One loop contribution through \(\pi^+ \pi^- \rightarrow \pi^0 \pi^0\) charge exchange \(\mathcal{M}_1\):
   - conserved isospin symmetry \((m_{\pi^+} = m_{\pi^0})\):
     \[
     \mathcal{M}_1 = -2 a_0^0 - a_2^0 f_s \sqrt{|q^2| \left( 1 + q^2 \right)} \quad q^2 = \frac{S_\pi - 4m_{\pi^+}^2}{4m_{\pi^+}^2}
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Michal Zamkovský on behalf of NA48/2 collaboration  
Studies of the KE4 decay at NA48/2
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Studies of the \( K_{e4} \) decay at NA48/2
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Studies of the \( K_{e4} \) decay at NA48/2
The amplitude $M_1$ changes from real to imaginary at $2m_{\pi^+}$ with the consequence that $M_1$ interferes destructively with $M_0$ in the region below $2m_{\pi^+}$ threshold, while it adds quadratically above it:

$$|M|^2 = |M_0 + iM_1|^2 = |M_0|^2 + |M_1|^2,$$
above threshold

$$|M|^2 = |M_0 + M_1|^2 = |M_0|^2 + |M_1|^2 + 2|M_0||M_1|,$$
below threshold
Related measurements on NA48 experiment

Isospin correction - χPT approach
Colangelo Gasser Rusetsky
EPJ C59, 777(2009)

\[ \delta = \frac{1}{32\pi F^2} \left\{ (4\Delta_\pi + s)\sigma + (s - M_{\pi^0}^2) \left( 1 + \frac{3}{2R} \right) \sigma_0 \right\} - \delta_1 + O(p^4) \]

where

\[ \Delta_\pi = M_{\pi^+}^2 - M_{\pi^0}^2, \quad \sigma = \sqrt{1 - \frac{4M_\pi}{s}}, \quad R = \frac{m_s - \tilde{m}}{m_d - m_u} \]
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Studies of the $K_{e4}$ decay at NA48/2

Michal Zamkovský on behalf of NA48/2 collaboration
Branching ratio measurement:

\[
\text{BR} \left( K_{e4}^0 \right) = \frac{N \left( K_{e4}^0 \right)}{N \left( K_{3\pi}^0 \right)} \cdot \frac{A \left( K_{3\pi}^0 \right)}{A \left( K_{e4}^0 \right)} \cdot \frac{\epsilon \left( K_{3\pi}^0 \right)}{\epsilon \left( K_{e4}^0 \right)} \cdot \text{BR} \left( K_{3\pi}^0 \right)
\]

Result:

\[
\text{BR} \left( K_{e4}^0 \right) = (2.552 \pm 0.010_{\text{stat}} \pm 0.010_{\text{syst}} \pm 0.032_{\text{ext}}) \times 10^{-5}
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\[
\text{BR} \left( K_{3\pi}^0 \right) = (1.761 \pm 0.022) \times 10^{-2}
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<thead>
<tr>
<th>Source</th>
<th>(\delta\text{BR}/\text{BR} \times 10^2)</th>
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<tr>
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</table>
Sample of 65000 $K^{00}_{e4}$ reconstructed events has been studied (JHEP 08 (2014) 159)

- First measurement of form factor $F_s$ parametrized by described $a, b, c, d$ constants obtained from the fit in $(S_\pi, S_e)$ plane
- Significantly improved precision of BR measurement
- Observation of the cusp singularity which can be related to $\pi - \pi$ scattering - consistent with $a_0^0, a_2^0$ values measured in $K^{\pm-}_{e4}$ mode

Prospects

- NA62 is starting data taking (see Augusto Ceccucci talk in plenary session)
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Thank you for the attention!

Michal Zamkovský on behalf of NA48/2 collaboration