First $\pi K$ atom lifetime measurement and recent results from the DIRAC experiment

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Kraków, MESON 2014
The DIRAC Collaboration

- **1998–2003** Lifetime measurement of $\pi^+\pi^-$-atoms ($A_{2\pi}$)
- **2007–2012** Search for and lifetime measurement of $\pi^\pm K^\mp$-atoms ($A_{\pi K}$)

68 physicists from Czechia, Italy, Japan, Romania, Russia, Spain and Switzerland

Use double-arm spectrometer at CERN Proton Syncrotron (24 GeV/c)
Contents

1. $\pi^\pm K^\mp$ atoms
   - Theory and experimental method
   - The DIRAC spectrometer
   - First evidence and lifetime measurement of $\pi^\pm K^\mp$ atoms

2. Further work
   - Better precision for $\pi K$ scattering lengths
   - Progress in pionium lifetime measurement
   - Long-lived $\pi^+\pi^-$ atoms

3. Results and Outlook
\( \pi K \) atoms lifetime

Hydrogen-like atoms, formed by \( \pi \) and \( K \) mesons, \( a_B = 249 \) fm, \( p_B = 0.79 \) MeV/c

**Lifetime** is limited by charge-exchange process

\[
\pi^+ K^- \rightarrow \pi^0 \bar{K}^0 \quad \text{or} \quad \pi^- K^+ \rightarrow \pi^0 K^0
\]

\[
\frac{1}{\tau} = \frac{8}{9} \alpha^3 \mu^2 p \left( a_0^{1/2} - a_0^{3/2} \right)^2 (1 + \delta_K)
\]


**SU(3) ChPT predictions** [J. Bijnens et al. JHEP 0405 (2004) 036]:

\[
M_\pi a_0^- = M_\pi \frac{1}{3} \left( a_0^{1/2} - a_0^{3/2} \right) = \\
= 0.071 \ (CA) \rightarrow 0.0793 \ (1l) \rightarrow 0.089 \ (2l) \rightarrow 0.090 \pm 0.005 \ \text{(dis)}
\]


\[
M_\pi a_0^- = 0.090 \pm 0.005, \quad \delta_K = 0.040 \pm 0.022 \quad \Rightarrow \quad \tau = (3.5 \pm 0.4) \cdot 10^{-15} \ \text{s}
\]

**Lattice calculations**

[NPLQCD, Phys. Rev. D74 (2006) 114503] \( M_\pi a_0^- = 0.077 \pm 0.001^{+0.002}_{-0.005} \)

[Z. Fu, Phys. Rev. D85 (2012) 074501] \( M_\pi a_0^- = 0.0777 \pm 0.0013 \pm \)?

[PACS-CS, Phys. Rev. D89 (2014) 054502] \( M_\pi a_0^- = 0.081 \pm 0.006 \pm 0.012 \)
Experimental way to observe $\pi K$ atoms

- **Annihilation:** $A_{\pi K} \rightarrow \pi^0 K^0$ or $\pi^0 \bar{K}^0$

  $$\lambda_{\text{anh}} = \beta \gamma \tau \approx 20 \mu m \text{ at } \gamma \approx 20$$

Interaction of $A_{\pi K}$ with target atoms


- Excitation/de-excitation of $A_{\pi K}$

  $$\lambda_{\text{int}}^{1S} \approx 50 \mu m \text{ in Ni}$$

- $A_{\pi K}$ ionization $\Rightarrow$ characteristic “atomic” pairs $\pi^\pm K^\mp$ ($n_A$):

  $$q_{\text{CMS}} < 3 \text{ MeV}/c \Rightarrow \text{ in laboratory frame} \begin{bmatrix} E_+ \approx E_- \\ \Theta < 3 \text{ mrad} \end{bmatrix}$$

- Unique $P_{\text{ion}} = \frac{n_A}{N_A} = P_{\text{ion}}(\tau)$ relation
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- **Unique** $P_{\text{ion}} = \frac{n_A}{N_A} = P_{\text{ion}}(\tau)$ relation
$P_{\text{ion}} = P_{\text{ion}}(\tau)$

$A_{\pi K}$ propagation in matter: annihilation/ionisation/excitation

- Total/excitation cross-sections in Born approximation
- Glauber approximation + ionization cross-sections
- Multiphoton exchange
- Density matrix formulas
- Direct calculation of $P_{\text{ion}}(\tau)$
$A_{\pi K}$ generation

$p + \text{Ni} \rightarrow \ldots$ at 24 GeV/c

- **Atoms** are generated in $nS$-states

  \[ |\Psi_{nS}(0)|^2 \propto \frac{1}{n^3} : \]
  - $1S$: 83%, $2S$: 10%, ...

Other sources of inclusive $\pi^\pm K^\mp$-pairs:

- **Coulomb pairs**
  \[ N_A = kN_C(q < q_0) \]
  \[ A_C(q) = \frac{4\pi \mu_{\pi K} \alpha/q}{1 - \exp(-4\pi \mu_{\pi K} \alpha/q)} \]

- **Non-correlated pairs**

  \[ P_{\text{ion}} = \frac{n_A}{N_A} = \frac{n_A}{kN_C} \]
  \[ \Rightarrow P_{\text{ion}} = P_{\text{ion}}(\tau) \]
The DIRAC spectrometer

Resolution in momentum

Momentum range

Rel. momentum resolution in c.m.s.

\[ \frac{\sigma_p}{p} \approx 3 \cdot 10^{-3} \]

\[ p_\pi \in [1.2, 2.5] \text{ GeV/c} \]

\[ p_K \in [4.0, 8.9] \text{ GeV/c} \]

\[ \sigma_{Q_x} \approx \sigma_{Q_y} \approx 0.2 \text{ MeV/c} \]

\[ \sigma_{Q_L} \approx 0.85 \text{ MeV/c} \]
First evidence for $\pi^\pm K^\mp$ atoms

Thin Pt target 28µm, 2007:

\[ n_A(\pi^- K^+) = 143 \pm 53, \quad n_A(\pi^+ K^-) = 29 \pm 15 \]

Evidence for $\pi K$-atoms observation with DIRAC

\[ n_A(\pi^- K^+ + \pi^+ K^-) = 173 \pm 54 \]
\[ N_A(\pi^- K^+ + \pi^+ K^-) = kN_C = 280 \pm 70 \]
\[ \tau > 0.8 \cdot 10^{-15} \text{s (CL=0.9)} \]
Lifetime measurement of $\pi^{\pm}K^{\mp}$ atoms

Ni targets 98 $\mu$m and 108 $\mu$m, 2008–2010
Two-dimensional $(Q_T, Q_L)$ fit of experimental data:

$\pi^- K^+$

$\pi^+ K^-$

$N_A = 465 \pm 37.$

$n_A = 96 \pm 41.$

$P_{Br} = 0.207 \pm 0.101$

$N_A = 188 \pm 21.$

$n_A = 82 \pm 26.$

$P_{Br} = 0.44 \pm 0.18$
Lifetime measurement of $\pi^\pm K^\mp$ atoms

<table>
<thead>
<tr>
<th>Year</th>
<th>$N_A$</th>
<th>$n_A$</th>
<th>$P_{br}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\pi^- K^+$ over $Q_T, Q_L$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>132 ± 16</td>
<td>14 ± 19</td>
<td>0.11 ± 0.15</td>
</tr>
<tr>
<td>2009</td>
<td>169 ± 24</td>
<td>33 ± 26</td>
<td>0.20 ± 0.17</td>
</tr>
<tr>
<td>2010</td>
<td>164 ± 23</td>
<td>49 ± 26</td>
<td>0.30 ± 0.19</td>
</tr>
<tr>
<td>All</td>
<td>465 ± 37</td>
<td>96 ± 41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\pi^+ K^-$ over $Q_T, Q_L$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>51 ± 11</td>
<td>21 ± 13</td>
<td>0.41 ± 0.33</td>
</tr>
<tr>
<td>2009</td>
<td>78 ± 13</td>
<td>26 ± 16</td>
<td>0.34 ± 0.24</td>
</tr>
<tr>
<td>2010</td>
<td>60 ± 12</td>
<td>35 ± 16</td>
<td>0.58 ± 0.36</td>
</tr>
<tr>
<td>All</td>
<td>188 ± 21</td>
<td>82 ± 26</td>
<td></td>
</tr>
</tbody>
</table>

$n_A(\pi^- K^+ + \pi^+ K^-) = 178 \pm 49$

$$\tau = \left( 2.5 \pm 3.0 \atop -1.8 \right) \cdot 10^{-15} \text{s} \left( 2.5 \pm 3.0 \atop -1.8 \right) \text{fs}$$

πK scattering lengths

\[ \frac{1}{\tau} = \frac{8}{9} \alpha^3 \mu^2 p (a_{1/2} - a_{3/2})^2 (1 + \delta_K) \]

\[ |a_0^-| m_\pi = \frac{1}{3} |a_{1/2} - a_{3/2}| m_\pi = 0.11^{+0.09}_{-0.04}. \]

$\pi K$ scattering lengths: experimental results

Inelastic $Kp$ or $Kn$-scattering with $\pi K$ in a final state:

<table>
<thead>
<tr>
<th>$a_{1/2}m_{\pi}$</th>
<th>$a_{3/2}m_{\pi}$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.237</td>
<td>$-0.074$</td>
<td>[Nuovo Cimento 41A (1977) 73]</td>
</tr>
<tr>
<td>0.240 ± 0.002</td>
<td>$-0.05 \pm 0.06$</td>
<td>[Nuovo Cimento 43A (1978) 376]</td>
</tr>
<tr>
<td>0.13 ± 0.09</td>
<td>$-0.13 \pm 0.03$</td>
<td>[J.Phys.G6 (1980) 583]</td>
</tr>
</tbody>
</table>

$$|a_0^-|m_{\pi} = \frac{1}{3}|a_{1/2} - a_{3/2}|m_{\pi} = 0.11^{+0.09}_{-0.04} \quad [\text{DIRAC, arXiv:1403.0845}]$$
Work towards better precision in $A_{\pi K}$ lifetime measurement

$$|a_0^-| m_\pi = 0.11^{+0.09}_{-0.04}.$$  

- to include events with high background in forward detectors ($\sim 1/3$ of statistics)
- Combination of Pt and Ni measurements
  Pt: $\tau > 0.8 \cdot 10^{-15}$s (CL=0.9)
  Ni: $\tau = \left( 2.5 \pm 3.0 \right) \cdot 10^{-15}$s
### Progress in pionium lifetime measurement

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$n_A$ stat. error</td>
<td>6530 ± 294</td>
<td>21277 ± 407</td>
<td>&gt;22000</td>
</tr>
<tr>
<td>$\tau$, $10^{-15}$ s stat. error, $10^{-15}$ s</td>
<td>2.91 ± 0.45 − 0.38</td>
<td>3.15 ± 0.20 − 0.19</td>
<td></td>
</tr>
<tr>
<td>$\tau$, $10^{-15}$ s syst. error, $10^{-15}$ s</td>
<td>+0.19</td>
<td>+0.20 *</td>
<td></td>
</tr>
<tr>
<td>$\tau$, $10^{-15}$ s tot. error, $10^{-15}$ s</td>
<td>−0.49</td>
<td>−0.18</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>a_0^0 - a_0^2</td>
<td>$, $m_{\pi^+}^{-1}$</td>
<td>0.264</td>
</tr>
<tr>
<td>$</td>
<td>a_0^0 - a_0^2</td>
<td>$, $m_{\pi^+}^{-1}$ tot. error</td>
<td>+0.033</td>
</tr>
</tbody>
</table>


* Systematic uncertainty is dominated by multiple scattering in the target and in forward detectors — we have performed a direct measurement of scattering in them.
Experimental results on \((a_0, a_2)\)

- **\(K_{e4}\) decay** \((K^\pm \to \pi^+\pi^- e^{\pm} \nu_e)\)
  
  \[
  a_0 = 0.233 \pm 0.016 \pm 0.007 \text{(syst)}
  \]
  
  \[
  a_2 = -0.0471 \pm 0.011 \pm 0.004 \text{(syst)}
  \]
  

- **Cusp-effect** \((K^\pm \to \pi^\pm \pi^0 \pi^0)\)
  
  \[
  a_0 - a_2 = 0.2571 \pm 0.0048 \text{(stat)} \pm 0.0029 \text{(syst)} \pm 0.0088 \text{(theor)}
  \]
  
  [NA48/2, EPJ C64 (2009) 589]

- **\(\pi^+\pi^-\) atoms**
  
  \[
  |a_0 - a_2| = 0.2533 \pm 0.0078 \pm 0.0072 \]
  

- **\(K_{e4} \& K \to 3\pi\)**
  
  \[
  a_0 - a_2 = 0.2639 \pm 0.0020 \text{(stat)} \pm 0.0015 \text{(syst)}
  \]
  
  [NA48/2, EPJ C70 (2010) 635]

- **ChPT**
  
  \[
  a_0 = 0.220 \pm 0.005, \ a_2 = -0.0444 \pm 0.0010
  \]
  

We expect progress both by experiments and in theory

[see Peter Stoffer, MESON 2014]
Experimental results on $(a_0, a_2)$

- $K_{e4}$ decay ($K^\pm \rightarrow \pi^+\pi^-e^\pm\nu_e$)
  
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  a_2 = -0.0471 \pm 0.011 \pm 0.004\text{(syst)}
  \]

- Cusp-effect $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$
  
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  [NA48/2, EPJ C64 (2009) 589]

- $\pi^+\pi^-$ atoms
  
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- $K_{e4}$ & $K \rightarrow 3\pi$
  
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  [NA48/2, EPJ C70 (2010) 635]

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  a_0 = 0.220 \pm 0.005, \quad a_2 = -0.0444 \pm 0.0010
  \]

We expect progress both by experiments and in theory
[see Peter Stoffer, MESON 2014]
Method to observe long-lived $\pi^+\pi^-$ atoms

The observation of long-lived states of $\pi^+\pi^-$ atoms opens the possibility to measure the energy difference between $ns$ and $np$ states $\Delta E^{(ns-np)}$ and the value of $\pi\pi$ scattering lengths $|2a_0 + a_2|$.

for $\gamma = 17$:
- $l(1s) = 0.02$ mm
- $l(2s) = 0.14$ mm
- $l(2p) = 5.7$ cm
- $l(3s) = 0.46$ mm
- $l(3p) = 19$ cm

Kink in $Q_y$ for all charged pairs, but not for neutral atoms.
The ratio of yields at the proton momentum 450 GeV/c and angle 4° (CERN SPS) to the yields at the proton momentum 24 GeV/c and angle 5.7° (CERN PS):

<table>
<thead>
<tr>
<th></th>
<th>35</th>
<th>27</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\pi^+ K^-}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{K^+ \pi^-}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{2\pi}$</td>
<td></td>
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</table>
Evidence for $\pi^\pm K^\mp$ atoms on Pt and Ni targets

Pt: $n_A = 173 \pm 54$,  Ni: $n_A = 178 \pm 49$

First measurement of $A_{\pi K}$ lifetime

$$\tau = (2.5^{+3.0}_{-1.8})_{\text{tot}} \text{ fs}$$

Main tasks for DIRAC:
- Analysis of Pt and Ni data to achieve $A_{\pi K}$ observation
- Improve precision in pionium lifetime measurement
- Observation of long-lived states of $\pi^+\pi^-$ atoms
- Looking forward higher beam momenta (SPS 450 GeV/$c$)
Further work

Results and Outlook

\[ (a_0^0, a_0^2) \pi \pi \text{ scattering lengths} \]

ChPT:

\[ O(p^2): F_\pi, m_\pi \]

\[ O(p^4): l_1, l_2, l_3, l_4 \]
Quark condensate in ChPT

\[ M_\pi^2 = (m_u + m_d) \lim_{m_u,m_d \to 0} \frac{|\langle 0 | \bar{u}u | 0 \rangle|}{F_\pi^2} + O(m_q^2) = M^2 + O(m_q^2) \]

[M. Gell-Mann, R.G. Oakes, B. Renner, Phys. Rev. 175 (1968) 2195]

\[ M_\pi^2 = M^2 - \frac{\bar{I}_3}{32\pi^2 F^2} M^4 + O(M^6) \]