Last results of DIRAC experiment on study hadronic hydrogen-like atoms at PS CERN

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on behalf of the DIRAC collaboration

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totally 68 physicists from 20 Institutes
$K\pi$-atom $(A_{K\pi})$ is a hydrogen-like atom consisting of $K^\pm$ and $\pi^\mp$ mesons:

$E_B = -2.9 \text{ keV} \quad r_B = 249 \text{ fm} \quad p_B = 0.79 \text{ MeV}$

The $K\pi$-atom lifetime ground state $1S$, $\tau = 1/\Gamma$ is dominated by the annihilation process into $K^0\pi^0$:

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

\begin{align*}
A_{K^+\pi^-} &\rightarrow \pi^0 K^0 \\
A_{\pi^+ K^-} &\rightarrow \pi^0 \overline{K}^0 \\
\mu &\equiv 109 \text{ MeV}/c^2 \\
p^* &\equiv 11.8 \text{ MeV}/c \\
\delta_K &\equiv 0.040 \pm 0.022
\end{align*}


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

\[ \frac{1}{3} M_\pi \left( a_{1/2} - a_{1/3} \right) = M_\pi a_0^- = 0.071 (CA) \rightarrow 0.079 (1l) \rightarrow 0.89 (2l) \]  
\[ \rightarrow 0.090 \pm 0.005 \text{(dispersion)} \rightarrow \tau \]

\[ = \left( 3.5 \pm 0.4 \right) \times 10^{-15} \text{s} \]

Lattice QCD calculations of ChPT low energy constant


\[ M_\pi a_0^- = 0.077 \pm 0.001 \pm 0.002 \]
\[ M_\pi a_0^- = 0.0777 \pm 0.0013 \pm ? \]
\[ M_\pi a_0^- = 0.0811 \pm 0.0143 \]
What new will be known if $\pi K$ scattering length will be measured?

The measurement of the $s$-wave $\pi K$ scattering lengths would test our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD ($u, d$ and $s$ quarks), while the measurement of $\pi\pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking ($u, d$ quarks).

This is the principal difference between $\pi\pi$ and $\pi K$ scattering!

Experimental data on the $\pi K$ low-energy phases are absent
For the charged pairs from the short-lived sources and small relative momentum $Q$ there is strong Coulomb interaction in the final state. This interaction increases the production yield of the free pairs with $Q$ decreasing and creates atoms.

There is precise ratio between the number of produced Coulomb pairs ($N_C$) with small $Q$ and the number of atoms ($N_A$) produced simultaneously with these Coulomb pairs:

$$N_A = K(Q_0)N_C(Q \leq Q_0), \quad \frac{\delta K(Q_0)}{K(Q_0)} \leq 10^{-2}$$

$n_A$ - atomic pairs number, $P_{br} = \frac{n_A}{N_A}$
Method of $K\pi$ atom observation and investigation

Target Ni 98 µm

Atomic pairs
- $K^+ (K^-)$
- $\pi^- (\pi^+)$

Coulomb pairs
- $K^+ (K^-)$
- $\pi^- (\pi^+)$
- $\pi$
- $K^- (K^+)$
- $\pi^- (\pi^+)$

Non-Coulomb pairs
- $K^+ (K^-)$
- $\pi^- (\pi^+)$
- $\pi^+ (\pi^-)$
- $\pi^0$

Accidental pairs
- $K^+ (K^-)$
- $\pi^- (\pi^+)$
During propagation in matter $A_{\pi K}$:

- **annihilate**
- **break up (ionized)**
- **excitate**

Solution of the transport equations for atomic level populations provides one-to-one dependence of the measured break-up probability ($P_{br}$) on atom lifetime $\tau$.

Accuracy of $P_{br}$ is better than $10^8 \mu$m Ni.
1 Target station with Ni foil; 2 First shielding; 3 Micro Drift Chambers; 4 Scintillating Fiber Detector; 5 Ionization Hodoscope; 6 Second Shielding; 7 Vacuum Tube; 8 Spectrometer Magnet; 9 Vacuum Chamber; 10 Drift Chambers; 11 Vertical Hodoscope; 12 Horizontal Hodoscope; 13 Aerogel Čerenkov; 14 Heavy Gas Čerenkov; 15 Nitrogen Čerenkov; 16 Preshower; 17 Muon Detector
## Experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>SFD</th>
<th>DC</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinate precision</td>
<td>$\sigma_X = 60 , \mu m$</td>
<td>$\sigma = 85 , \mu m$</td>
<td>$\sigma = 100 , ps$</td>
</tr>
<tr>
<td>Time precision</td>
<td>$\sigma^t_X = 380 , ps$</td>
<td>$\sigma^t = 380 , ps$</td>
<td>$\sigma^t = 512 , ps$</td>
</tr>
<tr>
<td></td>
<td>$\sigma^t_Y = 512 , ps$</td>
<td></td>
<td>$\sigma^t_W = 522 , ps$</td>
</tr>
<tr>
<td></td>
<td>$\sigma^t_W = 522 , ps$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectrometer</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Relative resolution on the particle momentum in L.S.</td>
<td>$3 \cdot 10^{-3}$</td>
<td>$\sigma_{QL} = 0.5 , MeV/c (\pi\pi)$</td>
<td>$\sigma_{QL} = 0.9 , MeV/c (\pi K)$</td>
</tr>
<tr>
<td>Precision on Q-projections</td>
<td>$\sigma_{QX} = \sigma_{QY} = 0.5 , MeV/c$</td>
<td>$\sigma_{QL} = 0.5 , MeV/c (\pi\pi)$</td>
<td>$\sigma_{QL} = 0.9 , MeV/c (\pi K)$</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>98%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>for pairs with</td>
<td>$Q_L &lt; 28 , MeV/c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_X &lt; 6 , MeV/c$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_Y &lt; 4 , MeV/c$</td>
<td></td>
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</tbody>
</table>
2007, Platinum target 28µm:

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

Evidence for \( \pi K \) -atoms observation with DIRAC


\[ n_A(\pi^+ K^- + \pi^- K^+) = 173 \pm 54 \ (3.2\sigma) \]

\[ N_A(\pi^+ K^- + \pi^- K^+) = k N_c = 280 \pm 70 \]

\[ \tau > 0.8 \times 10^{-15} \text{s} \ (\text{CL}=0.9) \]
Run 2008-2010, statistics with low and medium background (2/3 of all statistics)
100 µm Nickel target

\( \pi^+ K^- \), \( Q_T < 4 \text{ MeV/c} \)

\( K^+ \pi^- \) atoms, \( |Q_L| \) distribution analysis on \( |Q_L| \) and \( Q_T \) for \( Q_T < 4 \text{ MeV/c} \)

\( K^- \pi^+ \) atoms, \( |Q_L| \) distribution analysis on \( |Q_L| \) and \( Q_T \) for \( Q_T < 4 \text{ MeV/c} \)
### $K^+\pi^-$ and $K^-\pi^+$ pairs analysis

<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>(132±16)</td>
<td>(14±19)</td>
<td>0.11±0.15</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></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>
</tbody>
</table>

### $K^-\pi^+$

<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>(51±11)</td>
<td>(21±13)</td>
<td>0.41±0.33</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></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>

$n_A(\pi^+K^- + \pi^-K^+) = 178 \pm 49 \ (3.6\sigma)$

\[ \tau = (2.5^{+3.0}_{-1.8}\ \text{stat}^{+0.3}_{-0.1}\ \text{syst}) \times 10^{-15}\ s = (2.5^{+3.0}_{-1.8}\ \text{tot}) \text{ fs} \]

The first measurements of $K\pi$ atom lifetime and $K\pi$ scattering lengths

Basing on $178\pm49$ detected atomic pairs and $653\pm42$ produced atoms we get the first results.

The first measurements of $K\pi$ atom lifetime!
\[ \tau^{\text{th}} = (3.5 \pm 0.4) \times 10^{-15} \text{s} \]
\[ \tau^{\text{exp}} = (2.5^{+3.0}_{-1.8}) \times 10^{-15} \text{s} \]

The first measurements of $K\pi$ scattering lengths!
\[ \frac{1}{3} |a_{1/2} - a_{3/2}|^{\text{exp}} = 0.107^{+0.09}_{-0.04} \]
\[ \frac{1}{3} |a_{1/2} - a_{3/2}|^{\text{th}} = 0.09 \pm 0.005 \]
During 2011-2012 the data were collected for observation of the long-lived states of $\pi^+\pi^-$ atom. This observation opens the future possibility to measure the energy difference between $ns$ and $np$ states $\Delta E(ns-np)$ and the value of $\pi\pi$ scattering length combination $|2a_0+a_2|$. 

Horizontal Magnetic field

Foil of 2 µm Platinum

Target of 100 µm Beryllium

proton

proton

long-live $A_{2\pi}$

100mm

for atomic pairs produced in the target $Q_x \approx 0$ MeV/c, $Q_y \approx 12.8$ MeV/c, $Q_L \approx 0$ MeV/c

for atomic pairs from long-lived atoms $Q_x \approx 0$ MeV/c, $Q_y \approx 2.3$ MeV/c, $Q_L \approx 0$ MeV/c

$A_{2\pi}$ breakup point
Distribution of $\pi^+\pi^-$ pairs over longitudinal component of relative momentum $Q_L$ with polynomial-fitted background. Cut $Q_t = \sqrt{Q_x^2 + (Q_y - 2.5\text{MeV/c})^2} < 1.5\text{MeV/c}$

The peak at zero at the level of $5\sigma$ is expected to be originate form breakup of the long-lived $\pi^+\pi^-$ atoms inside the Platinum foil of 2 µm placed at 100mm behind the primary target.
In 2013 DIRAC setup has been dismantled from the experimental hall of PS CERN. All detectors are stored for using in the future experiment.

DIRAC collaboration is planning to continue investigation of $\pi^- K^+$, $\pi^+ K^-$ and $\pi^+ \pi^-$ atoms at SPS accelerator at CERN. The correspondent gains in production rates of these atoms at SPS relative to PS (450 GeV vs. 24 GeV) are 18, 24 and 12. This allows to increase significantly the collected data and to check the precise prediction of Low-Energy QCD at a higher accuracy. Now the collaboration is planning to submit the Letter of Intend for study $\pi K$ and $\pi^+ \pi^-$ atoms at SPS to SPSC CERN.
Results and Outlook

- 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)
Thank you for your attention!