LIFETIME MEASUREMENT OF $\pi^+ \pi^-$ AND $\pi^\pm K^\mp$ ATOMS TO TEST LOW-ENERGY QCD
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<th>Institution</th>
<th>Location</th>
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<tr>
<td>CERN</td>
<td>Geneva, Switzerland</td>
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<tr>
<td>Czech Technical University</td>
<td>Prague, Czech Republic</td>
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<tr>
<td>Institute of Physics ASCR</td>
<td>Prague, Czech Republic</td>
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<td>Nuclear Physics Institute ASCR</td>
<td>Rez, Czech Republic</td>
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<td>Bern University</td>
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<td>Zurich University</td>
<td>Zurich, Switzerland</td>
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</table>
• Introduction

• Results on the ππ atom lifetime measurement using data 2001-2003.

• Result of 2007 run: evidence for πK atoms.

• Results of 2008 run and plans for 2009

• Request of 2010 run for observation of the long-lived states of ππ atoms.
Main goals of DIRAC in 2005-2009 and beyond

• Lifetime measurement of $A_{2\pi}$ atoms with precision better than 6%, which gives a precision for $|a_0 - a_2|$ better than 3%.

• Observation of $A_{\pi K}$ and $A_{K\pi}$ atoms.

• The measurement of their lifetime and difference of $\pi K$ scattering lengths $|a_{1/2} - a_{3/2}|$ with accuracy about 10%.

• Observation of the long-lived states of $A_{2\pi}$, with prospect to measure the Lamb shift and of determining the value of $2a_0 + a_2$ in a model-independent way.
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!
Method of $A_{\pi K}$ and $A_{K\pi}$ observation
and lifetime measurement

$\tau(A_{\pi K})$ is too small to be measured directly
e. m. interaction of $A_{\pi K}$ in the target

$A_{\pi K} \rightarrow \pi^+ K^-$

$A_{K\pi} \rightarrow K^+ \pi^-$

$Q < 3\text{MeV/c}, \ p_K = \frac{m_K}{m_\pi} p_\pi, \Theta_{lab} < 3 \text{ mrad}$

- Coulomb from short-lived sources
- non-Coulomb from long-lived sources

Main features of the DIRAC set-up
Thin targets: $\sim 7 \times 10^{-3} X_0$, Nuclear efficiency: $3 \times 10^{-4}$
Magnetic spectrometer
Proton beam $\sim 10^{11}$ proton/spill
Resolution on $Q$: $Q_x \approx Q_y \approx 0.5 \text{MeV/c}$, $Q_L \approx 1.0 \text{MeV/c}$
DIRAC Experimental results

$A_{2\pi}$ lifetime

2005 DIRAC (PL B619, 50)  
$\tau = \left( \begin{array}{c} 2.91^{+0.45}_{-0.38} \\ \pm 0.19 \\ \pm 0.49 \end{array} \right) \text{fs} = \left( \begin{array}{c} \ldots^{+0.49}_{-0.62} \\ \pm 3\% \pm 13\% \end{array} \right) \text{fs}$  
...based on 2001 data (6530 observed atoms)

\[ \Rightarrow |a_0 - a_2| = 0.264 \pm 7.2\% \pm 10\% \text{stat} \pm 3\% \pm 8\% \text{syst} = \ldots \pm 13\% \text{tot} \]

2008 DIRAC (SPSC 22/04/08)  
$\tau = \left( \begin{array}{c} 2.82^{+0.25}_{-0.23} \\ \pm 0.19 \end{array} \right) \text{fs} = \left( \begin{array}{c} \ldots^{+0.31}_{-0.30} \\ \pm 3.7\% \pm 5.5\% \end{array} \right) \text{fs}$  
...major part 2001-03 data (13300 observed atoms)

\[ \Rightarrow |a_0 - a_2| = 0.268 \pm 4.4\% \pm 3.7\% \text{stat} \pm 3.7\% \pm 5.5\% \text{syst} = \ldots \pm 5.5\% \text{tot} \]

Including GEM/MicroStripGasChambers $\Rightarrow$ number of reconstructed events is 17000

$\Rightarrow$ the statistical error in $|a_0-a_2|$ is 3\%, and the expected full error is $<5\%$. 
DIRAC preliminary results with GEM/MSGC

$Q_L$ distribution

← All events distribution

← After background subtraction
DIRAC preliminary results with GEM/MSGC

$Q_T$ distribution

$Q_L < 2 \text{ MeV/c}$

$Q_L > 2 \text{ MeV/c}$

$\leftarrow$ After background subtraction for $Q_L < 2 \text{ MeV/c}$
Comparition with other experimental results

\(K \rightarrow 3\pi:\)

2006 NA48/2 (PL B633, 173) ...with ChPT constraint between \(a_0\) and \(a_2\):

\[
\Rightarrow a_0 - a_2 = 0.264 \pm 2.3\% \big|_{\text{stat}} \pm 1.5\% \big|_{\text{syst}} \pm 4.9\% \big|_{\text{ext}} = \ldots \pm 5.6\% \big|_{\text{tot}}
\]

2008 NA48/2 (Confinement8, Mainz) ...with ChPT constraint between \(a_0\) and \(a_2\):

\[
\Rightarrow a_0 - a_2 = 0.266 \pm 1.1\% \big|_{\text{stat}} \pm 0.8\% \big|_{\text{syst}} \pm 0.4\% \big|_{\text{ext}} \pm \ldots \% \big|_{\text{th}}
\]

\(Ke_4:\)

2008 NA48/2 (EPJ C54, 411)

\[
\Rightarrow a_0 = 0.233 \pm 6.9\% \big|_{\text{stat}} \pm 3.0\% \big|_{\text{syst}} = \ldots \pm 7.5\% \big|_{\text{tot}}
\]

\[
\Rightarrow a_2 = -0.0471 \pm 23\% \big|_{\text{stat}} \pm 8.5\% \big|_{\text{syst}}
\]
The numbers to the right of the tracks lines are the $\pi^-$ and $K^+$ momenta in GeV/c.

The $A_{K\pi}$, $\pi^-$ and $K^+$ momenta are shown in the following table:

<table>
<thead>
<tr>
<th>$P_{\text{atom}}$ (GeV/c)</th>
<th>$P_\pi$ (GeV/c)</th>
<th>$P_K$ (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.13</td>
<td>1.13</td>
<td>4.0</td>
</tr>
<tr>
<td>5.77</td>
<td>1.27</td>
<td>4.5</td>
</tr>
<tr>
<td>6.41</td>
<td>1.41</td>
<td>5.0</td>
</tr>
<tr>
<td>10.26</td>
<td>2.26</td>
<td>8.0</td>
</tr>
</tbody>
</table>
Upgraded DIRAC experimental setup

- Single and multilayer targets
- MDC, 18 planes
- Shield 1
- Shield 2
- SFD
- Vacuum
- Magnet
- Heavy gas Cherenkov
- Aerogel
- 1 meter
- Target T1
- Target T2
- \(\pi^+, K^+, p\)
- \(\pi^-, K^-, \bar{p}\)

**Modified parts**
Micro Drift Chambers

Main features:

- **High spatial accuracy** \( \sigma \leq 80 \ \mu m \);
- **Efficiency** > 98%
  at \( I = 2 \times 10^{11} \) protons/spill;
- **total detector thickness** < \( 5 \times 10^{-3} \ X_0 \);
- **time resolution** < 1 ns;
- **readout time** < 3 \( \mu s \).
Scintillation Fiber Detector

Sensitive area = 98.5 x 107 mm²

- Pitch btw columns = 0.205 mm
- Total thickness = 3.1 mm
- 480 columns of 8 SciFIs

Clear Fibres transmitting scintillation light from the 480 SciFi columns on to the photocathodes of 30 x 16 ch H6566
(Only two columns in each of 6 segments are shown.)

i = 1-16
i = 17-32
i = 33-48
i = 49-64
i = 65-80

SciFi Bundle
Al Mylar

Gluing of SciFIs to Clear fibres with Optical Epoxy

Segment No.
I II III IV V VI

Reflector
Scintillation Fiber Detector

**Characteristics:**
- Size of the plane: $100 \times 100 \text{ mm}^2$
- Thickness of the material for one plane: $3 \text{ mm} \ (1\% \ X_0)$
- Mean light output: $\approx 11 \text{ p.e.}$
- Mean Detector Efficiency: $\approx 98 \%$
- Time Resolution without coordinate and amplitude corrections: $\approx 0.46 \text{ ns}$
- Space resolution: $\sigma \approx 60 \mu \text{m}$
- New electronics: 
  - *(ADC-TDC for each channel)*
  - 960 channels
Aerogel Cherenkov detector

Responsibility:
Zurich University (Zurich, Switzerland)

The $n=1.008$ counter

Status:
Aerogel detectors were installed on the setup
Proton rejection efficiency for a cut in the ADC 20 channels above pedestal:

- 94.2 % for the heavy aerogel @ p = 4.5-5 GeV/c
- 89.3 % for the light aerogel @ p = 6-8 GeV/c

Kaon detection efficiency for the same cut:

- 95.6 % for the heavy aerogel @ p = 4.5-5 GeV/c
- 92.4 % for the light aerogel @ p = 6-8 GeV/c
Cherenkov detector quality factor $N_0 = 125 \text{ cm}^{-1}$

Efficiency to detect pions with momenta $>4\text{ GeV}$ is $>99.5\%$

$N_{p.e.} = LN_0\left(1 - \frac{1}{\beta^2 n^2}\right) = LN_0 \sin^2 \Theta_C$

$\langle n(C_4F_{10}) \rangle = 1.00135$

$N_{p.e.}(\beta = 1) \approx 30\text{ p.e.}$
All Cherenkov detectors
Improvement of the proton beam time structure and the beam intensity distribution at spills.

Beam intensity about $1.9 \times 10^{11}$ proton/spill

$1^{\text{st}}$ level triggers numbers

$3200(\pi^+\pi^-)+2100(K^+\pi^-)+1000(\pi^+K^-)=6300$ 1/spill

Number of recorded events 2000 per spill is near to the hardware limit of DAQ

Full number of $\pi^+\pi^-$ and $\pi K$ events recorded during 2 months of data taking is $1.6 \times 10^9$

Run 2006 was lost because of the broken magnets in the beam-line.

Run 2007
π−p mass & π+π− signal in 2007

Setup calibration with Λ decays

Observation of π⁺π⁻ atoms with the Platinum target
Coulomb correlation in $\pi^-K^+$ pairs

Total background contribution

nonCoulomb pairs and accidentals
In total:
173±54 πK-atomic pairs are observed with a significance of 3.2σ.

τ > 0.8 * 10^{-15} s at 90%CL

RUN 2008

- The upgraded DIRAC setup with the new front-end electronics, readout system and DAQ was fully tuned.
- Data taking for the lifetime measurement of $A_{2\pi}$, observation of $A_{K\pi}$ and $A_{\pi K}$ and their lifetime measurement have been performed during 2.5 months and $1.6 \times 10^9$ events was collected.
- The full set of events collected in 2008 was processed in so call preselection mode, which includes the full events reconstruction and some very safe cuts on the relative momentum of pairs. The background level at the reconstructed events is expected to be by factor 4 less in respect to 2007 data due to the vertices detectors implementation.
Run 2009 will increase the statistics of $A_{2\pi}$, $A_{\pi K}$ and $A_{K\pi}$ on factor 2.5. For that, after 3-4 weeks of tuning, we need 5-6 spill per supercycle (about 40 seconds) till the end of PS physics this year.
Energy Splitting between np - ns states in (\( \pi^+ - \pi^- \)) atom

\[
\Delta E_n \equiv E_{ns} - E_{np} \\
\Delta E_n \approx \Delta E_{n}^{\text{vac}} + \Delta E_{n}^{s} \\
\Delta E_{n}^{s} \approx 2a_0 + a_2
\]

For \( n = 2 \)

\[
\Delta E_{2}^{\text{vac}} = -0.107 \text{ eV} \quad \text{from QED calculations} \\
\Delta E_{2}^{s} \approx -0.45 \text{ eV} \quad \text{numerical estimated value from ChPT} \\
a_0 = 0.220 \pm 0.005 \\
a_2 = -0.0444 \pm 0.0010
\]

\( (2001) \) G. Colangelo, J. Gasser and H. Leutwyler

\( \Rightarrow \) \[
\Delta E_{2} \approx -0.56 \text{ eV}
\]

(1979) A. Karimkhodzhaev and R. Faustov
(1983) G. Austen and J. de Swart
(1986) G. Efimov et al.
(1999) A. Gashi et al.
(2000) D. Eiras and J. Soto
A. Rusetsky, priv. comm.
For $p_A = 5.6$ GeV/c and $\gamma = 20$

\[
\begin{align*}
\tau_{1s} &= 2.9 \times 10^{-15} \text{ s} , & \lambda_{1s} &= 1.7 \times 10^{-3} \text{ cm} \\
\tau_{2s} &= 2.3 \times 10^{-14} \text{ s} , & \lambda_{2s} &= 1.4 \times 10^{-2} \text{ cm} \\
\tau_{2p} &= 1.17 \times 10^{-11} \text{ s} , & \lambda_{2p} &= 7 \text{ cm} \\
\tau_{2p} &= 1.17 \times 10^{-11} \text{ s} , & \lambda_{3p} &\approx 23 \text{ cm} \\
\tau_{2p} &= 1.17 \times 10^{-11} \text{ s} , & \lambda_{4p} &\approx 54 \text{ cm}
\end{align*}
\]

Illustration for observation of the $A_{2\pi}$ long-lived states with breaking foil.
Metastable Atoms

Probabilities of the $A_{2\pi}$ breakup (Br) and yields of the long-lived states for different targets provided the maximum yield of summed population of the long-lived states: $\Sigma(l \geq 1)$

<table>
<thead>
<tr>
<th>Target Z</th>
<th>Thickness Mm</th>
<th>Br</th>
<th>$\Sigma (l \geq 1)$</th>
<th>$2p_0$</th>
<th>$3p_0$</th>
<th>$4p_0$</th>
<th>$\Sigma (l = 1, m = 0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>04</td>
<td>100</td>
<td>4.45%</td>
<td>5.86%</td>
<td>1.05%</td>
<td>0.46%</td>
<td>0.15%</td>
<td>1.90%</td>
</tr>
<tr>
<td>06</td>
<td>50</td>
<td>5.00%</td>
<td>6.92%</td>
<td>1.46%</td>
<td>0.51%</td>
<td>0.16%</td>
<td>2.52%</td>
</tr>
<tr>
<td>13</td>
<td>20</td>
<td>5.28%</td>
<td>7.84%</td>
<td>1.75%</td>
<td>0.57%</td>
<td>0.18%</td>
<td>2.63%</td>
</tr>
<tr>
<td>28</td>
<td>5</td>
<td>9.42%</td>
<td>9.69%</td>
<td>2.40%</td>
<td>0.58%</td>
<td>0.18%</td>
<td>3.29%</td>
</tr>
<tr>
<td>78</td>
<td>2</td>
<td>18.8%</td>
<td>10.5%</td>
<td>2.70%</td>
<td>0.54%</td>
<td>0.16%</td>
<td>3.53%</td>
</tr>
</tbody>
</table>
Yields of the long-lived states $2p$ ($m = 0$) as a function of the $A_{2\pi}$ lifetime for Beryllium targets ($Z = 04$). Target thicknesses are given in microns on the right side of the picture.
Observation of the long-lived states of $A_{2\pi}$ is opening a possibility to measure the Lamb shift and to determine the new combination of $\pi\pi$ scattering lengths $2a_0 + a_2$.

For this observation, which was planned in our addendum, we need the run in 2010 during around 5 months in the same conditions as in 2009.
Thank you for your attention
External magnetic and electric fields

Atoms in a beam are influenced by external magnetic field and the relativistic Lorentz factor

\[ \vec{r} \equiv \text{relative distance between } \pi^+ \text{ and } \pi^- \text{ mesons in } A_{2\pi} \text{ atom} \]

\[ \vec{B}_{\text{Lab}} \equiv \text{laboratory magnetic field} \]

\[ \vec{F} \equiv \text{electric field in the CM system of an } A_{2\pi} \text{ atom} \]

\[ F = \beta \gamma B_{\text{Lab}} \approx \gamma B_{\text{Lab}} \]
The dependence of $A_{2\pi}$ life time in $2p$-states $\tau_{\text{eff}}$ from a strength of the electric field $F$

\[ \tau_{\text{eff}} = \frac{\tau_{2p}}{1 + \frac{|\xi|^2}{4} \frac{\tau_{2p}}{\tau_{2s}}} = \frac{\tau_{2p}}{1 + 120 |\xi|^2} \]

where:

\[ |\xi|^2 \approx \frac{F^2}{(E_{2p} - E_{2s})^2} \]

\[
\begin{align*}
B_{\text{Lab}} &= 4 \text{ Tesla} \\
\begin{cases}
\gamma = 20 & , & |\xi| = 0.1 & \Rightarrow & \tau_{\text{eff}} = \frac{\tau_{2p}}{2.2} \\
\gamma = 40 & , & |\xi| = 0.2 & \Rightarrow & \tau_{\text{eff}} = \frac{\tau_{2p}}{6}
\end{cases}
\end{align*}
\]
Yield of dimeson atoms per one proton-Ni interaction, detectable by DIRAC upgrade setup at $\Theta_L=5.7^\circ$

<table>
<thead>
<tr>
<th></th>
<th>$E_p$</th>
<th>$W_A$</th>
<th>$W_A^N$</th>
<th>$W_A/W_\pi$</th>
<th>$W_A^N/W_\pi^N$</th>
<th>Total gain</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>yield</td>
<td>24 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{2\pi}$</td>
<td>$1.1\cdot10^{-9}$</td>
<td>$0.52\cdot10^{-10}$</td>
<td>$0.29\cdot10^{-10}$</td>
<td>$0.13\cdot10^{-7}$</td>
<td>$0.71\cdot10^{-9}$</td>
<td>$1.1$</td>
</tr>
<tr>
<td>$A_{K^+\pi^-}$</td>
<td>$0.52\cdot10^{-10}$</td>
<td>$0.29\cdot10^{-10}$</td>
<td>$0.13\cdot10^{-7}$</td>
<td>$0.71\cdot10^{-9}$</td>
<td>$0.52\cdot10^{-10}$</td>
<td>$1.1$</td>
</tr>
<tr>
<td>$A_{\pi^+K^-}$</td>
<td>$0.29\cdot10^{-10}$</td>
<td>$0.13\cdot10^{-7}$</td>
<td>$0.71\cdot10^{-9}$</td>
<td>$0.29\cdot10^{-10}$</td>
<td>$0.13\cdot10^{-7}$</td>
<td>$1.1$</td>
</tr>
<tr>
<td>$W_{A^N}$</td>
<td>$1$</td>
<td>$1$</td>
<td>$1$</td>
<td>$12$</td>
<td>$3.8$</td>
<td>$1$</td>
</tr>
<tr>
<td>$W_{A/W_\pi}$</td>
<td>$3.4\cdot10^{-8}$</td>
<td>$16\cdot10^{-10}$</td>
<td>$9\cdot10^{-10}$</td>
<td>$1.3\cdot10^{-7}$</td>
<td>$1.3\cdot10^{-7}$</td>
<td>$1$</td>
</tr>
<tr>
<td>$W_{A^N/W_\pi^N}$</td>
<td>$1$</td>
<td>$1$</td>
<td>$1$</td>
<td>$3.8$</td>
<td>$6.2$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

A multiplier due to different spill duration $\sim 4$

Total gain $1$ $1$ $1$ $15$ $25$ $32$
Present low-energy QCD predictions for $\pi\pi$ and $\pi K$ scattering lengths

$\pi\pi$  \[ \delta a_0 = 2.3\% \quad \delta a_2 = 2.3\% \quad \delta(a_0 - a_2) = 1.5\% \] will be improved by Lattice calculations

$\pi K$  \[ \delta(a_{1/2} - a_{3/2}) = 10\% \] will be significantly improved by ChPT calculations

Expected results of DIRAC ADDENDUM at PS CERN after 2008-2009

\[ \tau(A_{2\pi}) \rightarrow \delta(a_0 - a_2) = \pm 2\% (\text{stat}) \pm 1\% (\text{syst}) \pm 1\% (\text{theor}) \]

\[ \tau(A_{\pi K}) \rightarrow \delta(a_{1/2} - a_{3/2}) = \pm 10\% (\text{stat}) \pm \ldots \pm 1.5\% (\text{theor}) \]

2010-2011 Observation of metastable $\pi^+\pi^-$ atoms and estimation its Lamb shift

Study of the possibility to observe $K^+K^-$ and $\pi^\pm\mu^\mp$ atoms using 2008-2009 data.

DIRAC at SPS CERN beyond 2011

\[ \tau(A_{2\pi}) \rightarrow \delta(a_0 - a_2) = \pm 0.5\% (\text{stat}) \quad \tau(A_{\pi K}) \rightarrow \delta(a_{1/2} - a_{3/2}) = \pm 2.5\% (\text{stat}) \]

\[ (E_{np} - E_{ns})_{\pi\pi} \rightarrow \delta(2a_0 + a_2) \approx \pm 2.5\% (\text{stat}) \quad (E_{np} - E_{ns})_{\pi K} \rightarrow \delta(2a_{1/2} + a_{3/2}) \]

DIRAC at PS2 CERN beyond 2011 - under investigation
Aerogel Cherenkov detector I

Responsibility:
Zurich University (Zurich, Switzerland)
Examples of event

Status
During 2007 run Micro Drift Chambers with the new electrodes and all electronics were finally implemented into the DIRAC setup and DAQ system. Data with different MDC working condition were collected.

Online data 2007
Target: Pt (28µm)
Intensity: $2 \times 10^{11}$