LIFETIME MEASUREMENT OF $\pi^+\pi^-$ AND $\pi^\pm K^\mp$ ATOMS TO TEST LOW-ENERGY QCD
1. 2001-2003 data, processing and analysis using GEM/MSGC

2. Status of 2008 data on $\pi^+\pi^-$ and $K^+\pi^-/K^-\pi^+$ atoms

3. Status of 2009 data

4. Schedule of 2008 & 2009 data processing and analysis

5. Plan for the 2010 run

6. In autumn 2010: submission of the new ADDENDUM
   “Observation of LONG-LIVED $\pi^+\pi^-$ atoms”
DIRAC Collaboration

75 Physicists from 19 Institutes

- CERN, Geneva, Switzerland
- Czech Technical University, Prague, Czech Republic
- Institute of Physics ASCR, Prague, Czech Republic
- Nuclear Physics Institute ASCR, Rez, Czech Republic
- INFN-Laboratori Nazionali di Frascati, Frascati, Italy
- Trieste University and INFN-Trieste, Trieste, Italy
- University of Messina, Messina, Italy
- KEK, Tsukuba, Japan
- Kyoto Sangyou University, Kyoto, Japan
- Tokyo Metropolitan University, Tokyo, Japan
- IFIN-HH, Bucharest, Romania
- JINR, Dubna, Russia
- SINP of Moscow State University, Moscow, Russia
- IHEP, Protvino, Russia
- Santiago de Compostela University, Santiago de Compostela, Spain
- Bern University, Bern, Switzerland
- Zurich University, Zürich, Switzerland
DIRAC First Setup

target vacuum

SFD MSGC IH vacuum

magnet

DC VH HH

C PSh Mu

T1

positive 19º

1 m

T2 negative

absorber
DIRAC experimental results

$A_{2\pi}$ lifetime

2005 DIRAC (PL B619, 50)

\[
\tau = \left(2.91^{+0.45}_{-0.38}\right)_{\text{stat}} \pm 0.19_{\text{syst}} \text{fs} = \left(\ldots +0.49\right)_{\text{tot}} \text{fs}
\]

...based on 2001 data (6530 atomic pairs)

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

2008 DIRAC (SPSC 22/04/08)

\[
\tau = \left(2.82^{+0.25}_{-0.23}\right)_{\text{stat}} \pm 0.19_{\text{syst}} \text{fs} = \left(\ldots +0.31\right)_{\text{tot}} \text{fs}
\]

... part 2001-03 data (13300 atomic pairs)

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

Including GEM/MicroStripGasChambers => number of reconstructed atomic pairs is 20020

=> the statistical error in $|a_0-a_2|$ is 3.2%, and the full error will be <5%.
QL distribution

← All events

← After background subtraction:

\( n_A \sim 20020 \)
DIRAC results with GEM/MSGC

$Q_T$ distribution

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

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

$\leftarrow\text{After background subtraction for } Q_L<2\text{MeV/c: }$ $n_A \sim 20020$
QL for QT < 3 MeV/c

QL for QT < 4 MeV/c

QL for QT < 5 MeV/c
**Comparition with other experimental results**

**K→3π:**

2009 NA48/2 (EPJ C64, 589)

...without constraint between $a_0$ and $a_2$:

$$a_0 - a_2 = 0.2571 \pm 1.9\%_{\text{stat}} \pm 1.0\%_{\text{syst}} \pm 0.5\%_{\text{ext}} = \ldots \pm 2.2\%$$

and 3.4\% theory uncertainty

...with ChPT constraint between $a_0$ and $a_2$:

$$a_0 - a_2 = 0.2633 \pm 0.9\%_{\text{stat}} \pm 0.5\%_{\text{syst}} \pm 0.7\%_{\text{ext}} = \ldots \pm 1.3\%$$

and 2\% theory uncertainty

**K^e4:**

2009 NA48/2 (CD09, Bern)

...without constraint between $a_0$ and $a_2$:

$$a_0 = 0.2220 \pm 5.8\%_{\text{stat}} \pm 2.3\%_{\text{syst}} \pm 1.7\%_{\text{theo}} = \ldots \pm 6.4\%$$

$$a_2 = -0.0432 \pm 20\%_{\text{stat}} \pm 7.9\%_{\text{syst}} \pm 6.5\%_{\text{theo}} = \ldots \pm 22\%$$

...with ChPT constraint between $a_0$ and $a_2$:

$$a_0 = 0.2206 \pm 2.2\%_{\text{stat}} \pm 0.8\%_{\text{syst}} \pm 2.9\%_{\text{theo}} = \ldots \pm 3.7\%$$
Schedule for the 2001-2003 data process and analysis

1. Final values and evaluation of errors for the $\pi-\pi$ atoms breakup probabilities $W_{br}$: before the end of June 2010

2. Measurement of the $\pi-\pi$ atom life-time ($\tau$) using $W_{br}(\tau,p_A)$ averaged on the atom momentum $p_A$: before the end of July 2010

3. Final evaluation of the $\pi-\pi$ atom life-time measurement using $W_{br}(\tau,p_A)$ calculated for different atom momentum intervals: before the end of September 2010

4. Draft of the paper: before the middle of November 2010
Upgraded DIRAC experimental setup

2008 and 2009 data status

single and multilayer targets

MDC, 18 planes

SFD

IH

vacuum

shield1

shield2

magnet

heavy gas Cherenkov

aerogel

1 meter

T1

T2

π⁺, K⁺, p

π⁻, K⁻, p

Aerogel absorber

Ch

PSh

Mu

Modifided parts
Micro Drift Chambers II

The cell dimensions are:

- 2 mm along the beam direction
- 2.4 mm perpendicular to the beam direction.

Maximum drift time less than 30 ns.
Extrapolation to the target

The area where hits are expecting
Method of $A_{2\pi}$ observation and lifetime measurement

$\tau(A_{2\pi})$ is too small to be measured directly.

E. m. interaction of $A_{2\pi}$ in the target:

$A_{2\pi} \rightarrow \pi^+ \pi^-$

$Q < 3\text{MeV}/c$, $\Theta_{\text{lab}} < 3\text{ mrad}$

**Coulomb** from short-lived sources

$N_A = K(Q_0) N_C(Q<Q_0)$ with known $K(Q_0)$

Breakup probability: $P_{\text{br}} = n_A / N_A$

**non-Coulomb** from long-lived sources
Coulomb pairs and atoms

**Strong interaction**

\[
p \rightarrow \pi^+ \text{ (K+)}
\]

p

nucleus

\[
\pi^-
\]

*For small Q there are Coulomb pairs:*

\[
\pi\pi, \pi K \text{ C-pairs}
\]

\[
\pi\pi, \pi K \text{ atoms}
\]

*The yield strongly increases with Q decreasing.*
There is a precise (1%) ratio:

\[
\frac{d\sigma^A_{nm}}{dp} = (2\pi)^3 \frac{E}{M} |\psi^{(C)}_{nm}(0)|^2 \frac{d\sigma^0_s}{dp_1 dp_2} \propto \frac{d\sigma}{dp_1} \cdot \frac{d\sigma}{dp_2}
\]

for atoms \( \vec{v}_1 = \vec{v}_2 \) where \( \vec{v}_1, \vec{v}_2 \) = velocities of particles in the lab frame for all types of atoms

for \( A_{2\pi} \) production \( \vec{p}_1 = \vec{p}_2 \)

for \( A_{\pi K} \) production \( \vec{p}_\pi = \frac{m_\pi}{m_K} \vec{p}_K \)

Coulomb pairs can be constructed from experimental accidentals or from Monte Carlo.
$Q_L$ distributions from 2008 data

$Q_L$ distribution for $\pi^+\pi^-$ pairs from 2008 data

$Q_L$ distribution for $K^-\pi^+$ and $K^+\pi^-$ pairs from 2008 data
Q_L and Q_T distributions from 2007 data

Downstream tracking ONLY

QL distribution of K^+π^- pairs from 2007 data

QT distribution of K^+π^- pairs from 2007 data
### Predictions

#### Table 3: Predictions for $\pi K$ pairs of both signs with the Nickel target

<table>
<thead>
<tr>
<th>reconstruction efficiency</th>
<th>$N_A$</th>
<th>$n_A$</th>
<th>$n_A$/Error</th>
<th>$n_A$/Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>42%</td>
<td>255</td>
<td>79</td>
<td>3.06 ± 0.37</td>
<td>3.79 ± 0.46</td>
</tr>
<tr>
<td>63%</td>
<td>442</td>
<td>137</td>
<td>4.07 ± 0.49</td>
<td>5.15 ± 0.62</td>
</tr>
<tr>
<td>80%</td>
<td>561</td>
<td>174</td>
<td>4.54 ± 0.55</td>
<td>5.74 ± 0.70</td>
</tr>
</tbody>
</table>

#### Table 4: Prediction for $\pi K$ pairs of both signs with the Platinum target (2007) and Nickel target (2008+2009)

<table>
<thead>
<tr>
<th>reconstruction efficiency</th>
<th>$n_A$/Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>42%</td>
<td>3.82 ± 0.35</td>
</tr>
<tr>
<td>63%</td>
<td>4.67 ± 0.45</td>
</tr>
<tr>
<td>80%</td>
<td>5.08 ± 0.51</td>
</tr>
</tbody>
</table>
### Accuracy of $|a_{1/2} - a_{3/2}|$ measurement

<table>
<thead>
<tr>
<th>Accuracy of the measurement</th>
<th>5σ (20%)</th>
<th>6σ (17%)</th>
<th>6.5σ (15%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$ (s)</td>
<td>$(3.7 \pm 60% \pm 38%) \cdot 10^{-15}$</td>
<td>$(3.7 \pm 51% \pm 38%) \cdot 10^{-15}$</td>
<td>$(3.7 \pm 46% \pm 32%) \cdot 10^{-15}$</td>
</tr>
<tr>
<td>$\delta_{\text{average}}</td>
<td>a_{1/2} - a_{3/2}</td>
<td>$</td>
<td>26 %</td>
</tr>
</tbody>
</table>
\[ N_{A}^{\pi^{+}\pi^{-}} = 8000 \pm 190, \quad N_{A}^{K^{+}\pi^{-}} = 70 \pm 24, \quad N_{A}^{K^{-}\pi^{+}} = 45 \pm 18. \]

\[ \rho = \frac{N_{A}^{\pi^{+}\pi^{-}}}{\left( N_{A}^{K^{+}\pi^{-}} + N_{A}^{K^{-}\pi^{+}} \right)} = 70 \pm 18. \]

\[
\frac{d\sigma_{nlm}^{A}}{d\mathbf{p}_{A}} = (2\pi)^{3} \frac{E_{A}}{M_{A}} \left| \psi_{nlm}(0) \right|^{2} \frac{d\sigma_{s}^{0}}{d\mathbf{p}_{1} d\mathbf{p}_{2}} \bigg|_{v_{1}=v_{2}}
\]

\[
\frac{d\sigma_{s}^{0}}{d\mathbf{p}_{1} d\mathbf{p}_{2}} = \frac{1}{\sigma_{inel}} \frac{d\sigma}{d\mathbf{p}_{1} d\mathbf{p}_{2}} R(\mathbf{p}_{1}, \mathbf{p}_{2})
\]
Figure 8: Comparison of the experimental inclusive yield of $\pi^+$ from pAl interaction at 24 GeV with the simulated in FRITIOF-7 – solid line and FRITIOF-6 – dashed line.

Figure 9: Comparison of the experimental inclusive yield of $\pi^-$ from pAl interaction at 24 GeV with the simulated in FRITIOF-7 – solid line and FRITIOF-6 – dashed line.
Figure 10: Comparison of the experimental inclusive yield of $K^+$ from pAl interaction at 24 GeV with the simulated in FRITIOF-7 – solid line and FRITIOF-6 – dashed line.

Figure 11: Comparison of the experimental inclusive yield of $K^-$ from pAl interaction at 24 GeV with the simulated in FRITIOF-7 – solid line and FRITIOF-6 – dashed line.
The calibrations of the drift chambers and of all other detectors are completed.

The preselection of the experimental data will begin in one month.

The Monte-Carlo simulation will be equivalent to the 2008 one.
Schedule of 2008/9 data processing and analysis

$K\pi$ and $\pi\pi$ pairs from experimental and MonteCarlo data of 2008 will be processed using information from all detectors.

The experimental pairs will be analyzed and fitted using the Monte-Carlo distributions of Coulomb and non-Coulomb pairs.

The number of $K\pi$ and $\pi\pi$ atomic pairs will be evaluated. The total number of atoms produced will be estimated.

All experimental data for 2009 will be preselected and ntuples will be obtained.

All these results will be ready before the end of September 2010.
Plan for the 2010 run

Installation of the new memories to increase the reliability of the DAQ and to decrease the dead time of the readout system.

Check the 8 bunch injection to PS, proposed by R.Steerenberg.

Few days will be used to take data using a thin Be target (100 micrometers) to study the experimental conditions necessary to observe long-lived $\pi-\pi$ atoms.
The principal aim of this run is:

- the data taking needed for the $K^+ \pi^-$ and $K^- \pi^+$ atoms observation and their lifetime measurement.

- to obtain the statistics of $\pi^-\pi^-$ atoms which will allow to measure their lifetime with a precision of 6% or better and the difference of $\pi^-\pi^-$ scattering lengths with a precision of 3% or better.
The main aim of the new addendum is the observation of the long-lived $\pi^+\pi^-$ atoms. This observation will open the possibility to measure in a model independent way the Lamb shift and to determine the new combination of the $\pi\pi$ scattering lengths $2a_0 + a_2$. 
Energy Splitting between np - ns states in (π⁺ - π⁻) atom

\[ \Delta E_n = E_{ns} - E_{np} \]

\[ \Delta E_n \approx \Delta E_{vac}^n + \Delta E_s^n \quad \Delta E_s^n \approx 2a_0 + a_2 \]

For \( n = 2 \)

\[ \Delta E_{vac}^2 = -0.107 \text{ eV} \quad \text{from QED calculations} \]

\[ \Delta E_s^2 \approx -0.45 \text{ eV} \quad \text{numerical estimated value from ChPT} \]

\[ a_0 = 0.220 \pm 0.005 \]

\[ a_2 = -0.0444 \pm 0.0010 \]


\[ \Rightarrow \Delta E_2 \approx -0.56 \text{ eV} \]

(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.
Metastable Atoms

For \( p_A = 5.6 \text{ GeV/c} \) and \( \gamma = 20 \)

\[
\begin{align*}
\tau_{1s} &= 2.9 \times 10^{-15} \text{ s} , \\
\tau_{2s} &= 2.3 \times 10^{-14} \text{ s} , \\
\tau_{2p} &= 1.17 \times 10^{-11} \text{ s} ,
\end{align*}
\]

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

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

<table>
<thead>
<tr>
<th>Target $Z$</th>
<th>Thickness $\mu$</th>
<th>Br</th>
<th>$\Sigma (l \geq 1)$</th>
<th>2$p_0$</th>
<th>3$p_0$</th>
<th>4$p_0$</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>
Metastable Atoms - Backgrounds

Atomic pairs

Coulomb background

\[ 5 \mu \text{Ni} \rightarrow \]

\[ 100 \mu \text{Ni} \rightarrow \]

\[ Q_T, \text{MeV/c} \quad Q_L, \text{MeV/c} \quad Q, \text{MeV/c} \]
Thank you for your attention
Method of $A_{2\pi}$ observation and lifetime measurement

$\tau(A_{2\pi})$ is too small to be measured directly.

E. m. interaction of $A_{2\pi}$ in the target:

$A_{2\pi} \rightarrow \pi^+\pi^-$

$Q < 3\text{MeV/c}, \Theta_{lab} < 3 \text{ mrad}$

**Coulomb from short-lived sources**

$N_A = K(Q_0) N_C(Q<Q_0)$ with known $K(Q_0)$

Breakup probability: $P_{br} = n_A/N_A$

**non-Coulomb from long-lived sources**
Solution of the transport equations provides one-to-one dependence of the measured break-up probability ($P_{br}$) on pionium lifetime $\tau$.

Cross section calculation precision 0.6%

All targets have the same thickness in radiation lengths $6.7 \times 10^{-3} X_0$.

There is an optimal target material for a given lifetime.
**$A_{2\pi}$ and $A_{\pi K}$ production**

\[
\frac{d\sigma_{nlm}^A}{d\vec{P}} = (2\pi)^3 \frac{E}{M} |\psi_{nlm}^{(C)}(0)|^2 \frac{d\sigma_s^0}{dp_1 dp_2} \frac{d\sigma}{dp_1} \frac{d\sigma}{dp_2}
\]

for atoms $\vec{v}_1 = \vec{v}_2$ where $\vec{v}_1, \vec{v}_2$ – velocities of particles in the lab frame for all types of atoms

for $A_{2\pi}$ production $\vec{p}_1 = \vec{p}_2$

for $A_{\pi K}$ production $\vec{p}_\pi = \frac{m_\pi}{m_K} \vec{p}_K$

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Theoretical status

In ChPT the effective Lagrangian, which describes the $\pi\pi$ interaction, is an expansion in (even) terms:

$$L_{\text{eff}} = L^{(2)} + L^{(4)} + L^{(6)} + \cdots$$

Colangelo et al. in 2001, using ChPT (2-loop) & Roy equations:

$$a_0 = 0.220 \pm 2.3\%$$
$$a_2 = -0.0444 \pm 2.3\%$$

$$a_0 - a_2 = 0.265 \pm 1.5\%$$

These results (precision) depend on the low-energy constants (LEC) $l_3$ and $l_4$:

Lattice gauge calculations from 2006 provided values for these $l_3$ and $l_4$.

Because $l_3$ and $l_4$ are sensitive to the quark condensate, precision measurements of $a_0$, $a_2$ are a way to study the structure of the QCD vacuum.