First measurement of the $\pi^+\pi^-$ atom lifetime

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Lifetime Measurement of $\pi^+\pi^-$ atoms to test low energy QCD predictions

www.cern.ch/DIRAC
Pionium lifetime

Pionium is a hydrogen-like atom consisting of $\pi^+$ and $\pi^-$ mesons
\[ E_B = -1.86 \text{ keV}, \quad r_B = 387 \text{ fm}, \quad p_B \approx 0.5 \text{ MeV} \]

The lifetime of $\pi^+\pi^-$ atoms ($A_{2\pi}$) is dominated by charge exchange process into $\pi^0\pi^0$:

\[ \Gamma = \frac{1}{\tau} = \Gamma_{2\pi^0} + \Gamma_{2\gamma} \]

\[ \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4 \times 10^{-3} \]

\[ \Gamma_{1S,2\pi^0} = \frac{1}{\tau_{1S}} \propto |a_0 - a_2|^2 \]

$a_0$ and $a_2$ are the $\pi\pi$ S-wave scattering lengths for isospin $I=0$ and $I=2$. 

\[ \frac{\Delta \tau}{\tau} = 10\% \quad \Rightarrow \quad \frac{\Delta (a_0 - a_2)}{a_0 - a_2} = 5\% \]
Pionium lifetime in QCD

J.Gasser et al., Phys.Rev. D64 (2001) 016008:

\[ \Gamma_{2\pi^0} = \frac{1}{\tau} = \frac{2}{9} \alpha^3 p |a_0 - a_2|^2 (1 + \delta_\Gamma), \quad \delta_\Gamma = (5.8 \pm 1.2)\% \]

The $\pi\pi$ scattering lengths have been calculated in the framework of Chiral Perturbation Theory (ChPT):


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

\[ a_0 - a_2 = 0.265 \pm 0.004 \]

\[ \tau = (2.9 \pm 0.1) \times 10^{-15} \text{s} \]
Experimental results

$K^+ \to \pi^+\pi^-e^+\nu_e (K_{e4})$ decay

$a_0 = 0.26 \pm 0.05$ L. Rosselet et al., Phys. Rev. D 15 (1977) 574

$a_0 = 0.216 \pm 0.013$ New measurement at BNL (E865) ±0.003(syst) S.Pislak et al., Phys.Rev. D 67 (2003) 072004

$a_2 = -0.0454 \pm 0.0031$ ±0.0013(syst)

$\pi N \to \pi\pi N$ near threshold

$a_0 = 0.26 \pm 0.05$ C.D. Froggatt, J.L. Petersen, Nucl. Phys. B 129 (1977) 89

$a_0 = 0.204 \pm 0.014$ M. Kermani et al., Phys. Rev. C 58 (1998) 3431 ±0.008(syst)

$|a_0 - a_2| = 0.281 \pm 0.007 \text{ (stat.)}$ N.Cabibbo, Phys. Rev. Lett. 93, 121801 (2004)

$|a_0 - a_2| = 0.281 \pm 0.014 \text{ (syst.)}$ N.Cabibbo, G.Isidori, hep-ph/0502130

$K^+ \to \pi^+\pi^0\pi^0$ and $K_L \to 3\pi^0$ NA48

K$^+$→π$^+$π$^0$π$^0$ and $K_L$→3π$^0$ NA48

$|a_0 - a_2| = 0.281 \pm 0.007 \text{ (stat.)}$ N.Cabibbo, Phys. Rev. Lett. 93, 121801 (2004)

$|a_0 - a_2| = 0.281 \pm 0.014 \text{ (syst.)}$ N.Cabibbo, G.Isidori, hep-ph/0502130
Production of pionium

Atoms are Coulomb bound state of two pions produced in one proton-nucleus collision

\[
\frac{d\sigma_n}{d\vec{P}} = (2\pi)^3 \frac{E_A}{M_A} \left|\psi^{(C)}_{nlm}(0)\right|^2 \frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-} \bigg|_{\vec{p}_+ = \vec{p}_-}
\]

Background processes:

Coulomb pairs. They are produced in one proton nucleus collision from fragmentation or short lived resonances and exhibit Coulomb interaction in the final state

\[
\frac{d^2\sigma_C}{d\vec{p}_+ d\vec{p}_-} = A_C(q) \frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}, \quad A_C(q) = \frac{2\pi m_\pi \alpha / q}{1 - \exp(-2\pi m_\pi \alpha / q)}
\]

Non-Coulomb pairs. They are produced in one proton nucleus collision. At least one pion originates from a long lived resonance. No Coulomb interaction in the final state

Accidental pairs. They are produced in two independent proton nucleus collision. They do not exhibit Coulomb interaction in the final state
Method of pionium detection


Pionium is created in nS states then it interacts with target material:

**Annihilation:** \( A_{2\pi} \rightarrow \pi^0\pi^0 \)

\[
\lambda_{\text{decay}} = \gamma ct \approx 15 \mu m \text{ for } \gamma \approx 17
\]

**Excitation:** transitions between atomic levels

\[
\lambda_{\text{int}}^{1S} \approx 20 \mu m \text{ for Ni}
\]

**Break-up (ionisation):** characteristic “atomic” pairs \( n_A \)

- \( Q_{\text{cms}} < 3 \text{MeV/c} \)
- \( \rightarrow \) in laboratory system \( E_+ \approx E_- \), small opening angle \( \theta < 3 \text{ mrad} \)

Coulomb and atomic pairs are detected simultaneously

\[
P_{\text{br}} = \frac{n_A}{N_A} = \frac{n_A}{k N_C}
\]
Solution of the transport equations provides one-to-one dependence of the measured break-up probability ($P_{br}$) on pionium lifetime $\tau$.

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.

The detailed knowledge of the cross sections (Afanasyev&Tarasov; Trautmann et al) (Born and Glauber approach) together with the accurate description of atom interaction dynamics (including density matrix formalism) permits us to know the curves within 1%.
DIRAC Spectrometer

Upstream detectors:
MSGCs, SciFi, IH.

Downstream detectors:
DCs, VH, HH, C, PSh, Mu.
**Setup features:**

angle to proton beam $\Theta=5.7^\circ$

channel aperture $\Omega=1.2 \cdot 10^{-3}$ sr

magnet $2.3 \text{ T} \cdot \text{m}$

momentum range $1.2 \leq p_\pi \leq 7$ GeV/$c$

resolution on relative momentum $\sigma_{Q_X} \approx \sigma_{Q_Y} \leq 0.5$ MeV/$c$, $\sigma_{Q_L} \approx 0.5$ MeV/$c$
Trigger performance

![Graph showing trigger performance with different categories: T1, DNA or RNA, T4, T4.and.(DNA.or.RNA)]
Calibrations

Positive arm mass spectrum, obtained by TOF difference, under $\pi^-$ hypothesis in the negative arm.

Time difference spectrum at VH with $e^+e^-$ T1 trigger.

Mass distribution of $p\pi^-$ pairs from $\Lambda$ decay. $\sigma_{\Lambda} = 0.43$ MeV$/c^2$ $< 0.49$ MeV$/c^2$ (Hartouni et al.).
Analysis based on MC

Atoms are generated in nS states using measured momentum distribution for short-lived sources. The atomic pairs are generated according to the evolution of the atom while propagating through the target.

Background processes:

Coulomb pairs are generated according to $A_c(Q)Q^2$ using measured momentum distribution for short-lived sources.

Non-Coulomb pairs are generated according to $Q^2$ using measured momentum distribution for long-lived sources.
Atomic pairs MC

solid line: after target

dashed line: at break-up

$q$

$q_L$

$q, |q_L| [\text{MeV}/c]$
Atomic pairs

![Graphs showing Coulomb and non-Coulomb interactions with event counts.
6518 events vs. Q[MeV/c].
6509 events vs. |Q_L| [MeV/c].]
Break-up probability

\[ P_{\text{br}} = \frac{n_A}{N_A} = \frac{n_A^{\text{rec}}(Q \leq Q_{\text{cut}})}{k(Q_{\text{cut}})N_C^{\text{rec}}(Q \leq Q_{\text{cut}})} \]

<table>
<thead>
<tr>
<th></th>
<th>( n_A )</th>
<th>( N_C(Q_{\text{cut}}) )</th>
<th>( P_{\text{br}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q )</td>
<td>6518±373</td>
<td>106500±1130</td>
<td>0.442±0.026</td>
</tr>
<tr>
<td>( Q_L )</td>
<td>6509±330</td>
<td>82289±873</td>
<td>0.445±0.023</td>
</tr>
<tr>
<td>( Q&amp;Q_L )</td>
<td>6530±294</td>
<td>106549±1004</td>
<td>0.447±0.023</td>
</tr>
</tbody>
</table>

\( k(Q_{\text{cut}}=4 \text{ MeV/c})=0.1384, \quad k(Q_{L,\text{cut}}=2 \text{ MeV/c})=0.1774 \)

*Due to target impurities by atoms with \( Z<28 \) \( P_{\text{br}} \) has to be increased by 0.005*
Breakup probability

\[ P_{br} = 0.452 \pm 0.023_{stat}^{+0.009}_{-0.032} \stackrel{syst}{=} 0.452^{+0.025}_{-0.039} \]

Summary of systematic uncertainties:

<table>
<thead>
<tr>
<th>source</th>
<th>( \sigma )</th>
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<tr>
<td>CC-background</td>
<td>( \pm 0.007 )</td>
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<tr>
<td>signal shape</td>
<td>( \pm 0.002 )</td>
</tr>
<tr>
<td>multiple scattering angle ( +5%)( -10% )</td>
<td>( +0.006 )( -0.013 )</td>
</tr>
<tr>
<td>( K^+K^- ) and ( pp ) pairs admixture</td>
<td>( +0.000 )( -0.024 )( +0.000 )( -0.017 )</td>
</tr>
<tr>
<td>correlation function for non-point production</td>
<td>( +0.009 )( -0.032 )</td>
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Lifetime of Pionium

Result from DIRAC:

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

ChPT prediction:

\[
\tau = \left( 2.9 \pm 0.1 \right) \text{ fs}
\]

Results from DIRAC

- DIRAC collaboration has built up the double arm spectrometer which provides a pair relative momentum ($Q$) resolution of 1 MeV/c for $Q<30$ MeV/c
- Observation of more than 15000 of $\pi^+\pi^-$ pairs from pionium break-up
- The analysis of Ni 2001 data provides a lifetime measurement:
  \[ \tau = \left( 2.91^{+0.49}_{-0.62} \right) \text{ fs} \]
  \[ |a_0 - a_2| = 0.264^{+0.033}_{-0.020} m_{\pi}^{-1} \]
- Improvements to come:
  1. to improve on statistics: analyse full $\pi^+\pi^-$ data sample
  2. to improve on systematics:
     - different analysis procedures
     - study of correlation function
     - detailed study of multiple scattering
     - analysis of data taken with single-multi layer target
# Atomic pairs

## Number of Atomic pairs

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<tbody>
<tr>
<td><strong>With upstream detectors</strong> $(Q_L&lt;1.5 \text{ MeV/c} \quad Q_T&lt;4 \text{ MeV/c})$</td>
<td>282 ± 96</td>
<td>1353 ± 385</td>
<td>935 ± 273</td>
<td>1476 ± 330</td>
<td>5733 ± 577</td>
<td>1925 ± 390</td>
<td>2555 ± 525</td>
<td>1410 ± 264</td>
<td>15387 ± 1078</td>
</tr>
<tr>
<td><strong>Without upstream detectors</strong> $(Q_L&lt;1.5 \text{ MeV/c} \quad Q_T&lt;6 \text{ MeV/c})$</td>
<td>219 ± 137</td>
<td>3839 ± 579</td>
<td>1767 ± 414</td>
<td>3314 ± 539</td>
<td>9050 ± 822</td>
<td>3040* ± 480</td>
<td>4030* ± 550</td>
<td>2230* ± 410</td>
<td>27270* ± 1470</td>
</tr>
</tbody>
</table>

* - estimation
Goals of the experiment

- The proposed experiment is the further development of the current DIRAC experiment at CERN PS. It aims to measure simultaneously the lifetime of $\pi^+ \pi^-$ atoms ($A_{2\pi}$), to observe $\pi K$ atoms ($A_{\pi K}$) and to measure their lifetime using 24 GeV proton beam PS CERN and the upgraded DIRAC setup.

- The precision of $A_{2\pi}$ lifetime measurement will be better than 6% and the difference $|a_0 - a_2|$ will be determined within 3% or better.

- The accuracy of $A_{\pi K}$ lifetime measurement will be at the level of 20% and the difference $|a_{1/2} - a_{3/2}|$ will be estimated at the level of 10%.

- The pion-pion and pion-kaon scattering lengths have never been verified by experimental data with the sufficient accuracy. For this reason the proposed measurements will be a crucial check of the low energy QCD predictions and our understanding of the nature of the QCD vacuum.

- The observation of the long-lived (metastable) $A_{2\pi}$ states is also considered with the same setup. This will allow us to measure the energy difference between $ns$ and $np$ states and to determine the value of $2a_0 + a_2$ in a model-independent way.
DIRAC II Set-up

single and multilayer targets

vacuum

shield1

MDC

IH

SFD

vacuum

shield2

magnet

heavy gas Cherenkov

aerogel

DC

VH

HH

1 meter

T1

T2

π⁺K⁺

absorber

Ch

PSh

Mu

π⁻K⁻