Investigation of $\pi^+\pi^-$ and πK - atoms

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on behalf of DIRAC collaboration

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Contents

DIRAC collaboration

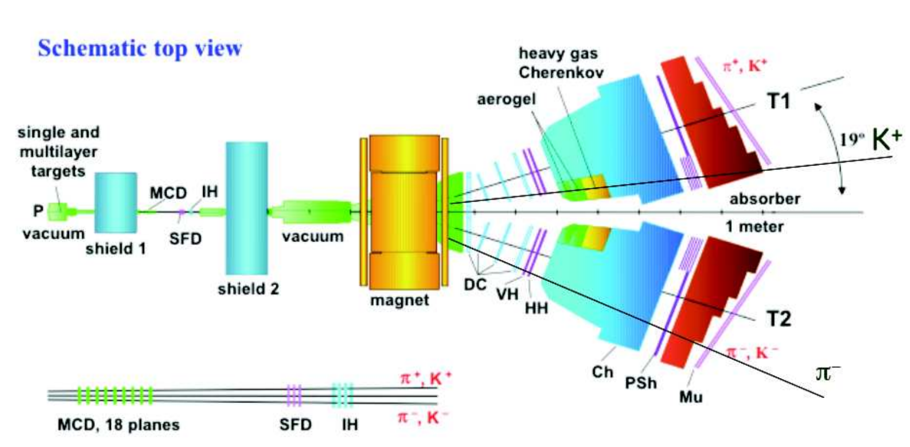
- CERN
- Czech Technical University
- Institute of Physics ASCR
- Nuclear Physics Institute ASCR
- INFN-Laboratori Nazionali di Frascati
- University of Messina
- KEK
- Kyoto University
- Kyoto Sangyou University
- Tokyo Metropolitan University
- IFIN-HH
- JINR
- SINP of Moscow State University
- IHEP
- Santiago de Compostela University
- Bern University
- Zurich University

Experiment DIRAC

DIRAC= **DI**meson **R**elativistic **A**tomic **C**omplex

- using the proton beam (24GeV/c) from PS at CERN
- detector : a double-arm magnetic spectrometer
- over 90 physicists from 24 institutes and universities
- data collection from 2001 (since that time several upgrades)
- the main goals:
  1. measurement of the lifetime of $\pi^+\pi^-$ atom in the order of 3 fs with an accuracy of 10%
  2. after upgrade in 2006 $\rightarrow$ first observation of $K\pi$ atoms, their lifetime and scattering length measurement
  3. long-lived atom observation

DIRAC experimental setup



ChPT predicts s-wave scattering lengths

$\pi\pi$: $a_0 = 0.220 \pm 0.005$ $a_2 = -0.0444 \pm 0.0010$

$$a_0 - a_2 = 0.265 \pm 0.004$$ [1]

G. Colangelo et al., Nucl. Phys. B 603 (2001) 125

$$\Rightarrow \tau = (2.9 \pm 0.1)\ \text{fs} \qquad (\Gamma = \frac{1}{\tau} \sim k|a_0 - a_2|^2)$$

πK:

1-loop approx.

$a_{1/2} = 0.19 \pm 0.02$ $a_{3/2} = -0.05 \pm 0.02$

V.Bernard, N. Kaiser, U. Meissner 1991

$$a_{1/2} - a_{3/2} = 0.238 \pm 0.002$$

B. Kubis, U.G. Meissner 2002

2-loop approx. $a_{1/2} - a_{3/2} = 0.267$

J. Bijnens, P.P. Dhonte, P.Talavera 2004

(Roy-Steiner equations) $a_{1/2} - a_{3/2} = 0.269 \pm 0.015$

P. Büttiker et al. 2004

$$\Rightarrow \tau = (3.7 \pm 0.4)\ \text{fs}$$

[1] the indices 0 and 2 refer to the isospin of the $\pi\pi$-system (1/2 and 3/2 refer to the isospin of the πK-system)

Production of pionium

$\pi^+\pi^-$ atom - Coulomb bound state of two pions produced in one proton-nucleus interaction (N_A).

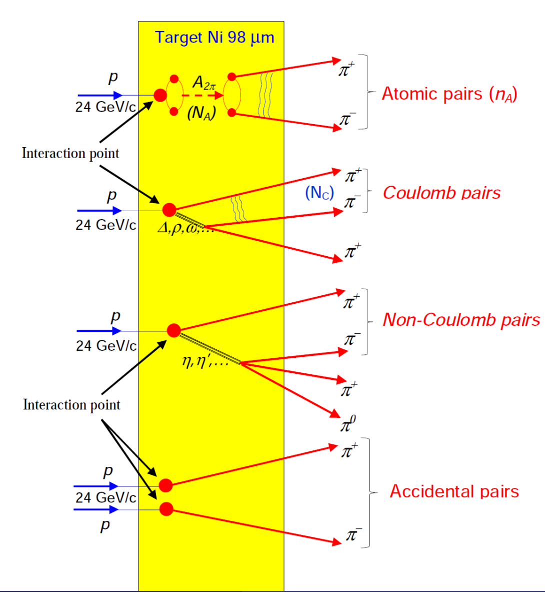
Atomic pairs - ionised $\pi^+\pi^-$ atoms (n_A).

Background processes:

Coulomb pairs -produced in one proton-nucleus collision from fragmentation or short-lived resonances (ρ, ω, Δ) and exhibit Coulomb interaction in the final state (N_{CC}).

Non-Coulomb pairs - produced in one proton-nucleus collision. At least one pion originates from a long-lived source (η, η'). No Coulomb interaction in the final state (N_{NC}).

Accidental pairs - produced in two independent proton-nucleus collisions. No Coulomb interaction in the final state (N_{AC}).

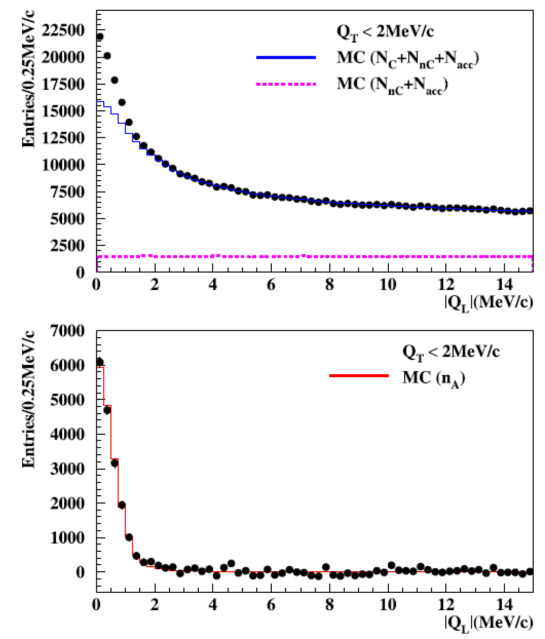


Method of measurement

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

When pionium ($A_{2\pi}$) moves through the target, following processes can occour:

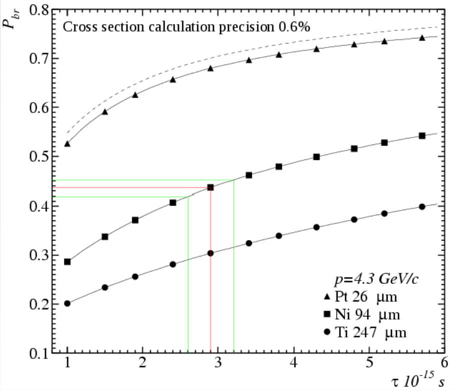
1. Annihilation ... *(strong interaction)*
   - $A_{2\pi} \to \pi^0 + \pi^0$ (decay ratio 99.6%, $\tau \approx$ 3 fs , $A_{2\pi} \to \gamma\gamma$ contributes 0.36%)
2. Excitation/Deexcitation ... *(electromagnetic interaction)*
   - transition between atomic levels
3. Break-up (ionisation) ... *(electromagnetic interaction)*
   - $A_{2\pi} \to \pi^+ + \pi^-$; characteristic “atomic pairs” (n_A)
   - Q_{CMS} <3MeV/c
   - in LAB $E_+ \approx E_-$, small opening angle Θ <3mrad



Caption:

$|Q_L|$ fit projections of the $\pi^+\pi^-$ spectrum from data (dots) and simula- tion (MC lines). The top plot shows the experimental spectrum compared with the simulated background components (no pionium signal), with (solid line) and with-out (dotted line) Coulomb pairs (N_{CC}). The bottom plot shows the experimental $|Q_L|$ spectrum after background subtraction and the simulated pionium spectrum.

Break-up probability



an example of lifetime (2.9±0.3) fs

Calculation of P_{br}

$$P_{br} = \frac{n_A}{N_A} = \frac{n_A}{k\ N_{CC}}$$

- → n_A ...number of ionized $A_{2\pi}$ atoms; N_A ...number of produced $A_{2\pi}$ atoms
- → there exists a precise relation between N_A and the total number N_{CC} of Coulomb pairs with small Q :

  $N_A = k\ N_{CC}$ $\quad k \approx 0.6 \ldots Q \leq 2$ MeV/c
- → P_{br} function of target material and thickness, atom lifetime τ and $A_{2\pi}$ momentum
- → given lifetime ⇒ optimal target material

Published results on $\pi\pi$ atom: lifetime & scattering length

- the analysis of 2001-2003 data leads to the $A_{2\pi}$ lifetime $\tau = (3.15 \pm 0.28)$ fs
- the derived scattering length difference is $|a_0 - a_2| = (0.2533 \pm 0.011) m_\pi^{-1}$

DIRAC data	τ1s (10–15s)					|a0 – a2|					Reference
	value	stat	syst	theo*	tot	value	stat	syst	theo*	tot	
2001	2.91	$^{+0.45}_{-0.38}$	$^{+0.19}_{-0.49}$		$\left[^{+0.49}_{-0.62}\right]$	0.264	$^{+0.017}_{-0.020}$	$^{+0.022}_{-0.009}$		$\left[^{+0.033}_{-0.020}\right]$	PL B 619 (2005) 50
2001-03	3.15	$^{+0.20}_{-0.19}$	$^{+0.20}_{-0.18}$		$\left[^{+0.28}_{-0.26}\right]$	0.2533	$^{+0.0078}_{-0.0080}$	$^{+0.0072}_{-0.0077}$		$\left[^{+0.0106}_{-0.0111}\right]$	PL B 704 (2011) 24

* theoretical uncertainty included in systematic error

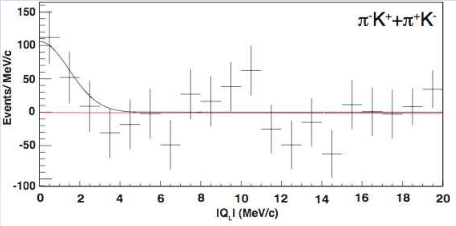
NA48	K-decay	a0 – a2					Reference
		value	stat	syst	theo	tot	
2009	K3π	0.2571	±0.0048	±0.0029	0.0088		EPJ C64 (2009) 589
2010	Ke4 & K3π	0.2639	±0.0020	±0.0015			EPJ C70 (2010) 635

πK atom - motivation

- the study of electromagnetically bound hadronic pairs allows us to probe the low energy QCD
- the low energy interaction between the pion and the kaon (which contains the strange quark) is a proper tool to study the 3-flavour (u,d,s) structure of hadronic interaction or quark condensate in Chiral Perturbation Theory
- a measurement of the πK-atom lifetime is an important tool to determine the difference $|a_{1/2} - a_{3/2}|$ of the s-wave πK-scattering lengths [2]

[2] the indices 1/2 and 3/2 refer to the isospin of the πK-system

πK atom signal



Residuals between data and the fitted background for $\pi^+ K^-$ and $\pi^- K^+$. A Gaussian fit has been applied (solid line) to illustrate the distribution of atomic-pairs.

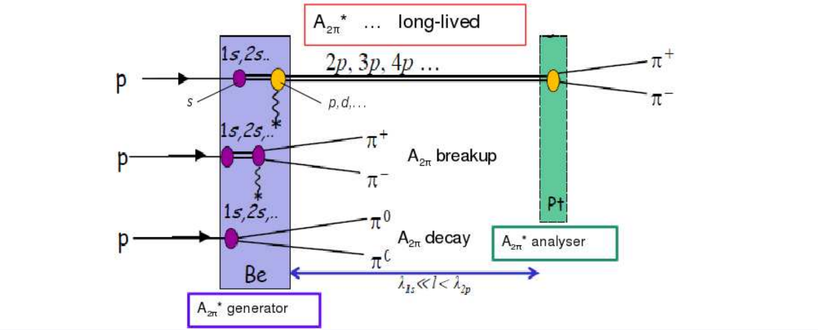
277±52 πK atoms were observed
with a significance of 5.3σ

numbers of πK atoms	
$\pi^- K^+$	157±43
$\pi^+ K^-$	120±29

The ultimate goal of the DIRAC experiment is to measure the lifetime of $K\pi$ atoms with a precision of 20% (or better).

Long-lived atom - observation

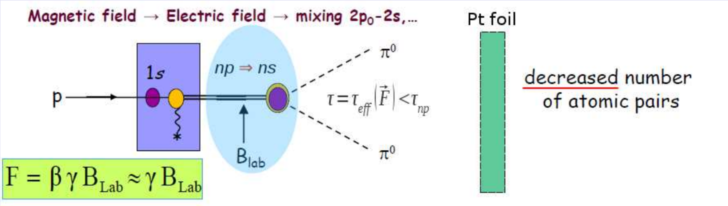
- $\sim$ 6% of the atoms $A_{2\pi}$, generated in the target, exit the target in a long-lived state $A^*_{2\pi}$ (mainly 1$s \rightarrow np$)
- the main part of these atoms are in the 2p-state
- the $A^*_{2\pi}(np)$ decay into two π^0 is forbidden [3] and $A^*_{2\pi} \rightarrow \pi^0 + \gamma$ is also strongly suppressed
- the lifetime of the $A^*_{2\pi}$ atom in the 2p state ($\tau_{2p} = 1.17 \times 10^{-11}$s) is determined by the 2$p \rightarrow$ 1s radiative transition with subsequent annihilation from 1s state ($\tau_{1s} \approx 3 \times 10^{-15}$s) $\Rightarrow$ the lifetime in np-states is about 10^3 times larger than for ns-states



[3] the conservation law of the angular momentum

Long-lived atoms - “Lamb shift” measurement

- it is possible to measure **the** $2s - 2p$ **energy splitting** by exerting a magnetic field ($\Rightarrow$ an electric field F) on the atom $\Rightarrow$ measurement of the decay probability dependence on the field (mixing of *ns* and *np*-states in the electric field) [4]



- electric field influences $A^*_{2\pi}$ lifetime $\tau_{eff} \Rightarrow$ “Lamb shift” ΔE_{2s-2p} $\Rightarrow$S-wave pion-pion scattering length combination $2a_0 + a_2$

[4] a small admixture of the 2*s*-state in the 2*p*-state $\rightarrow$ faster decay; for B_0=4 T and γ = 20 the decay rate increases more than a factor of two

Conclusion

- the lifetime of $A_{2\pi}$ atoms and the absolute value of difference of $\pi\pi$ scattering lengths were measured

$$\tau = (3.15 \pm 0.28)\ \text{fs}$$
$$|a_0 - a_2| = (0.2533 \pm 0.011) m_\pi^{-1}$$

- the number of πK atoms detected by DIRAC corresponds to more than 5σ effect
- our goals for future:
  1. a measurement of the πK atom lifetime
  2. till the end of 2012 an observation of the $\pi\pi$ long-lived atoms $A^*_{2\pi}$

Thank you for your attention!

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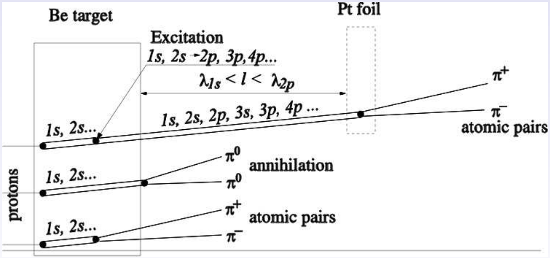
Published results on $\pi\pi$ atom: lifetime & scattering length - II.

- based on more than 21000 breaking $A_{2\pi}$ atoms
  $\Rightarrow$ statistical accuracy better than 10%
- to decrease systematic error, multiple scattering and an admixture of K^+K^- and $p\bar{p}$ pairs are measured
- systematic error due to detector response is estimated

Long-lived atoms - few numbers

- as the best target has been found 100μm thick Be target
- the corresponding decay length is 5.7 cm for 2p-state, 19 cm for 3p-state, 44 cm for 4p-state, 84.5 cm for 5p-state (γ=16.1 in DIRAC)
- as the break-up foil has been chosen Pt foil with thickness of 2 μm [5]
- the shortest distance between the Be target and the Pt foil can be around 10 cm to avoid interactions of the primary beam halo with the foil

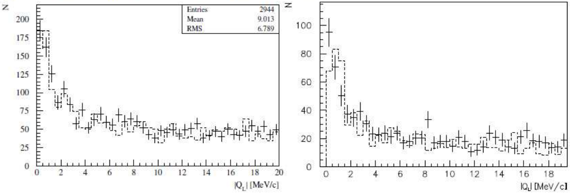


[5] the breakup probability of long-lived states is 0.94

Production of $A_{2\pi}$ in the Be target

2010	N_A = 736±75
2011	N_A = 368±32

Distribution over $|Q_L|$ of $\pi^+\pi^-$ pairs collected in 2010 (left) and in 2011 (right) with Beryllium target with the cut $Q_T < 1$ MeV/c. Experimental data (points with error bars) have been fitted by a sum of the simulated distribution of "Coulomb" and "non-Coulomb" pairs (dashed line).



Produced atom numbers normalized on the proton flux:

$N_{A_{2\pi}}/p = (5.1 \pm 0.5) \times 10^{-14}$ *(2010)*

$N_{A_{2\pi}}/p = (5.9 \pm 0.5) \times 10^{-14}$ *(2011)*

The dependence of $A_{2\pi}$ lifetime in $2p$-state τ_{eff} from a strength of the electric field F

$$\tau_{eff} = \frac{\tau_{2p}}{1+120|\xi|^2}$$

where

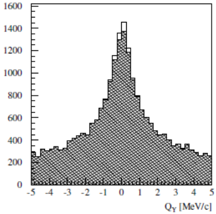
$$|\xi|^2 \approx \frac{F^2}{\left(E_{2p}-E_{2s}\right)}$$

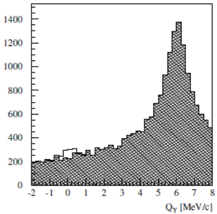
$$B_{Lab} = 4 \text{ Tesla} \begin{cases} \gamma = 20, \quad |\xi| = 0.1 \quad \Rightarrow \quad \tau_{eff} = \frac{\tau_{2p}}{2.2} \\ \gamma = 40, \quad |\xi| = 0.2 \quad \Rightarrow \quad \tau_{eff} = \frac{\tau_{2p}}{6} \end{cases}$$

SPS(450GeV): yield of $A_{2\pi}$ and $A_{\pi K}$ will increase of a factor 20 per proton-nucleus interaction.

Simulation of the permanent magnet influence

Simulated "atomic pairs" from long-lived atoms (light area) over Q_Y above the background of $\pi^+\pi^-$ pairs produced in Beryllium target with cuts $|Q_X| < 1$ MeV/c, $|Q_L| < 1$ MeV/c (hatched area). In left side without the magnet and in right side with magnet used in 2011





Simulated distribution of $\pi^+\pi^-$ pairs over Q_Y produced in Beryllium target with cuts $|Q_X| < 1$ MeV/c, $|Q_L| < 1$ MeV/c. The events without magnet (solid line) are distributed around 0 and events with the new magnet are shifted by 15 MeV/c (dashed line)