Exotic atoms by the DIRAC experiment

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CERN, the European Organization for Nuclear Research

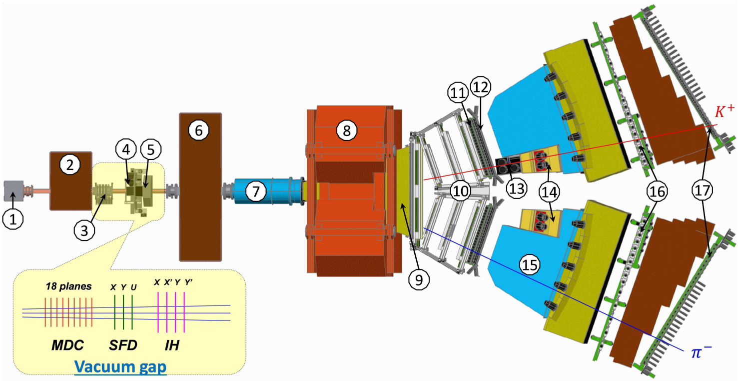
Kraków, MESON 2018

The DIRAC Collaboration

- **1998–2003** Lifetime measurement of $\pi^{+}\pi^{-}$-atoms ($A_{2\pi}$)
- **2007–. . .** Search for and lifetime measurement of $\pi^{\pm}K^{\mp}$-atoms ($A_{\pi K}$)

68 physicists from Czechia, Italy, Japan, Romania, Russia, Spain and Switzerland

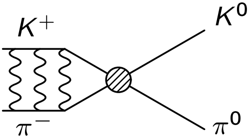
Use double-arm spectrometer at CERN Proton Syncrotron (24 GeV/c)



Contents

πK atoms lifetime

Hydrogen-like atoms, formed by π and K mesons, $a_B = 249$ fm, $p_B = 0.79$ MeV$/c$
Lifetime is limited by charge-exchange process



$$\pi^+K^- \to \pi^0\bar{K}^0 \quad \text{or} \quad \pi^-K^+ \to \pi^0 K^0$$

$$\frac{1}{\tau} = \frac{8}{9}\alpha^3\mu^2 p\left(a_0^{1/2} - a_0^{3/2}\right)^2(1+\delta_K)$$

[S.Bilenky et al., Sov. J. Nucl. Phys. 10 (1969) 469]
[J. Schweizer, Phys. Lett. B 587 (2004) 33]

SU(3) ChPT predictions [J. Bijnens et al. JHEP 0405 (2004) 036]:
+ Roy-Steiner equations [P.Büttiker et al., Eur. Phys. J. C33 (2004) 409]:

$$M_\pi a_0^- = 0.090 \pm 0.005, \quad \delta_K = 0.040 \pm 0.022 \quad \Rightarrow \quad \tau = (3.5 \pm 0.4)\cdot 10^{-15}\text{ s}$$

$$M_\pi a_0^- = M_\pi \frac{1}{3}\left(a_0^{1/2} - a_0^{3/2}\right) =$$

$$= 0.071\ (CA) \to 0.0793\ (1l) \to 0.089\ (2l) \to 0.090 \pm 0.005\ (\text{dis})$$

Recent Lattice QCD calculations

[NPLQCD, Phys. Rev. D74 (2006) 114503] $M_\pi a_0^- = 0.077 \pm 0.001^{+0.002}_{-0.005}$

[PACS-CS, Phys. Rev. D89 (2014) 054502] $M_\pi a_0^- = 0.081 \pm 0.006 \pm 0.012$

[T. Janowski et al., LATTICE2014] $M_\pi a_0^- = 0.0745 \pm 0.00020$

Experimental way to observe πK atoms

- Annihilation: $A_{\pi K} \to \pi^0 K^0$ or $\pi^0 \overline{K^0}$

$$\lambda_{\text{anh}} = \beta\gamma\tau \approx 20\ \mu\text{m at } \gamma \approx 20$$

Interaction of $A_{\pi K}$ with target atoms
[L. Nemenov, Sov. J. Nucl. Phys. 41 (1985) 629]

- Excitation/de-excitation of $A_{\pi K}$

$$\lambda_{\text{int}}^{1S} \approx 40\ \mu\text{m in Ni}$$

- $A_{\pi K}$ ionization $\Rightarrow$ characteristic "atomic" pairs $\pi^\pm K^\mp$ (n_A):

$$q_{\text{CMS}} < 3\ \text{MeV}/c \ \Rightarrow\ \text{in laboratory frame} \left[\begin{array}{l} E_+ \approx E_- \\ \Theta < 3\ \text{mrad} \end{array} \right.$$

- Unique $P_{\text{ion}} = \dfrac{n_A}{N_A} = P_{\text{ion}}(\tau)$ relation

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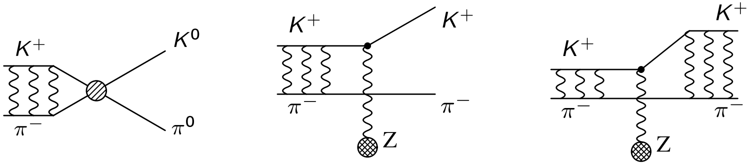
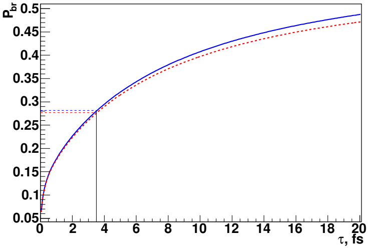
- Unique $P_{\text{ion}} = \dfrac{n_A}{N_A} = P_{\text{ion}}(\tau)$ relation

$P_{\text{ion}} = P_{\text{ion}}(\tau)$

$A_{\pi K}$ propagation in matter: annihilation/ionisation/excitation





$P_{ion}(\tau)$ better than 1%

- Total/excitation cross-sections in Born approximation
  [St. Mrowczynski, 1986, Phys. Rev. A33, 1549]
  [L. Afanasyev, A. Tarasov, 1996, Sov. J. Nucl. Phys 59, 2130]
- Glauber approximation + ionization cross-sections
  [T. Heim et al., 2001, J. Phys. B34, 3763]
- Multiphoton exchange
- Density matrix formulas
  [O. Voskresenskaya, 2003, J. Phys. B36, 3293]
- Direct calculation of $P_{\text{ion}}(\tau)$
  [M. Zhabitsky, 2008, Sov. J. Nucl. Phys 71, 1040]

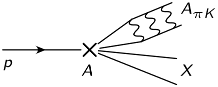
$A_{\pi K}$ generation

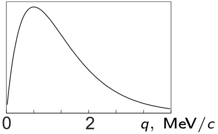
$$\mathrm{p} + \mathrm{Ni} \to \ldots \text{ at 24 GeV}/c$$

- Atoms are generated in nS-states

  $|\Psi_{nS}(0)|^2 \propto \frac{1}{n^3}$:

  $1S$: 83%, $2S$: 10%, ...



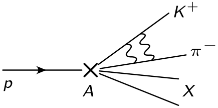


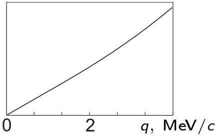
Other sources of inclusive $\pi^\pm K^\mp$-pairs:

- Coulomb pairs

  $N_A = kN_C(q < q_0)$

  $$A_C(q) = \frac{4\pi\mu_{\pi K}\alpha/q}{1-\exp(-4\pi\mu_{\pi K}\alpha/q)}$$

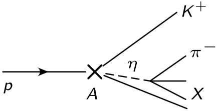


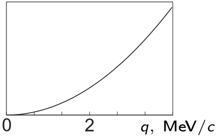


- Non-correlated pairs

$$P_{\text{ion}} = \frac{n_A}{N_A} = \frac{n_A}{kN_C}$$

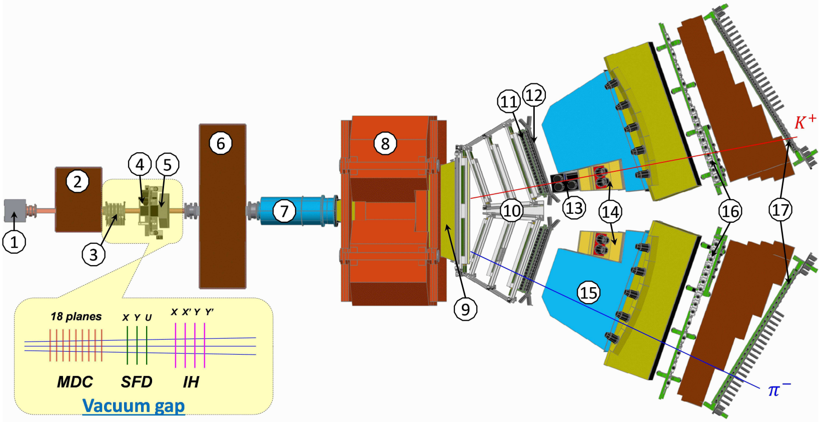
$$\Rightarrow P_{\text{ion}} = P_{\text{ion}}(\tau)$$



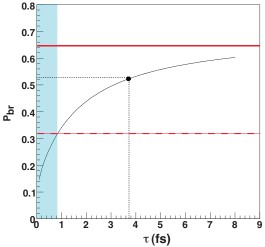


The DIRAC spectrometer

Resolution in momentum	$\sigma_p/p \approx 3 \cdot 10^{-3}$
Momentum range	$p_\pi \in [1.2, 2.5]$ GeV/c
	$p_K \in [4.0, 8.9]$ GeV/c
Rel. momentum resolution in c.m.s.	$\sigma_{Q_x} \approx \sigma_{Q_y} \approx 0.35$ MeV/c
	$\sigma_{Q_l} \approx 0.9$ MeV/c



First observation $\pi^\pm K^\mp$ atoms



Evidence for πK-atoms observation with DIRAC

[Adeva et al. (DIRAC Collaboration) Phys. Lett. B674 (2009) 11]

Thin Pt target 28μm, 2007:

$$n_A(\pi^- K^+ + \pi^+ K^-) = 173 \pm 54$$

$$N_A(\pi^- K^+ + \pi^+ K^-) = kN_C = 280 \pm 70$$

$$\tau > 0.8 \cdot 10^{-15}\text{s (CL=0.9)}$$

Further analysis of data collected on Pt and Ni targets:

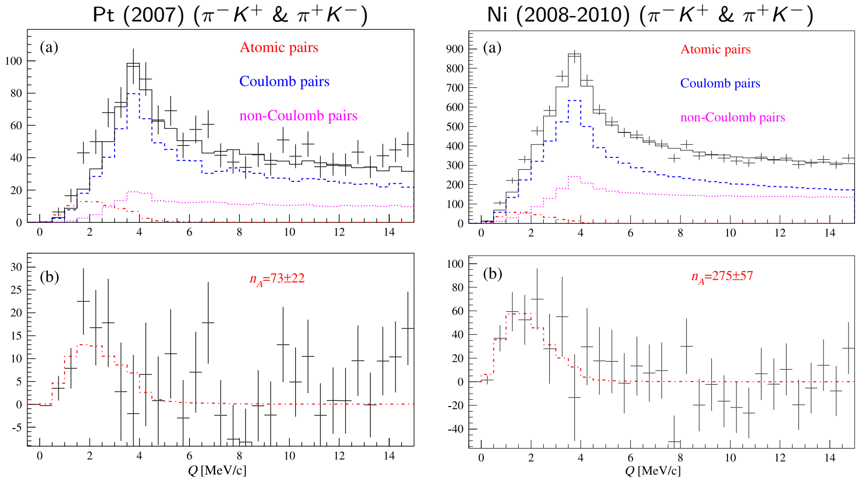
Observation of πK atoms

[Adeva et al. (DIRAC Collaboration) Phys. Rev. Lett. 117, 112001 (2016)]

$$n_A = 349 \pm 62|_{tot} \quad (5.6\sigma)$$

Lifetime measurement of $\pi^\pm K^\mp$ atoms

Two analysis: Q and $(|Q_L|, Q_T)$ fits of experimental data:



Lifetime measurement of $\pi^\pm K^\mp$ atoms (Q analyses)

P_{br} from Q-analyses ($Q_T < 4$ MeV/c)

Atom	Year	s, μm	P_{br}
$A_{\pi K}$	2007	Pt, 25.7	1.2 ± 1.3
$A_{\pi K}$	2008	Ni, 98	0.53 ± 0.39
$A_{\pi K}$	2009	Ni, 108	0.29 ± 0.20
$A_{\pi K}$	2010	Ni, 108	0.33 ± 0.22
$A_{K\pi}$	2007	Pt, 25.7	1.09 ± 0.52
$A_{K\pi}$	2008	Ni, 98	0.32 ± 0.20
$A_{K\pi}$	2009	Ni, 108	0.23 ± 0.16
$A_{K\pi}$	2010	Ni, 108	0.41 ± 0.17

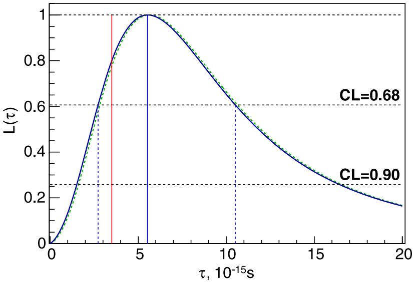
Systematic uncertainties in Pt

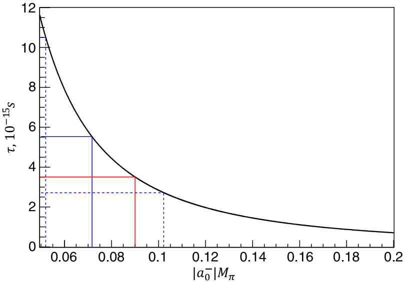
πK lab momenta	0.09
Lab. mom. of bg pairs	0.22
Total	0.24

Systematic uncertainties in Ni

Multiple scattering	0.0051
πK lab momenta	0.0052
$P_{br}(\tau)$ relation	0.0055
Total	0.0092

$A_{\pi K}$ lifetime and πK scattering lengths (Q analyses)





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

$$\tau = \left(5.5^{+5.0}_{-2.8}\Big|_{\text{tot}}\right)\times 10^{-15}\ \text{s} \quad\Rightarrow\quad |a_0^-|m_\pi = \frac{1}{3}|a_{1/2} - a_{3/2}|m_\pi = 0.072^{+0.031}_{-0.020}\Big|_{\text{tot}}$$

($|Q_L|$, Q_T analysis):

$$\tau = \left(3.8^{+3.5}_{-2.1}\Big|_{\text{tot}}\right)\times 10^{-15}\ \text{s} \quad\Rightarrow\quad |a_0^-|m_\pi = \frac{1}{3}|a_{1/2} - a_{3/2}|m_\pi = 0.087^{+0.044}_{-0.024}\Big|_{\text{tot}}$$

[DIRAC Collaboration, Phys. Rev. D 96, 052002 (2017)]

πK scattering lengths: experimental results

Inelastic Kp or Kn-scattering with πK in a final state:

$a_{1/2}m_\pi$	$a_{3/2}m_\pi$	
0.237	-0.074	[Nuovo Cimento 41A (1977) 73]
0.240 ± 0.002	-0.05 ± 0.06	[Nuovo Cimento 43A (1978) 376]
0.13 ± 0.09	-0.13 ± 0.03	[J.Phys.G6 (1980) 583]

$$|a_0^-|m_\pi = \frac{1}{3}|a_{1/2} - a_{3/2}|m_\pi = 0.072^{+0.031}_{-0.020}\Big|_{\text{tot}}$$ [DIRAC Phys. Rev. D **96**, 052002 (2017)]

The measurement of the S-wave πK scattering lengths sensitively checks low energy QCD (LQCD) predictions. Provides the way to understand the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD (u, d and s quarks).

Progress in pionium lifetime measurement

	2001[1]	2001–2003[2]	2008–2010
n_A stat. error	6530 ± 294	21277 ± 407	>22000
τ, 10^{-15} s stat. error, 10^{-15} s syst. error, 10^{-15} s tot. error, 10^{-15} s	2.91 $^{+0.45}_{-0.38}$ $^{+0.19}_{-0.49}$ $^{+0.49}_{-0.62}$	3.15 $^{+0.20}_{-0.19}$ $^{+0.20}_{-0.18}$ * $^{+0.28}_{-0.26}$	
$\lvert a_0^0 - a_0^2\rvert$, $m_{\pi^+}^{-1}$ tot. error, $m_{\pi^+}^{-1}$	0.264 $^{+0.033}_{-0.020}$	0.253 $^{+0.011}_{-0.011}$	

1 [DIRAC Collaboration, Phys. Lett. B619 (2005) 50]
2 [Adeva et al. (DIRAC Collab.), Phys. Lett. B704 (2011) 24]
* Systematic uncertainty is dominated by multiple scattering in the target and in forward detectors — we have performed a direct measurement of scattering in them

Experimental results on (a_0, a_2)

- K_{e4} decay ($K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu_e$)
  $a_0 = 0.233 \pm 0.016 \pm 0.007(\text{syst})$
  $a_2 = -0.0471 \pm 0.011 \pm 0.004(\text{syst})$
  [NA48, Eur. Phys. J. C54 (2008) 411]
- Cusp-effect $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$
  $a_0 - a_2 = 0.2571 \pm 0.0048(\text{stat}) \pm 0.0029(\text{syst}) \pm 0.0088(\text{theor})$
  [NA48/2, EPJ C64 (2009) 589]
- $\pi^{+}\pi^{-}$ atoms
  $|a_0 - a_2| = 0.2533 \ {}^{+0.0078}_{-0.0080}\Big|_{\text{stat}} \ {}^{+0.0072}_{-0.0077}\Big|_{\text{syst}}$
  [DIRAC, Phys. Lett. B704 (2011) 24]
- K_{e4} & $K \to 3\pi$
  $a_0 - a_2 = 0.2639 \pm 0.0020(\text{stat}) \pm 0.0015(\text{syst}))$
  [NA48/2, EPJ C70 (2010) 635]
- ChPT
  $a_0 = 0.220 \pm 0.005, \ a_2 = -0.0444 \pm 0.0010$
  [G. Colangelo et al., Nucl. Phys. B 603 (2001) 125]

We expect progress both by experiments and in theory
[see Peter Stoffer, MESON 2014]

Long-lived $\pi^+\pi^-$ atoms

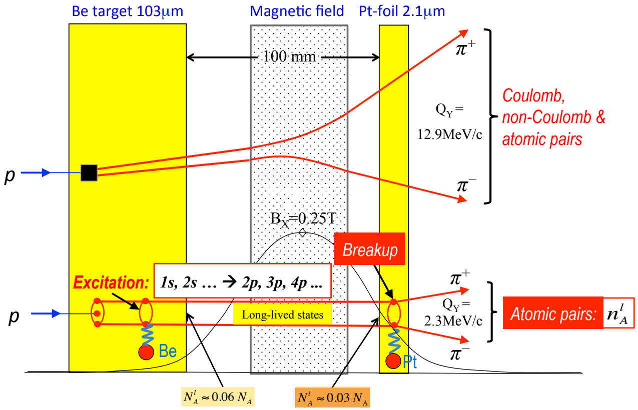
- Atoms are produced in nS-states as $|\Psi_{nS}(0)|^2 \propto \frac{1}{n^3}$
- Atoms get excited, e.g. into nP or nD-states, and leave a target
- Atoms in nS states: lifetime due to annihilation:

  $\tau_{nS} = \tau \cdot n^3$, where $\tau \approx 3 \cdot 10^{-15}$ s
- In vacuum atoms with $l > 0$ can not annihilate as $|\Psi_{nl}(0)|^2 \neq 0$
- Atoms with $l > 0$ undergo radiative deexcitation, e.g. $2P \to 1S$

  $\tau_{2p}^{\text{rad}} = 1.17 \cdot 10^{-11}$ s $\quad \gg \quad \tau \approx 3 \cdot 10^{-15}$ s
- Experimental setup: two thin foils separated by a gap as a target. For $\gamma = 17$: $\lambda(2p) = 5.7$ cm, $\lambda(3p) = 19$ cm
- The observation of long-lived states of $\pi^+\pi^-$ atoms opens the possibility to measure the energy difference between ns and np states $\Delta E^{(ns-np)}$ and the value of $\pi\pi$ scattering lengths $|2a_0 + a_2|$.

Method to observe long-lived $\pi^+\pi^-$ atoms

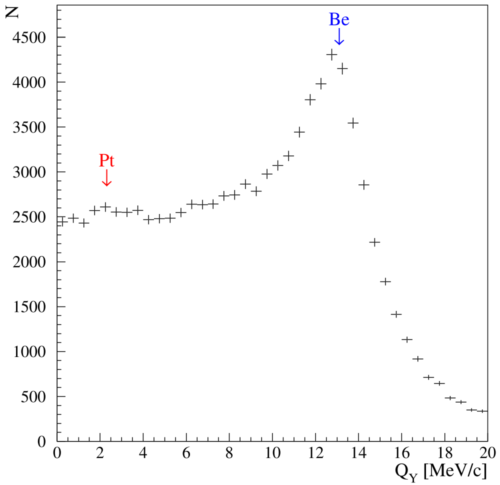
$$\tau_{2p}^{\text{rad}} = 1.17 \cdot 10^{-11}\ \text{s} \gg \tau = 2.9 \cdot 10^{-15}\ \text{s}$$



for $\gamma = 17$:
$\lambda(1s) = 0.02$ mm
$\lambda(2s) = 0.14$ mm
$\lambda(2p) = 5.7$ cm
$\lambda(3s) = 0.46$ mm
$\lambda(3p) = 19$ cm
…

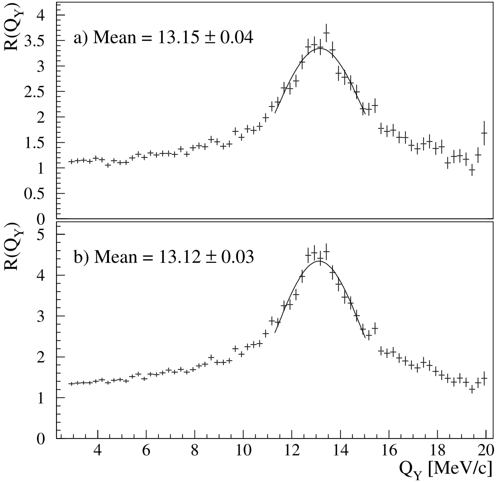
Kink in Q_y for all charged pairs, but not for neutral atoms

Long-lived $\pi^+\pi^-$ atoms: experimental data

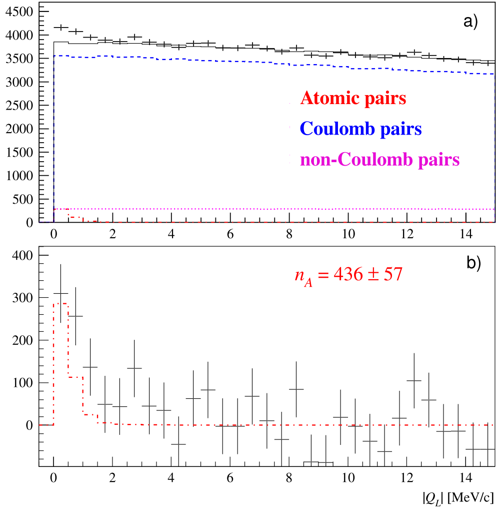


- Kink on Q_y by the magnetic field ($0.02\ \mathrm{T}\cdot\mathrm{m}$):
- 13.1 MeV/c for all charged pairs from Be
- 2.3 MeV/c for pairs from Pt
- Magnetic field is controlled by observing e^+e^- pairs originated either from Be or Pt target

Experiment vs simulation: ratio prompt $\pi^+\pi^-$ over accidentals from Be



First observation of long-lived $\pi^+\pi^-$ atomic pairs



Experimental data

$Q_y = 2.3$ MeV/c kink subtracted

$Q_T < 2$ MeV/c cut

$(|Q_L|, Q_T)$-analysis

Shapes from MC

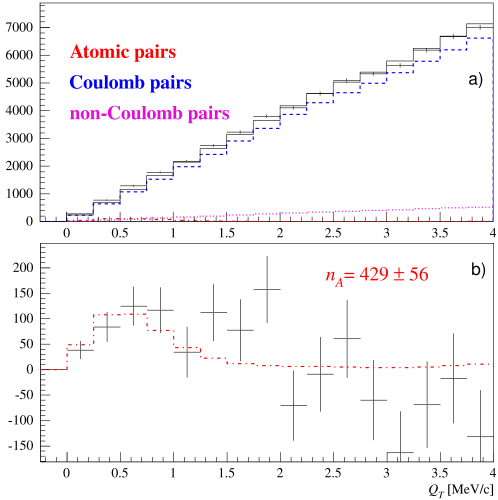
Fit parameters:
n_A^L from Pt
N_{CC} from Be
N_{nC} from Be

$n_A^L = 436 \pm 57|_{stat} \pm 23|_{syst}$

$n_A^L = 436 \pm 61|_{tot}$

[DIRAC, PLB 751 (2015) 12]

First observation of long-lived $\pi^{+}\pi^{-}$ atomic pairs (II)



Experimental data

$Q_y = 2.3$ MeV/c kink subtracted

$|Q_L| < 2$ MeV/c cut

$(|Q_L|, Q_T)$-analysis

Shapes from MC

Fit parameters:

n_A^L from Pt

N_{CC} from Be

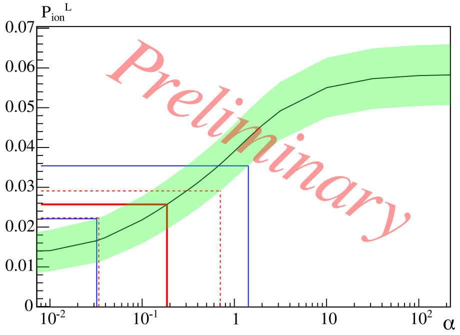
N_{nC} from Be

$n_A^L = 436 \pm 57|_{stat} \pm 23|_{syst}$

$n_A^L = 436 \pm 61|_{tot}$

[DIRAC, PLB 751 (2015) 12]

Long-lived $\pi^+\pi^-$ atom lifetime



Numbers of $\pi^+\pi^-$ atoms:

- $N_A = 16960 \pm 130$ produced in Be
- $n_A^{L,Be} = (6.8 \pm 0.6) \cdot 10^{-2} \times N_A$ left Be in states with $l \geqslant 1$
- Radiative dexcitation between Be and Pt foils $\left(\tau_{2p}^{rad} = 1.17 \cdot 10^{-11}\ s\right)$
- $n_A^{L,Be} = (4.3 \pm 0.6) \cdot 10^{-2} \times N_A$ enter Pt target
- Ionised in Pt and detected
  $n_A^L = (3.9 \pm 0.7) \cdot 10^{-2} \times N_A$ (theory)
  $n_A^L = 436 \pm 61$ (exp)

Factor $\alpha = \frac{\tau_{2p}^{free}}{\tau_{2p}^{rad}} \approx \frac{\tau_{|nlm\rangle}^{free}}{\tau_{|nlm\rangle}^{rad}}$ as a free parameter.

$$P_{ion}^{L} = \frac{n_A^L}{N_A} = 0.0257 \pm 0.0034\Big|_{stat} \,{}^{+0.0091}_{-0.0014}\Big|_{syst} = 0.026^{+0.010}_{-0.004}\Big|_{tot}$$

$$\Rightarrow \quad \alpha = 0.185^{+0.53}_{-0.15}\Big|_{stat} \,{}^{+1.22}_{-0.15}\Big|_{tot}$$

$$\alpha\tau_{2p}^{rad} = \left(2.2^{+14.2}_{-1.8}\Big|_{tot}\right) \cdot 10^{-12}\ s \quad \gg \quad \tau = 2.9 \cdot 10^{-15}\ s$$

Accuracy of a_0^- measurement (πK atoms) with 450 GeV beam

Estimation of time needed to measure a_0^- with statistical accuracy $\delta_{a_0^-}$ on different setups:

- **DIRAC** is the current setup and beam condition (Ni target)
- **Mod1** is for the DIRAC setup at 450 GeV/c beam (small modification due to another geometry of secondary particle channel)
- **Mod2** is for the essentially modified DIRAC setup at 450 GeV/c beam with higher intensity (I_B).

It is assumed that at 450 GeV/c experiment would obtain 3000 spills per day.

Setup	E_p GeV	I_b p/spill	θ_{lab}	Solid angle sr	Beam time s	Run time months	$\delta_{a_0^-}$ $\times 10^{-2}$
DIRAC	24	$2.7 \cdot 10^{11}$	5.7	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{6}$	14.5	43.
Mod1	450	$1.0 \cdot 10^{11}$	4.0	$0.6 \cdot 10^{-3}$	$5.5 \cdot 10^{6}$	13.6	5.
Mod2	450	$1.0 \cdot 10^{12}$	4.0	$0.6 \cdot 10^{-3}$	$6.5 \cdot 10^{5}$	1.6	5.

Results and Outlook — To the memory of Valery Yazkov (Dec. 2017)

- Double exotic atoms are unique systems to study strong interaction at threshold
- First measurement of $A_{\pi K}$ lifetime

$$\tau = 5.5^{+5.0}_{-2.8}\Big|_{\text{tot}} \times 10^{-15}\text{s}$$

and corresponding πK scattering length

$$|a_0^-|m_\pi = \frac{1}{3}|a_{1/2} - a_{3/2}|m_\pi = 0.072^{+0.031}_{-0.020}\Big|_{\text{tot}}$$

- First measurement of long-lived $\pi^+\pi^-$ atom lifetime

$$\alpha\tau_{2p}^{\text{rad}} = \left(2.2^{+14.2}_{-1.8}\Big|_{\text{tot}}\right)\cdot 10^{-12}\text{ s} \quad \gg \quad \tau = 2.9\cdot 10^{-15}\text{ s}$$

Main tasks for DIRAC:

- Improve precision in pionium lifetime measurement
- Finalize analysis of Coulomb correlated K^+K^- pairs
- Proposal for higher beam momenta (SPS 450 GeV/c)