First πK atom lifetime measurement and recent results from the DIRAC experiment

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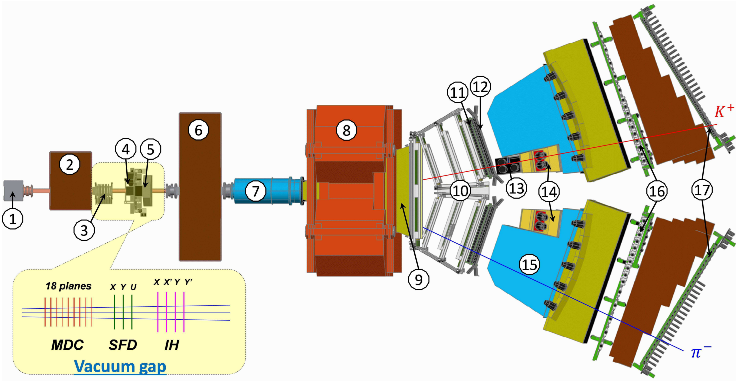
The DIRAC Collaboration

- **1998–2003** Lifetime measurement of $\pi^+\pi^-$-atoms ($A_{2\pi}$)
- **2007–2012** 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

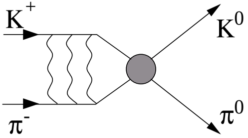
Use double-arm spectrometer at CERN Proton Syncrotron (24 GeV/c)



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]:

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

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

[P.Büttiker et al., Eur. Phys. J. C33 (2004) 409]:

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

Lattice calculations

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

[Z.Fu, Phys. Rev. D85 (2012) 074501] $\quad M_\pi a_0^- = 0.0777 \pm 0.0013 \pm ?$

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

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 $A_{\pi K}$

$$\lambda_{\text{int}}^{1S} \approx 50\ \mu\text{m in Ni}$$

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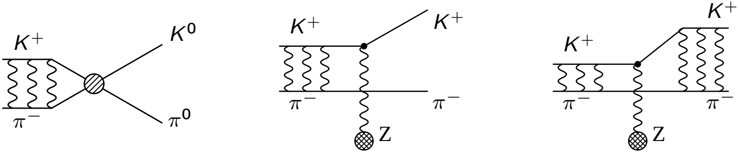
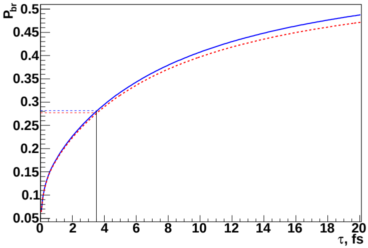
- Unique $P_{\text{ion}} = \dfrac{n_A}{N_A} = P_{\text{ion}}(\tau)$ relation

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

$A_{\pi K}$ 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 $P_{\rm ion}(\tau)$
  [M. Zhabitsky, 2008, Sov. J. Nucl. Phys 71, 1040]

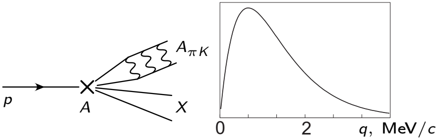
$A_{\pi K}$ generation

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

- Atoms are generated in nS-states

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

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

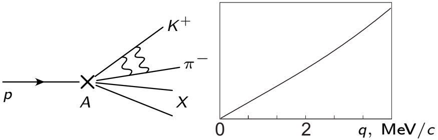


Other sources of inclusive $\pi^{\pm}K^{\mp}$-pairs:

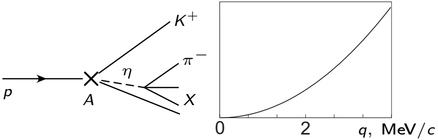
- Coulomb pairs

  $N_A = kN_C(q < q_0)$

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



- Non-correlated pairs

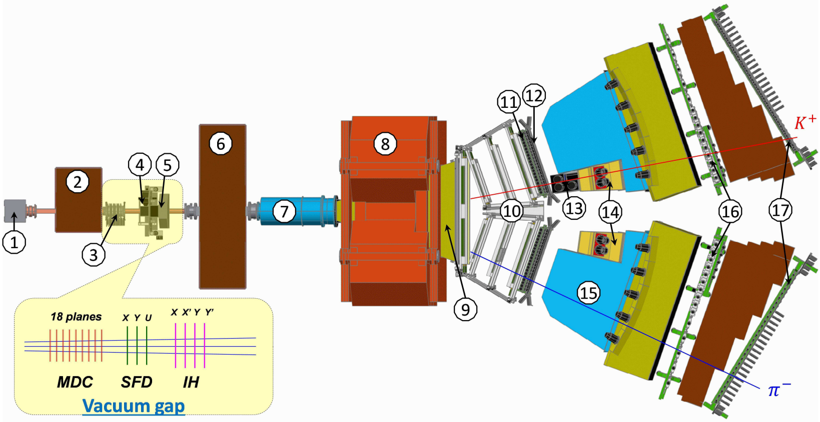


$$P_{\text{ion}} = \frac{n_A}{N_A} = \frac{n_A}{kN_C}$$

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

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.	$\sigma_{Q_x} \approx \sigma_{Q_y} \approx 0.2$ MeV/c
	$\sigma_{Q_l} \approx 0.85$ MeV/c

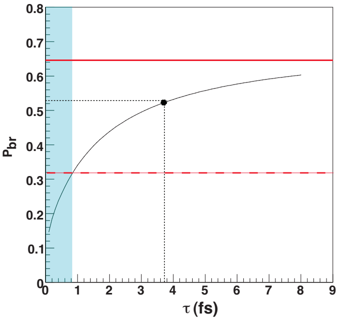


First evidence for $\pi^{\pm}K^{\mp}$ atoms

Thin Pt target 28μm, 2007:

$$n_A(\pi^- K^+) = 143 \pm 53, \quad n_A(\pi^+ K^-) = 29 \pm 15$$

Evidence for πK-atoms observation with DIRAC
[Adeva et al. (DIRAC Collaboration) Phys. Lett. B674 (2009) 11]



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

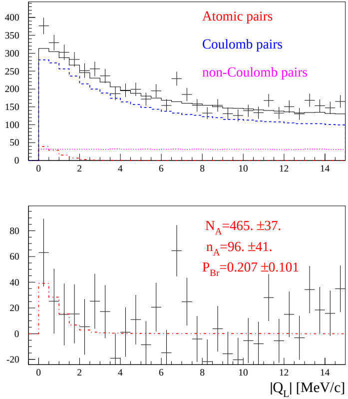
$$N_A(\pi^- K^+ + \pi^+ K^-) = kN_C = 280 \pm 70$$

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

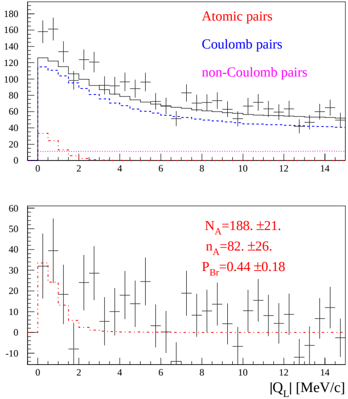
Lifetime measurement of $\pi^{\pm}K^{\mp}$ atoms

Ni targets 98 μm and 108 μm, 2008–2010
Two-dimensional (Q_T, Q_L) fit of experimental data:

$\pi^- K^+$

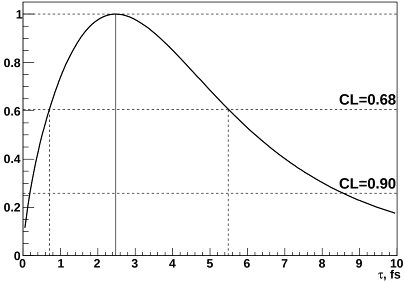


$\pi^+ K^-$



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

Year	N_A	n_A	P_{br}
π^-K^+ over Q_T, Q_L			
2008	132 ± 16	14 ± 19	0.11 ± 0.15
2009	169 ± 24	33 ± 26	0.20 ± 0.17
2010	164 ± 23	49 ± 26	0.30 ± 0.19
All	465 ± 37	96 ± 41	
π^+K^- over Q_T, Q_L			
2008	51 ± 11	21 ± 13	0.41 ± 0.33
2009	78 ± 13	26 ± 16	0.34 ± 0.24
2010	60 ± 12	35 ± 16	0.58 ± 0.36
All	188 ± 21	82 ± 26	

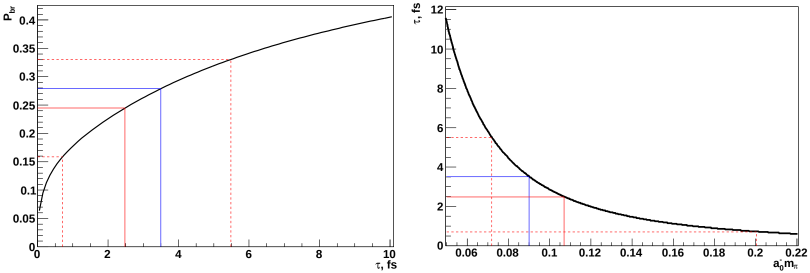


$$n_A(\pi^-K^+ + \pi^+K^-) = 178 \pm 49$$

$$\tau = \left(2.5\ {}^{+3.0}_{-1.8}\Big|_{\text{stat}}\ {}^{+0.3}_{-0.1}\Big|_{\text{syst}}\right) \cdot 10^{-15}\text{s} = \left(2.5\ {}^{+3.0}_{-1.8}\Big|_{\text{tot}}\right)\ \text{fs}$$

[DIRAC Collaboration, subm. Phys. Lett. B (2014), CERN-PH-EP-2014-030, arXiv:1403.0845]

πK scattering lengths



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

$$|a_0^-|m_\pi = \frac{1}{3}|a_{1/2} - a_{3/2}|m_\pi = 0.11^{+0.09}_{-0.04}.$$

[DIRAC Collaboration, subm. Phys. Lett. B (2014), CERN-PH-EP-2014-030, arXiv:1403.0845]

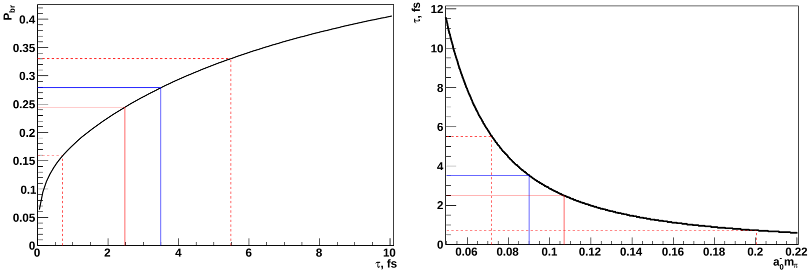
πK scattering lengths: experimental results

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]

$$|a_0^-|m_\pi = \frac{1}{3}|a_{1/2} - a_{3/2}|m_\pi = 0.11^{+0.09}_{-0.04}$$ [DIRAC, arXiv:1403.0845]

Work towards better precision in $A_{\pi K}$ lifetime measurement



$$|a_0^-|m_\pi = 0.11^{+0.09}_{-0.04}.$$

- to include events with high background in forward detectors ($\sim 1/3$ of statistics)
- Combination of Pt and Ni measurements
  Pt: $\tau > 0.8 \cdot 10^{-15}$s (CL=0.9)
  Ni: $\tau = \left(2.5\ {}^{+3.0}_{-1.8}\Big|_{\text{tot}}\right) \cdot 10^{-15}$s

Progress in pionium lifetime measurement

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

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]

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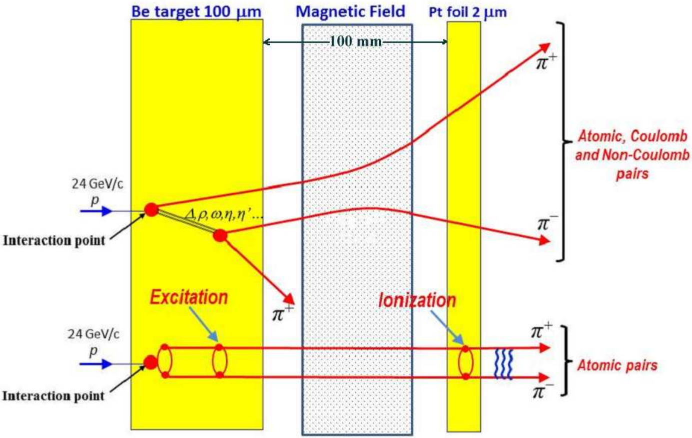
Method to observe long-lived $\pi^+\pi^-$ atoms



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

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

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 $|2a_0 + a_2|$.

$A_{2\pi}$ and $A_{\pi K}$ production on PS and SPS at CERN

The ratio of yields at the proton momentum 450 GeV$/c$ and angle 4° (CERN SPS) to the yields at the proton momentum 24 GeV$/c$ and angle 5.7° (CERN PS):

$A_{\pi^+K^-}$	35
$A_{K^+\pi^-}$	27
$A_{2\pi}$	17

Results and Outlook

- Evidence for $\pi^{\pm}K^{\mp}$ atoms on Pt and Ni targets

$$\text{Pt: } n_A = 173 \pm 54, \quad \text{Ni: } n_A = 178 \pm 49$$

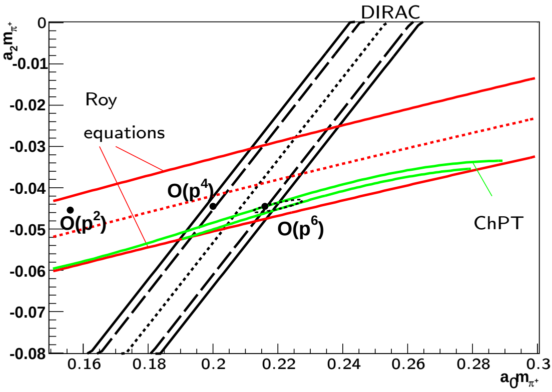
- First measurement of $A_{\pi K}$ lifetime

$$\tau = \left(2.5\ {}^{+3.0}_{-1.8}\Big|_{\text{tot}}\right) \text{ fs}$$

Main tasks for DIRAC:

- Analysis of Pt and Ni data to achieve $A_{\pi K}$ observation
- Improve precision in pionium lifetime measurement
- Observation of long-lived states of $\pi^{+}\pi^{-}$ atoms
- Looking forward higher beam momenta (SPS 450 GeV/c)

(a_0^0, a_0^2) $\pi\pi$ scattering lengths



ChPT:

$O(p^2)$: F_π, m_π

$O(p^4)$: l_1, l_2, l_3, l_4

Quark condensate in ChPT

$$M_\pi^2 = (m_u + m_d) \lim_{m_u, m_d \to 0} \frac{|\langle 0|\bar{u}u|0\rangle|}{F_\pi^2} + O(m_q^2) = M^2 + O(m_q^2)$$

[M. Gell-Mann, R.G. Oakes, B. Renner, Phys. Rev. 175 (1968) 2195]

$$M_\pi^2 = M^2 - \frac{\bar{l}_3}{32\pi^2 F^2} M^4 + O\left(M^6\right)$$