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

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Abstract. We report evidence for πK atoms production, using 24 GeV/c proton beam from CERN PS interacting with a thin Ni target. We have identified (178 ± 49) πK pairs, which were produced in a bound state — πK atom, which was subsequently broken-up (ionized) in the Ni target. Our analysis yields a first measurement of the πK atom lifetime $(2.5^{+3.0}_{-1.8})$ fs [1]. This lifetime is connected in a model-independent way to the S-wave isospin-odd πK scattering length $|a_0^-| = \frac{1}{3}|a_{1/2} - a_{3/2}| = (0.11^{+0.09}_{-0.04}) M_\pi^{-1}$ (a_I for isospin I).

1 Introduction

Low-energy QCD and specifically Chiral Perturbation Theory (ChPT) [2] predict $\pi\pi$ and πK scattering lengths with high precision [3, 4]. For processes involving u - and d -quarks theoretical predictions have been experimentally checked by $\pi^+\pi^-$ atom lifetime measurement [5] and by analysis of K -decays [6, 7]. Detection and lifetime measurement of πK atom cast a look into processes which involve s -quark as well.

$A_{\pi K}$ (πK atom) is an exotic atom — a hydrogen-like bound system of oppositely charged π and K mesons. Its ground state binding energy is 2.9 keV, Bohr radius $a_B = 249$ fm and Bohr momentum is 0.79 MeV/c. Lifetime of πK atoms is limited by strong interaction through the decay into a pair of neutral pion and kaon, $\pi^0 K^0$ or $\pi^0 \bar{K}^0$, other decay channels contribution is of the order 10^{-3} . The $A_{\pi K}$ decay width $\Gamma_{\pi K}$ in the ground state (1S) is directly related to the S-wave isospin-odd πK scattering length $a_0^- = \frac{1}{3}(a_{1/2} - a_{3/2})$ [8, 9]:

$$\Gamma_{\pi K} = \frac{1}{\tau} \simeq \Gamma(A_{\pi K} \rightarrow \pi^0 K^0 \text{ or } \pi^0 \bar{K}^0) = 8\alpha^3 \mu^2 p^* (a_0^-)^2 (1 + \delta_K). \quad (1)$$

Here τ is the lifetime in the ground state, a_I is the scattering length for isospin I , α is the fine structure constant, μ is the reduced mass of $\pi^\pm K^\mp$ pair, p^* is the outgoing π^0 momentum in the atomic rest frame, and δ_K summarizes corrections due to isospin breaking.

Inserting in (1) the value $M_\pi a_0^- = 0.090 \pm 0.005$ calculated with the dispersion analysis [10] and using $\delta_K = 0.040 \pm 0.022$ [9] predicts the πK atom lifetime

$$\tau = (3.5 \pm 0.4) \cdot 10^{-15} \text{ s}. \quad (2)$$

DIRAC experiment aims to measure the πK atom lifetime, thus checking the ChPT prediction.

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2 Experimental method

The method of $A_{\pi K}$ lifetime measurement [11] used by DIRAC experiment is as follows. $A_{\pi K}$ originate from collisions of 24 GeV/c protons with Ni atoms. Atoms are produced in nS-states, depending on the principal quantum number as n^{-3} [11]:

$$\frac{d\sigma_A}{d\vec{p}_A} = (2\pi)^3 \frac{E_A}{M_A} \frac{d^2\sigma_s^0}{d\vec{p}_K d\vec{p}_\pi} \bigg|_{\substack{\vec{p}_K \approx \vec{p}_\pi \\ M_K \approx M_\pi}} \cdot |\psi_n(0)|^2 = (2\pi)^3 \frac{E_A}{M_A} \frac{1}{\pi a_B^3 n^3} \frac{d^2\sigma_s^0}{d\vec{p}_K d\vec{p}_\pi} \bigg|_{\substack{\vec{p}_K \approx \vec{p}_\pi \\ M_K \approx M_\pi}}, \quad (3)$$

where $\vec{p}_A$, E_A and M_A are the momentum, total energy and mass of the πK atom in the laboratory system, respectively, and $\vec{p}_K$ and $\vec{p}_\pi$ the momenta of the charged kaon and pion with equal velocities. The inclusive production cross section from short-lived sources without final state interaction is denoted as σ_s^0 , $\psi(0)$ stands for the atomic wave function at the origin.

On a similar way, free $\pi^\pm K^\mp$ pair production from short-lived sources is enhanced by a Gamow-Sommerfeld-Sakharov factor [12] as a function of their relative momentum q :

$$\frac{d^2\sigma_C}{d\vec{p}_K d\vec{p}_\pi} = \frac{d^2\sigma_s^0}{d\vec{p}_K d\vec{p}_\pi} \frac{4\pi\mu\alpha/q}{1 - \exp(-4\pi\mu\alpha/q)}. \quad (4)$$

Thus the total number N_A of produced atoms is proportional to the number N_C of Coulomb pairs generated with small relative momentum:

$$N_A = k(q_0)N_C(q \leq q_0). \quad (5)$$

While crossing the target, πK atoms can be excited or even ionized (break-up) due to Coulomb interaction with target atoms. Pairs of $\pi^\pm K^\mp$ mesons from πK atom break-up, called atomic pairs later in the text, are characterized by low relative momenta q in their center of mass system. Thanks to their distinct shape, atomic pairs can be revealed in a reconstructed Q distribution (Q stands for experimental relative momentum) by an experiment with sufficiently high momentum resolution. Thus a number n_A of atomic pairs can be identified from the experimental Q -spectra over background of free πK pairs. Ionization of πK atoms in the target is in competition with their annihilation. Therefore the probability $P_{br} = n_A/N_A$ of $A_{\pi K}$ ionization in the target is a unique function of its lifetime τ , which is calculated with sufficient precision [13, 14] (Fig. 1).

Figure 1. Probability of $A_{\pi K}$ ionization as a function of the ground state lifetime τ calculated for Ni targets of thickness 98 μm (dashed red line) and 108 μm (solid blue line). The theoretically predicted lifetime τ (Eq. 2) corresponds to $P_{br} = 0.28$.

Earlier this method was successfully applied to measure the lifetime of exotic $\pi^+\pi^-$ atoms [5]. First evidence for πK atoms through the observation of (173 ± 54) πK atomic pairs produced on 26 μm Pt target in 2007 has been published [15]. In the current work data from Ni targets is analysed, as for Ni a function $P_{br}(\tau)$ provides better sensitivity to the lifetime τ .

3 Experimental setup

The DIRAC Collaboration constructed the double arm magnetic spectrometer which is optimized to detect and identify $\pi^+\pi^-$, π^+K^- and π^-K^+ pairs with small relative momenta Q . The sketch of the apparatus is shown on Fig. 2.

Figure 2. General view of the DIRAC setup: 1 — target station; 2 — first shielding; 3 — microdrift chambers; 4 — scintillating fiber detector; 5 — ionisation hodoscope; 6 — second shielding; 7 — vacuum channel; 8 — spectrometer magnet; 9 — vacuum chamber; 10 — drift chambers; 11 — vertical hodoscope; 12 — horizontal hodoscope; 13 — aerogel Cherenkov; 14 — heavy gas Cherenkov; 15 — nitrogen Cherenkov; 16 — preshower; 17 — muon detector.

The experiment uses a 24 GeV/c primary proton beam from the CERN PS. Protons are directed onto a pure Ni thin foil with a radiation thickness of $\sim 7 \cdot 10^{-3} X_0$. The DIRAC apparatus with its secondary channel is inclined by 5.7° with respect to the primary proton beam. Tracking detectors are positioned in two groups: between the target station and the spectrometer magnet ($BL = 2.2 \text{ T}\cdot\text{m}$), and downstream the magnet. The resolution of the setup on components of pair relative momenta in c.m.s. $\sigma_{Q_x} \approx \sigma_{Q_y} \approx 0.2 \text{ MeV}/c$ and $\sigma_{Q_L} \approx 0.85 \text{ MeV}/c$ is comparable to $A_{\pi K}$ Bohr momentum. Particle identification ($e/\mu/\pi/K/p$) is performed through a combination of time-of-flight technique, threshold Cherenkov detectors and muon veto.

4 Experimental results

The data sample was collected on two Ni targets with thickness $(98 \pm 1) \mu\text{m}$ in 2008 and $(108 \pm 1) \mu\text{m}$ in 2009 and 2010. Events containing $\pi^\pm K^\mp$ pairs with low relative momenta Q in their centre-of-mass system were selected. Then the reconstructed 2-dimensional (Q_T, Q_L) distribution of πK pairs was fitted by a sum of simulated distributions of atomic, Coulomb and non-Coulomb pairs with abundances of each component as free fit parameters. Here Q_L corresponds to a component of the relative momentum parallel to the direction of pair total momentum, while Q_T comprises the transverse component. In the low Q_L region (Fig. 3), where atomic pairs are expected, there is an excess of events over the background of free pairs. Fit results for all data periods are summarized in

Figure 3. Experimental distributions on $|Q_L|$ for $\pi^- K^+$ (left) and $\pi^+ K^-$ pairs (right). Top: experimental $|Q_L|$ distribution (crosses) is fitted by the sum of simulated distributions of atomic (red), Coulomb (blue) and non-Coulomb pairs (pink). The sum of free pair (Coulomb and non-Coulomb) distributions is shown by solid black line. Bottom: the difference between experimental and free pair distributions is compared to simulated distribution for atomic pairs.

Table 1. Experimental results for number of produced atoms N_A , number of observed atomic pairs n_A and probability of break-up P_{br} reconstructed by (Q_T, Q_L) -analysis from collected data.

Year	N_A	n_A	P_{br}
$\pi^- K^+$ from (Q_T, Q_L) -analysis			
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	
$\pi^+ K^-$ from (Q_T, Q_L) -analysis			
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	

Table 1. In total, the number of reconstructed atomic pairs of both charge combinations amounts to $n_A(\pi^- K^+ + \pi^+ K^-) = 178 \pm 49$.

The lifetime dependence $P_{br,i}(\tau)$ for each period i of data taking was calculated, which takes into account the target thickness and experimental spectrum on $\pi^+ K^-$ or $\pi^- K^+$ laboratory momenta. The maximum likelihood method has been applied

$$L(\tau) = \exp\left(-U^T G^{-1} U/2\right), \quad (6)$$

Figure 4. Likelihood function for $A_{\pi K}$ lifetime estimation based on both charged combinations $\pi^+ K^-$ and $\pi^- K^+$ and all data periods combined, systematic uncertainties are included.

Figure 5. Dependence of $A_{\pi K}$ lifetime in the ground state τ on πK scattering length a_0^- . Experimental result (red) is compared to theoretical prediction (blue).

where $U_i = \Pi_i - P_{\text{br},i}(\tau)$ is a vector of differences between measured Π_i (P_{br} in Table 1) and theoretical breakup probability $P_{\text{br},i}(\tau)$ for data sample i . The error matrix G includes both statistical and systematic uncertainties [16]. The combined likelihood function $L(\tau)$ for both charge combinations is shown on Fig. 4. Its maximum yields the following estimation of πK atom lifetime in the ground state:

$$\tau = \left(2.5^{+3.0}_{-1.8} \Big|_{\text{stat}} {}^{+0.3}_{-0.1} \Big|_{\text{syst}} \right) \text{fs} = \left(2.5^{+3.0}_{-1.8} \Big|_{\text{tot}} \right) \text{fs}. \quad (7)$$

The estimated ground state lifetime (7) corresponds to the πK scattering length (1)

$$|a_0^-| M_\pi = \frac{1}{3} |a_{1/2} - a_{3/2}| M_\pi = 0.11^{+0.09}_{-0.04}, \quad (8)$$

to be compared with the theoretical predictions (Eq. 2, Fig. 5).

5 Conclusions

The analysis of πK data collected by DIRAC experiment in 2008–2010 leads to the observation of $n_A(\pi^- K^+ + \pi^+ K^-) = 178 \pm 49$ (3.6 sigma) characteristic atomic pairs of both charge combinations. The probability of $A_{\pi K}$ ionization (break-up) has been measured. Combined with the known dependence of break-up probability on atom lifetime, this results in a first measurement of the πK atom lifetime in the ground state $\tau = \left(2.5^{+3.0}_{-1.8} \Big|_{\text{tot}} \right) \text{fs}$. As the atom lifetime is related to a scattering length, a measurement of the S-wave isospin-odd πK scattering length $|a_0^-| = \left(0.11^{+0.09}_{-0.04} \right) M_\pi^{-1}$ has been presented.

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References

- [1] B. Adeva et al. (DIRAC Collaboration), Phys. Lett. **B** 735 (2014) 288; arXiv:1403.0845.

- [2] J. Gasser, H. Leutwyler, Nucl. Phys. **B** 250 (1985) 465.
- [3] G. Colangelo, J. Gasser, H. Leutwyler, Nucl. Phys. **B** 603 (2001) 125.
- [4] J. Bijnens, P. Dhonte, P. Talavera, JHEP05 (2004) 036.
- [5] B. Adeva et al. (DIRAC Collaboration), Phys. Lett. **B** 704 (2011) 24.
- [6] J.R. Batley et al. (NA48/2 Collaboration), Eur. Phys. J. **C** 64 (2009) 589.
- [7] J.R. Batley et al. (NA48/2 Collaboration), Eur. Phys. J. **C** 70 (2010) 635.
- [8] S.M. Bilen'kii et al., Sov. J. Nucl. Phys. 10 (1969) 469.
- [9] J. Schweizer, Phys. Lett. **B** 587 (2004) 33.
- [10] P. Buettiker, S. Descotes-Genon, B. Moussallam, Eur. Phys. J. **C** 33 (2004) 409.
- [11] L.L. Nemenov, Sov. J. Nucl. Phys. 41 (1985) 629.
- [12] A. Sakharov, Zh. Eksp. Teor. Fiz. 18 (1948) 631;
reprinted in Sov. Phys. Usp. 34 (1991) 375.
- [13] C. Santamarina et al., J. Phys. **B** 36 (2003) 4273.
- [14] M. Zhabitsky, Phys. At. Nucl. 71 (2008) 1040.
- [15] B. Adeva et al. (DIRAC Collaboration), Phys. Lett. **B** 674 (2009) 11.
- [16] V. Yazkov, M. Zhabitsky, DIRAC NOTE-2013-06 (cds.cern.ch/record/1628544).