PoS PROCEEDINGS OF SCIENCE

First observation of $\pi^- K^+$ and $\pi^+ K^-$ atoms, their lifetime measurement and πK scattering lengths evaluation

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The Low Energy QCD allows to calculate the $\pi\pi$ and πK scattering lengths with high precision. There are accurate relations between these scattering lengths and $\pi^+\pi^-$, $\pi^- K^+$, $\pi^+ K^-$ atoms lifetimes. The experiment on the first observation of $\pi^- K^+$ and $\pi^+ K^-$ atoms is described. The atoms were generated in Nickel and Platinum targets hit by the PS CERN proton beam with momentum of 24 GeV/c. Moving in the target, part of atoms break up producing characteristic πK pairs (atomic pairs) with small relative momentum Q in their c.m.s. In the experiment, we detected $n_A = 349 \pm 62$ (5.6 standard deviations) $\pi^- K^+$ and $\pi^+ K^-$ atomic pairs. The main part of πK pairs are produced in free state. The majority of such particles are generated directly or from short-lived sources as ρ, ω and similar resonances. The electromagnetic interactions in the final state create Coulomb pairs with a known sharp dependence on Q. This effect allows to evaluate the number of these Coulomb pairs. There is a precise ratio ($\sim$1%) between the number of $\pi^- K^+$ ($\pi^+ K^-$) Coulomb pairs with small Q and the number of produced $\pi^- K^+$ ($\pi^+ K^-$) atoms. Using this ratio, we obtained the numbers of generated $\pi^- K^+$ and $\pi^+ K^-$ atoms. The atom breakup probability in a target $P_{\rm br} = n_A/N_A$ depends on the atom lifetime. Using such dependences for the Ni and Pt targets, known with a precision about 1%, the πK atom lifetime was measured and from this value the πK scattering lengths were evaluated.

The presented analysis shows that the $\pi^- K^+$ and $\pi^+ K^-$ atoms production in the p-nucleus interactions increases by 16 and 38 times respectively if the proton momentum is increased from 24 GeV/c up to 450 GeV/c.

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1. Introduction

The DIRAC experiment aims to observe and study hydrogen-like atoms formed by pairs of $\pi^+\pi^-$ and $\pi^\pm K^\mp$ mesons using the 24 GeV extracted beam of PS CERN. The lifetime of these atoms is dictated by the strong interaction between the components. Thus combining of hadrons into a hydrogen-like atom opens a unique possibility to study a property of the strong interaction at the very low relative momenta which are of order of the atom Bohr momentum. For $\pi^+\pi^-$ atom it is 0.5 MeV, for πK — 0.8 MeV. Hence the region of QCD confinement becomes available for investigation.

A measurement of the πK atom lifetime provides a direct determination of an S-wave πK scattering length difference [1]. This atom is an electromagnetically bound πK state with a Bohr radius of a_B = 249 fm and a ground state binding energy of E_B = 2.9 keV. It decays predominantly by strong interaction into two neutral mesons $\pi^0 K^0$ or $\pi^0 \bar{K}^0$. The atom decay width $\Gamma_{\pi K}$ in the ground state (1S) is given by the relation [2]:

$$\Gamma_{\pi K} = \frac{1}{\tau} \simeq \Gamma(A_{K\pi} \to \pi^0 K^0 \; or \; \pi^0 \bar{K}^0) = 8\,\alpha^3\,\mu^2\,p^*\,(a_0^-)^2\,(1+\delta_K). \tag{1.1}$$

The S-wave isospin-odd πK scattering length $a_0^- = \frac{1}{3}(a_{1/2} - a_{3/2})$, a_I for isospin I, is defined in pure QCD for quark masses $m_u = m_d$, α is the fine structure constant, μ = 109 MeV/c^2 the reduced mass of the $\pi^\mp K^\pm$ system, p^* = 11.8 MeV/c the outgoing π^0 or K^0 ($\bar{K}^0$) momentum in the πK atom system, and δ_K accounts for corrections, due to isospin breaking, at order α and quark mass difference $(m_u - m_d)$.

The $M_\pi a_0^-$ value were calculated in SU(3) ChPT at the 1 and 2-*loop* level [3] and using Roy-Steiner equations [4] (M_π is charged pion mass). This leads to the lifetime estimation $\tau = (3.5 \pm 0.4) \cdot 10^{-15}$ s. Last results of Lattice QCD [5] confirm this calculation.

The first πK atom investigation have been performed with Platinum target by DIRAC in 2007 [6]. An enhancement of πK pairs at low relative momentum is observed and corresponds to 173 ± 54 πK atomic pairs.

For a lifetime measurement a target material like Ni was used because of its breakup probability rapidly rising with lifetime around $3.5 \cdot 10^{-15}$ s. In the dedicated experiment performed in 2008–2010 at $P_\mathrm{p} = 24$ GeV/c and Ni target [7] has been detected 178 ± 49 atomic pairs. The analysis yields a first value for the πK atom lifetime of $\tau = (2.5^{3.0}_{1.8}) \cdot 10^{-15}$ s and a first model-independent measurement of the πK scattering length $\left|a_0^-\right| = \left(0.11^{+0.09}_{-0.04}\right) M_\pi^{-1}$.

In the present work experimental data obtained on Pt target has been analysed using all available data and improved background description. The setup software tuning and calibration, background suppression and background admixture evaluation have been improved.

2. Experimental setup

The apparatus [8] sketched in Fig. 1 detects and identifies $\pi^+\pi^-$, $\pi^- K^+$ and $\pi^+ K^-$ pairs with small Q. The structure of these pairs after the magnet is approximately symmetric for $\pi^+\pi^-$ and asymmetric for πK. Originating from a bound system these particles travel with the same velocity, and therefore for πK the kaon momentum is by a factor of about $\frac{M_K}{M_\pi} = 3.5$ larger than the pion momentum (M_K is charged kaon mass). The 2-arm vacuum magnetic spectrometer as presented is optimized for simultaneous detection of these pairs.

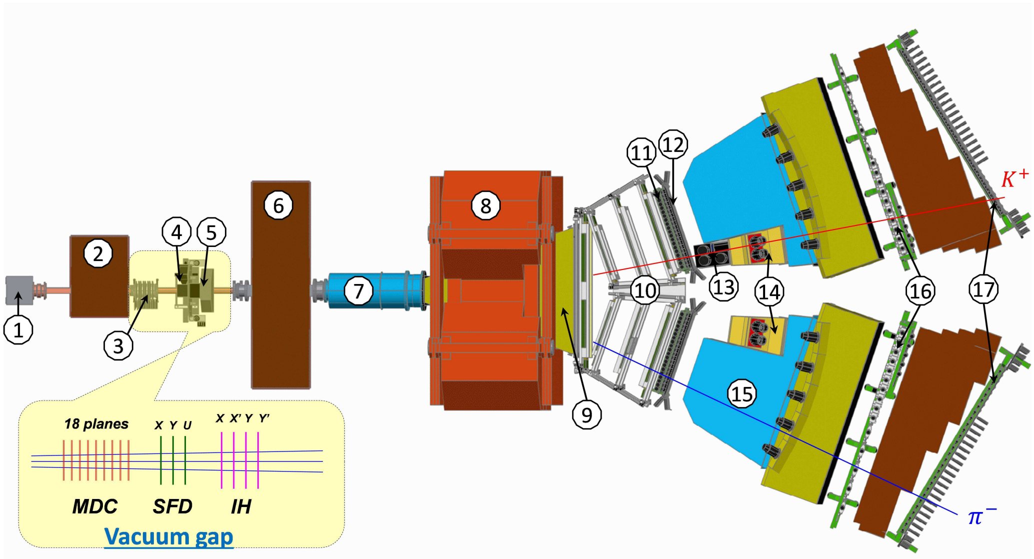

Figure 1: General view of the DIRAC setup: 1 – target station; 2 – first shielding; 3 – microdrift chambers; 4 – scintillating fiber detector; 5 – ionisation hodoscope; 6 – second shielding; 7 – vacuum tube; 8 – spectrometer magnet; 9 – vacuum chamber; 10 – drift chambers; 11 – vertical hodoscope; 12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

The 24 GeV/c primary proton beam from the CERN PS hits Pt target with thickness (26 ± 1) μm, Ni targets with thicknesses of (98 ± 1) μm (Ni-1) in 2008 and (108 ± 1) μm (Ni-2) in 2009 and 2010. The secondary channel(solid angle $\Omega = 1.2 \cdot 10^{-3}$ sr)) with the whole setup is vertically inclined relative to the proton beam by 5.7° upward. Secondary particles are confined by the rectangular beam collimator inside of the second steel shielding wall, and the angular divergence in the horizontal (X) and vertical (Y) planes is $\pm 1°$. With a spill duration of 450 ms the beam intensity has been (10.5–12)$\cdot 10^{10}$ protons/spill and, correspondingly, the single counting rate in one plane of the ionisation hodoscope (IH) (5–6)$\cdot 10^{6}$ particles/spill. Secondary particles propagate mainly in vacuum up to the Al foil at the exit of the vacuum chamber, which is located between the poles of the dipole magnet (B_{max} = 1.65 T and BL = 2.2 Tm).In the vacuum gap MicroDrift Chambers (MDC) with 18 planes and a Scintillating Fiber Detector (SFD) with 3 planes (X, Y, U) have been installed to measure particle coordinates ($\sigma_{SFDx} = \sigma_{SFDy} = 60$ μm, $\sigma_{SFDu} = 120$ μm) and particle time ($\sigma_{tSFDx} = 380$ ps, $\sigma_{tSFDy} = \sigma_{tSFDu} = 520$ ps). The four IH planes serve to identify unresolved double tracks (signal only from one SFD column).

Each spectrometer arm is equipped with the following subdetectors: drift chambers (DC) to measure particle coordinates with $\approx$85 μm precision; vertical hodoscope (VH) to measure time with 110 ps accuracy for particle identification via time-of-flight determination; horizontal hodoscope (HH) to select in the two arms particles with vertical distances less than 75 mm (Q_Y less than 15 MeV/c); aerogel Cherenkov counter (ChA) to distinguish kaons from protons; heavy gas

(C_4F_{10}) Cherenkov counter (ChF) to distinguish pions from kaons; nitrogen Cherenkov (ChN) and preshower (PSh) detector to identify e^+e^- pairs; iron absorber and two-layer muon scintillation counter (Mu) to identify muons. In the "negative" arm no aerogel counter has been installed, because the number of antiprotons is small compared to K^-.

3. Observation and lifetime measurement of $\pi^{\pm}K^{\mp}$ atoms

Figures 2 present experimental data on observation of πK atomic pairs of both sign for 1-dimensional analysis over Q. Table 1 summarize number of observed πK atomic pairs for all types of analysis. After account systematic errors the final results for 2-dimensional analysis over $(|Q_L|, Q_T)$ written:

$$n_A = 314 \pm 59(stat) \pm 10(syst) = 314 \pm 60(tot). \tag{3.1}$$

For 1-dimensional analysis over Q the most accurate value published in [9]:

$$n_A = 349 \pm 61(stat) \pm 9(syst) = 349 \pm 62(tot). \tag{3.2}$$

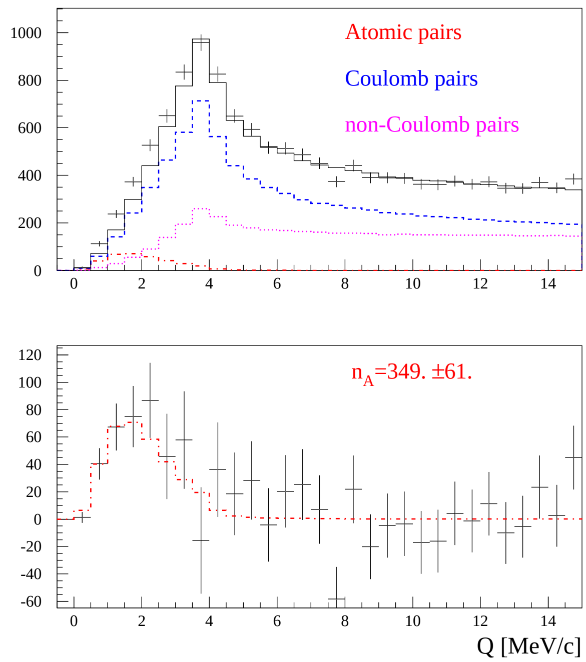

Figure 2: Experimental distribution of $K^+\pi^-$ and π^+K^- pairs (points with error bars) collected with Platinum and Nickel targets is fitted by a sum of simulated distributions of "atomic", "Coulomb" and "non-Coulomb" pairs. Background distribution of free pairs ("Coulomb" and "non-Coulomb") is shown by black line; b) difference of experimental and simulated distribution of "free" pairs is compared with simulated distributions of "atomic pairs" ($\chi^2/n = 41/37$, $n =$ number of degrees of freedom; in absence of "atomic pairs" $\chi^2/ndf = 73/38$).

Table 2 includes the measured value of break-up probability $P_{\rm br}$ of πK atoms for all data sets separately. Using these data and the calculated dependence of $P_{\rm br}$ on the lifetime, shown in Fig. 3,

Table 1: Number of detected πK atomic pairs for all analysis.

Analysis	$\pi^- K^+$	$\pi^+ K^-$	$\pi^- K^+$ and $\pi^+ K^-$
Q	243 ± 51 (4.7σ)	106 ± 32 (3.3σ)	349 ± 61 (5.7σ)
$\|Q_L\|$	164 ± 79 (2.1σ)	67 ± 47 (1.4σ)	230 ± 92 (2.5σ)
$\|Q_L\|, Q_T$	237 ± 50 (4.7σ)	78 ± 32 (2.5σ)	314 ± 59 (5.3σ)

Table 2: Break-up probability of πK atoms for all data sets

Year	Target	Q	Q_L	$\|Q_L\|, Q_T$
$\pi^- K^+$				
2007	Pt 26 μ	1.09 ± 0.52	1.42 ± 0.95	1.44 ± 0.59
2008	Ni 98 μ	0.32 ± 0.20	0.41 ± 0.34	0.44 ± 0.22
2009	Ni 108 μ	0.23 ± 0.16	0.04 ± 0.22	0.16 ± 0.15
2010	Ni 108 μ	0.41 ± 0.17	0.15 ± 0.20	0.33 ± 0.16
$\pi^+ K^-$				
2007	Pt 26 μ	1.2 ± 1.2	0.9 ± 1.6	0.27 ± 0.56
2008	Ni 98 μ	0.52 ± 0.39	0.50 ± 0.62	0.42 ± 0.38
2009	Ni 108 μ	0.29 ± 0.20	0.49 ± 0.37	0.33 ± 0.24
2010	Ni 108 μ	0.33 ± 0.22	-0.13 ± 0.20	0.21 ± 0.20

the maximum likelihood method has been applied to estimate the πK atom lifetime. Fitting result and evaluation of scattering lengths $|a_0^-|$ is shown in Fig. 4. The preliminary results are:

$$\tau = (3.8^{+3.3}_{-2.0}|_{stat} \ {}^{1.0}_{-0.6}|_{syst}) \cdot 10^{-15}\,\mathrm{s} = (3.8^{+3.5}_{-2.1}|_{tot}) \cdot 10^{-15}\,\mathrm{s} \tag{3.3}$$

$$|a_0^-| M_\pi = 0.087^{+0.043}_{-0.024} \tag{3.4}$$

4. Conclusion

In the experiment DIRAC at CERN, the dimesonic Coulomb bound states involving strangeness, the $\pi^- K^+$ and $\pi^+ K^-$ atoms have been observed with reliable statistics: 349 ± 62 events (5.6 σ).

Value of πK atom lifetime preliminary has been expracted to be $\tau = (3.8^{+3.5}_{-2.1}|_{tot})\, fs$. It provides a measurement of the S-wave isospin-odd πK scattering length $|a_0^-| = (0.087^{+0.043}_{-0.024}) \cdot M_\pi^{-1}$.

Simulation, based on results of experiment DIRAC, shoes that a S-wave isospin-odd πK scattering length $|a_0^-|$ could be measured with accuracy 5% in a reasonable time, using 450 GeV proton beam.

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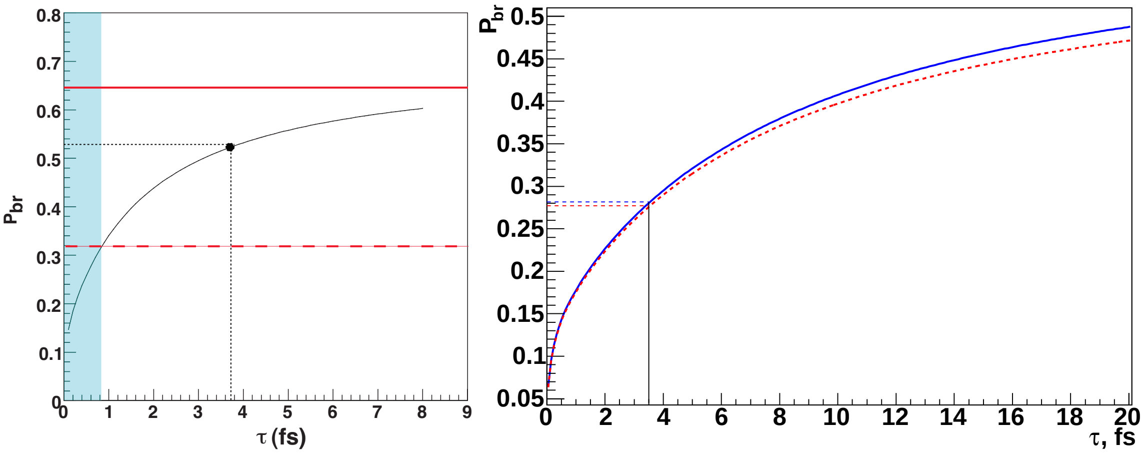

Figure 3: Probability of πK atom breakup as a function of ground state lifetime τ. Left: Platinum target of 26 μm with the measured in 2009 low limit for the lifetime $\tau > 0.8 \cdot 10^{-15}$ s. Right: Nickel targets of thicknesses 98 μm (Ni-1: dashed red) and 108 μm (Ni-2: solid blue). The predicted lifetime $\tau = 3.5 \cdot 10^{-15}$ s corresponds to the breakup probability $P_{\rm br} = 0.28$.

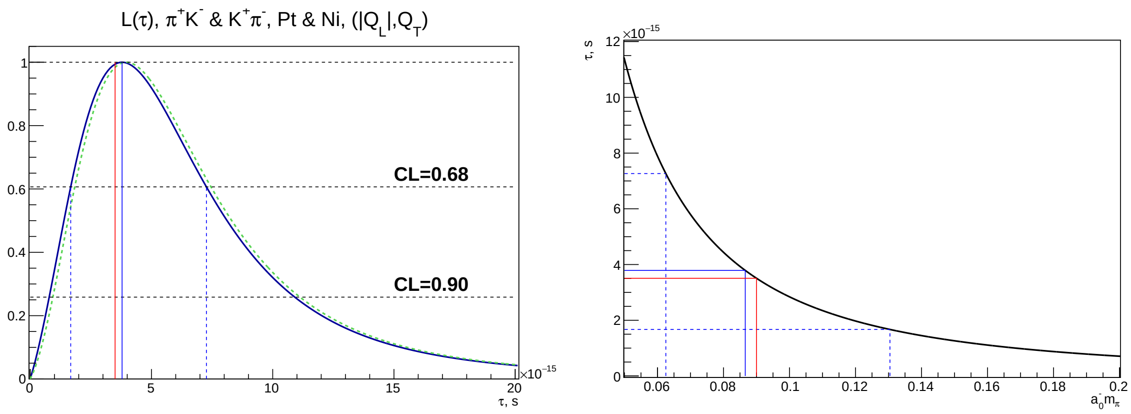

Figure 4: Left: Likelihood function for πK atom lifetime measurement for 2-dimensional fit over $|Q_L|, Q_T$. Right: Relation between measured value πK atom lifetime (τ) and a S-wave isospin-odd πK scattering length $|a_0^-|$

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