π K atom lifetime and π K scattering length measurements

V. Yazkov on behalf of the DIRAC collaboration

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Abstract Theory, using Low Energy QCD, calculated with high precision the ππ and πK scattering length. To check the theoretical calculations for processes, including s-quarks, we must measure the πK atom lifetime, that is connected to the πK scattering lengths by a precise relation. Evidence for πK atoms production is reported on a base of a number of produced πK atoms found to be $N_A = 653 \pm 42$ together with the value of the πK pairs from atoms that breakup in the same target $n_A = 178 \pm 49$. Using these results the analysis yields to a first value for the πK atom lifetime of $\tau = 2.5^{+3.0}_{-1.8} \text{ fs}$ and a first model-independent measurement of the S-wave isospin-odd πK scattering length $|a_0^-| = 1/3|a_0^{1/2} - a_0^{3/2}| = 0.11^{+0.09}_{-0.04} \pi M^{-1}$ (the $I$ and $L$ in $a_L^I$ stands for isospin and orbital momentum).

Keywords DIRAC experiment · Pion kaon scattering length · Hadronic atoms

1 Introduction

Chiral Perturbation Theory (ChPT) describes QCD processes at low energies. ChPT in 1-loop approximation predicts $S$—wave scattering lengths to be [1, 2]:

$$a_0^{1/2} = 0.19 \pm 0.2, a_0^{3/2} = -0.05 \pm 0.02, a_0^{1/2} - a_0^{3/2} = 0.23 \pm 0.01.$$  (1)

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✉ V. Yazkov
valeri.yazkov@cern.ch

1 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
ChPT with $L^{(2)}, L^{(4)}, L^{(6)}$ in 2-loop approximation predicts $S$–wave scattering length difference to be [3]:

$$a_{0}^{1/2} - a_{0}^{3/2} = 0.267.$$  \hfill (2)

Another prediction for scattering length difference have been obtained, using Roy-Steiner equations [4]:

$$a_{0}^{1/2} - a_{0}^{3/2} = 0.269 \pm 0.015.$$  \hfill (3)

In the framework of lattice QCD predictions for $\pi K$ scattering length [5] and their combination $a_0^-$ [6] have been obtained:

$$a_0^{1/2} = 0.183 \pm 0.039, \quad a_0^{3/2} = -0.0602 \pm 0.0040,$$

$$a_0^- = \frac{1}{3} \left( a_0^{1/2} - a_0^{3/2} \right) = 0.0811 \pm 0.0143.$$  \hfill (4)

(5)

The measurement of the s-wave $\pi K$ scattering lengths would test our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD (u, d and s quarks), while the measurement of $\pi \pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking (u,d quarks). This is the principal difference between $\pi \pi$ and $\pi K$ scattering.

Experimental data on the $\pi K$ low-energy phases are absent.

2 Method of $\pi K$ atom observation and investigation

$\pi K$-atom ($A_{\pi K}$) is a hydrogen-like atom consisting of $K^+$ ($K^-$) and $\pi^-$ ($\pi^+$) mesons. The $\pi K$-atom lifetime (ground state 1S), $\tau = \frac{1}{\Gamma}$ is dominated by the annihilation process into $\pi^0 K^0$. There is a relation between the width of $A_{\pi K}$ decay and $S$–wave $\pi K$ scattering lengths for isospin 1/2 and 3/2 [7]:

$$\Gamma_{1S,\pi^0 K^0} = 8\alpha^3 \mu^2 p^*(a_0^-)^2 (1 + \delta_K).$$  \hfill (6)

Here $\alpha$ is the fine structure constant, $\mu$ is the reduced mass of the $\pi^\pm K^\mp$ system, $p^*$ is the outgoing $\pi^0$ momentum in the $\pi K$ atom system, and $\delta_K$ accounts for corrections, due to isospin breaking, at order $\alpha$ and quark mass difference $(m_u - m_d)$.

With prediction of scattering length difference from (3), lifetime of $A_{\pi K}$ in ground state is estimated to be:

$$\tau = (3.5 \pm 0.4) \times 10^{-15}.$$  \hfill (7)

A method of investigation for $\pi^+ \pi^-$, $\pi K$ and other atoms, consisting from two oppositely charged mesons, has been proposed in [8]. Pairs of $K^+$ ($K^-$) and $\pi^-$ ($\pi^+$) mesons are producing in proton-target interactions. Pairs, which are generated from fragmentation and strong decay (“short-lived” sources), are affected by Coulomb interaction in the final state. Some of them form Coulomb bound states — atoms, other are generated as free pairs (“Coulomb pairs”). Number of produced atoms ($N_A$) is proportional to a number of “Coulomb pairs” ($N_C$) with low relative momentum $Q$ in a pair C.M. system: $N_A = K \cdot N_C$. The coefficient $K$ is calculated with an accuracy better than 1 %.

If at least one meson is generated from long-lived sources (electromagnetically or weakly decaying mesons or baryons: $\eta, \eta', K^0_s, \ldots$), then such pairs (“non-Coulomb pairs”) are not affected by interaction in the final states.
After production, $A_{\pi K}$ travel through the target and could to annihilate into $\pi^0 K^0$, or to be ionised due to interaction with the target matter, producing specific “atomic pairs”. These pairs have small relative momentum ($Q < 3$ MeV/$c$) and a number of such pairs $n_A$ could be measured experimentally. Ratio of “atomic pair” number to a number of atom produced is a breakup probability: $P_{br}(\tau) = n_A/N_A = n_A/(K \cdot N_C)$ [9, 10]. In Fig. 1 dependence of $A_{\pi K}$ breakup probability is shown for two nickel target are used in experiment DIRAC for pair laboratory momentum range $4.8 \div 7.6$ GeV/$c$. Value is averaged, using experimentally measured spectrum of atoms.
**Fig. 3** Distribution of $\pi^+ K^- \ (\text{left})$ and $K^+ \pi^- \ (\text{right})$ pairs over $Q_L$ (upper pictures), shown by points with error bars, is fitted by a sum of simulated distributions of “atomic” (red dotted-dashed), “Coulomb” (blue dashed) and “non-Coulomb” (magenta dotted) distributions, using parameters of fit for two-dimensional distribution over $Q_L, Q_T$. A sum of background distributions (“Coulomb” and “non-Coulomb”) is shown by a solid black line. Differences of experimental and background distributions are shown on lower pictures together with simulated distributions of “atomic pairs”.

### 3 DIRAC setup

DIRAC setup was created to detect $\pi^+ \pi^-$ with small relative momenta [11]. In 2004-2006 it has been modified in order to detect both $\pi^+ \pi^-$ and $\pi K$ pairs. New detectors for particle identification have been added: Cherenkov counters with heavy gas and aerogel for identification of $K$-mesons among background of pions and protons. Taking into account kinematic of $\pi K$ “atomic pairs”, new detectors cover only internal parts of each arm (see Fig. 2).

### 4 Investigation of $\pi^+ K^-$ and $K^+ \pi^-$ atoms

Distributions of experimental data over longitudinal ($Q_L$) and transverse ($Q_T$) projections of relative momentum $Q$ have been fitted by a sum of simulated distributions of “atomic”,...
Table 1  Number of produced atoms ($N_A$), “atomic pairs” ($n_A$) and estimation of breakup probability for $\pi^+K^-$ and $K^+\pi^-$ pairs, collected in 2008–2010

| Year | $K^+\pi^-$ over $Q_T, Q_L$ | $\pi^+K^-$ over $Q_T, Q_L$ |
|------|-----------------|---------------------|
|      | $N_A$ | $n_A$ | $P_{br}$ | $N_A$ | $n_A$ | $P_{br}$ |
| 2008 | 132 ± 16 | 14 ± 19 | 0.11 ± 0.15 | 51 ± 11 | 21 ± 13 | 0.41 ± 0.33 |
| 2009 | 169 ± 24 | 33 ± 26 | 0.20 ± 0.17 | 78 ± 13 | 26 ± 16 | 0.34 ± 0.24 |
| 2010 | 164 ± 23 | 49 ± 26 | 0.30 ± 0.19 | 60 ± 12 | 35 ± 16 | 0.58 ± 0.36 |
| All  | 465 ± 37 | 96 ± 41 | 0.21 ± 0.10 | 188 ± 21 | 82 ± 26 | 0.44 ± 0.18 |

“Coulomb” and “non-Coulomb” pairs. Contributions of simulated distributions are free parameters of fit. Procedure, which creates simulated distributions, takes into account resolution of the setup detectors, and multiple scattering in a nickel target, detector planes and partitions, in order to reproduce distribution of experimental pairs over relative momentum $Q$ and its projections.

Results are presented in Fig. 3.

Statistic of produced atoms ($N_A$), “atomic pairs” ($n_A$), and breakup probability estimations are presented in Table 1

Overall number of $\pi^+K^-$ and $K^+\pi^-$ “atomic pairs is found to be:

$$n_A^{\pi^+K^-} + n_A^{K^+\pi^-} = 178 \pm 49$$

(8)

5 Systematic errors

Sources of systematic errors have been analysed. Most of them are induced by imperfections in the simulation of the “atomic”, “Coulomb”, “non-Coulomb” $\pi K$ pairs and misidentified pairs. Effects of finite size of production region and uncertainty in a dependence $P_{br}(\tau)$ also have been taken into account. Estimation [12] of systematic errors for breakup probabilities of $K^+\pi^-$ and $\pi^+K^-$ atoms are found to be essentially less than values of statistical errors.

6 $\pi K$ scattering length estimation

Dependence of breakup probability on $\pi K$ atom lifetime (see Section 2), experimental measurements of breakup probability (Table 1) and investigation of systematic errors (see Section 5) allow to obtain estimation of $\pi K$ atom lifetime [13]:

$$\tau = \left(2.5^{+3.0}_{-1.8}\right)_{\text{stat}}^{+0.3}_{-0.1}\text{stat}_{\text{yyst}}$$

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

(9)

The estimated ground state lifetime (9) corresponds to the $\pi K$ scattering length difference [12, 13]:

$$|a_0^{\pi}| M_\pi = 0.107^{+0.093}_{-0.035} = 0.11^{+0.09}_{-0.04}$$

(10)
7 Summary

Analysis of $\pi K$ pairs statistic with low and medium background (2/3 of total statistic), collected from 2008 to 2010, allows to evaluate a number of atomic $\pi K$ pairs ($178 \pm 49$) as well as a number of produced $\pi K$ atoms (653 ± 42) and thus the breakup (ionisation) probability.

Value of $\pi K$ atom lifetime has been extracted to be $\tau = \left(2.5^{+3.0}_{-1.8}\right) \text{fs}$. It provides a measurement of the S-wave isospin-odd $\pi K$ scattering length: $|a_0^-| = \left(0.11^{+0.09}_{-0.04}\right) \cdot M_{\pi}^{-1}$.

Analysis of statistic with higher background (1/3 of total statistic) collected in 2008-2010 and data collected with Pt target in 2007 gives possibility for further improvement of accuracy.

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