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The investigation of $K^+\pi^-$, π^+K^- and $\pi^+\pi^-$ atoms

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Abstract. Theory, using Low Energy QCD, predicts with high precision the pion-pion and pion-kaon scattering lengths. There is accurate relation between $K^+\pi^-$ and π^+K^- atoms lifetime and pion-kaon S-wave scattering lengths with isospin 1/2 and 3/2. Experiment DIRAC at CERN PS detects 345 ± 61 pairs from $K^+\pi^-$ and π^+K^- atoms breakup. It allows to achieve the first observation of exotic atoms consisted of pion and kaon. Measured values of πK atom lifetime and corresponding pion-kaon scattering length difference are presented. It is shown, that experimental accuracy for pion-kaon scattering length difference could be significantly improved with an experiment at SPS energy.

1 Introduction

Chiral Perturbation Theory (ChPT) describes QCD processes at low energies. ChPT in 1-loop approximation predicts S-wave pion-kaon scattering lengths with isospin 1/2 ($a_0^{1/2}$) and 3/2 ($a_0^{3/2}$) to be [1, 2]:

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

ChPT with $L^{(2)}, L^{(4)}, L^{(6)}$ in 2-loop approximation predicts scattering length difference to be [3]:

$$a_0^{1/2} - a_0^{3/2} = 0.267\,. \tag{2}$$

Scattering length difference also has been predicted, using Roy-Steiner equations [4]:

$$a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015\,. \tag{3}$$

In the framework of lattice QCD, predictions for πK scattering length and their combination a_0^- have been obtained in [5] (Eq. 4), [6] (Eq. 5), [7] (Eq. 6):

$$a_0^{1/2} = 0.1725^{+0.0026}_{-0.0157},\ a_0^{3/2} = -0.0574^{+0.0029}_{-0.0060}, \tag{4}$$

$$a_0^{1/2} = 0.183 \pm 0.039,\ a_0^{3/2} = -0.0602 \pm 0.0040, \tag{5}$$

$$a_0^- = \frac{1}{3}(a_0^{1/2} - a_0^{3/2}) = 0.0811 \pm 0.0143\,. \tag{6}$$

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The measurement of the S-wave πK 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 πK scattering.

Experimental data on the πK low-energy phases are absent. The only experimental pion-kaon scattering length measurement has been done with estimation of πK atom lifetime [8]:

$$|a_0^-|M_\pi = 0.107^{+0.093}_{-0.035}\,. \tag{7}$$

2 Method of πK atom observation and investigation

πK-atom ($A_{\pi K}$) is a hydrogen-like atom consisting of K^+ (K^-) and π^- (π^+) mesons. The πK-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 πK scattering lengths for isospin 1/2 and 3/2 [9]:

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

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

Prediction of scattering length difference in Eq. (3) provides an estimation of lifetime of $A_{\pi K}$ in ground state to be: $\tau = (3.5 \pm 0.4) \times 10^{-15}$.

A method of investigation for $\pi^+\pi^-$, πK and other atoms, consisted of two oppositely charged mesons, has been proposed in [10]. Pairs of K^+ (K^-) and π^- (π^+) mesons are producing in proton-target interactions. Pairs, which are generated from fragmentation and strong decays ("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% [11].

If at least one meson is generated from long-lived sources (electromagnetically or weakly decaying mesons or baryons: $\eta, \eta', K_s^0, \ldots$), 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: $P_{\rm br}(\tau) = n_A/N_A = n_A/(K \cdot N_C)$ [12, 13]. 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 $5.1 \div 8.5$ GeV/c. Value is averaged, using experimentally measured spectrum of atoms.

3 DIRAC setup

DIRAC setup was created to detect $\pi^+\pi^-$ with small relative momenta [14]. In 2004-2006 it has been modified in order to detect both $\pi^+\pi^-$ and πK 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, correspondingly. Taking into account kinematic of πK "atomic pairs", new detectors cover only internal parts of each arm (see Fig. 2).

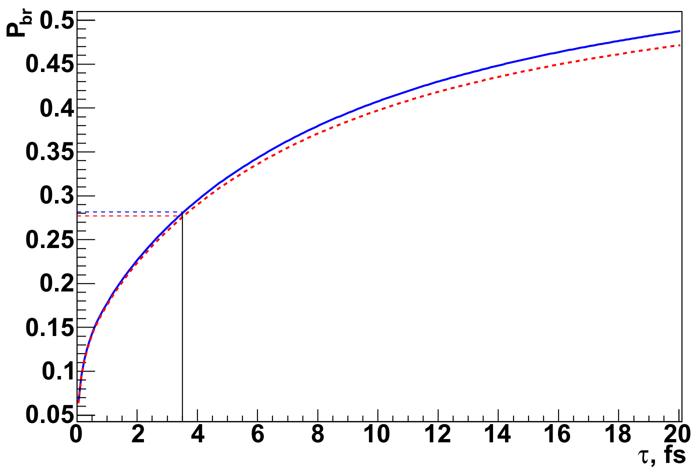

Figure 1. Dependence of the breakup probability $P_{\rm br}$ on $A_{\pi K}$ lifetime for 108μm (solid blue line) and 98μm (dashed red line) nickel targets, and an example how lifetime could be obtained from experimentally measured breakup probability

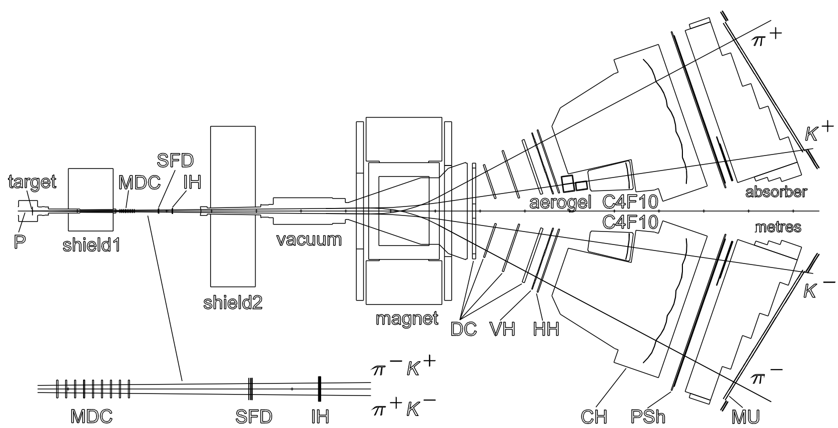

Figure 2. Upgraded DIRAC setup: MDC are microdrift gas chambers, SFD is a scintillating fiber detector and IH is a scintillation ionisation hodoscope. Downstream the spectrometer magnet there are drift chambers (DC), vertical (VH) and horizontal (HH) scintillation hodoscopes. Cherenkov detectors contain nitrogen (CH), heavy gas C4F10 and aerogel radiators. Shower detectors (PSh) and scintillation muon detectors (MU).

4 Observation of π^+K^- and $K^+\pi^-$ atoms

Analysis procedure selects events which have signals of detectors expected for π^+K^- and $K^+\pi^-$ pairs. Criteria on Q-projections are $|Q_L| < 15$ MeV/c, $Q_T < 4$ MeV/c. Distributions of experimental data over relative momentum Q and its projections Q have been fitted by a sum of simulated distributions of "atomic", "Coulomb" and "non-Coulomb" pairs. Contributions of simulated distributions are free parameters of fit. In order to reproduce distribution of experimental pairs over relative momentum Q and its projections, simulation procedure takes into account resolution and efficiency of the setup detectors, multiplicity of background particles and noise signals, multiple scattering in Platinum (run 2007) and Nickel (2008-2010) targets, detector planes and partitions. Results are presented in Fig. 3.

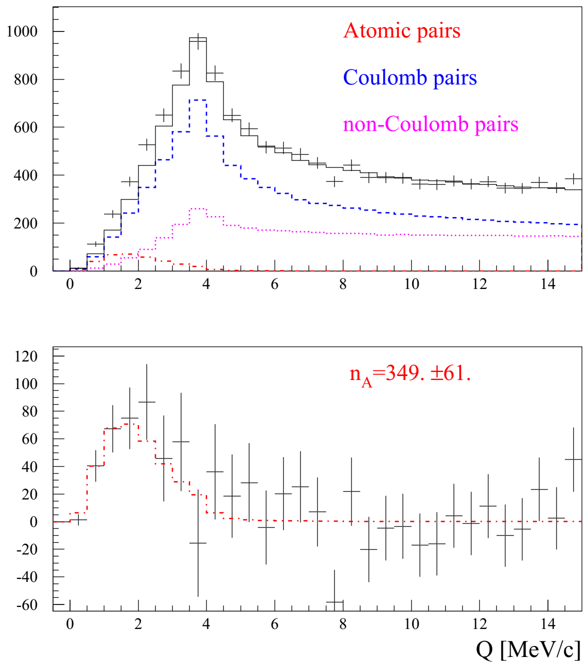

Figure 3. Distribution of π^+K^- and $K^+\pi^-$ pairs over Q (upper pictures), shown by points with error bars, is fitted by a sum of simulated distributions of "atomic" (red dotted-dashed), "Coulomb" (blue dashed) and "non-Coulomb" (magenta dotted) distributions ($\chi^2/n = 41/37$, n = number of degrees of freedom). A sum of background distributions ("Coulomb" and "non-Coulomb") is shown by a solid black line. Differences of experimental and background distributions are shown in lower picture together with simulated distributions of "atomic pairs".

Table 1. Atomic pair numbers n_A by analysing the 1-dimensional Q and $|Q_L|$ distributions and the 2-dimensional ($|Q_L|$, Q_T) distribution. Only statistical errors are given.

Analysis	π^-K^+	π^+K^-	π^-K^+ and π^+K^-?
Q	243 ± 52 (4.7σ)	106 ± 32 (3.3σ)	349 ± 61 (5.7σ)
$\lvert Q_L\rvert$	164 ± 79 (2.1σ)	67 ± 47 (1.4σ)	230 ± 92 (2.5σ)
$\lvert Q_L\rvert, Q_T$	237 ± 50 (4.7σ)	78 ± 32 (2.5σ)	314 ± 59 (5.3σ)

Numbers of π^+K^- and $K^+\pi^-$ "atomic pairs" obtained with analysis of one-dimensional distributions over Q, $|Q_L|$ and two-dimensional ($|Q_L|, Q_T$) distribution are presented in Table 1 (Ni and Pt target together). The best statistical accuracy are achieved by analysis of Q and ($|Q_L|, Q_T$) distributions. Signal to error ratio is more than 5. The 1-dimensional $|Q_L|$ analysis for all πK data yields $n_A = 230 \pm 92$, which does not contradict the values, obtained in the other two statistically more precise analyses.

Compared to the previous investigation [15], the Pt data was analysed including the upstream detectors. The consequence is a decrease of the statistics, but on the other hand an increase of the Q_T resolution. This better resolution improves the quality of data. Concerning the Ni target, the increase of n_A, compared to [8], is caused by optimizing the time-of-flight criteria, which decreases atomic pair losses for the same fraction of background in the final distributions.

The evaluation of the atomic pair number n_A is affected by several sources of systematic errors [16, 17]. These uncertainties lead to differences in the shapes of experimental and MC distributions for "atomic", "Coulomb" and to a much lesser extent for "non-Coulomb" pairs. The shape differences induce a bias in the value of the fit parameter n_A, corresponding to a systematic error of the atomic pair number. Sources of systematic error and estimation of error values are listed in Table 2.

Table 2. Estimations of systematic errors, which are induced by different sources, for analysis of data distribution over relative momentum Q, its longitudinal projection $|Q_L|$ and two dimensional distribution over $(|Q_L|, Q_T)$.

Sources of systematic errors	σ^{syst}_{Q}	$\sigma^{syst}_{Q_L}$	$\sigma^{syst}_{\|Q_L\|,Q_T}$
Uncertainty in Λ width correction	0.8	3.0	2.0
Uncertainty of multiple scattering in Ni (Pt) target	4.4	0.7	2.7
Accuracy of SFD simulation	0.2	0.0	0.1
Correction of Coulomb correlation function due to finite size production region	0.0	0.2	0.1
Uncertainty in πK pair laboratory momentum spectrum	3.3	5.4	7.8
Uncertainty in laboratory momentum spectrum of background pairs	6.6	1.6	5.4
Total	8.6	6.4	10.1

Table 3. Estimation of time needed for measurement a_0^- with statistical accuracy $\delta_{a_0^-}$ for present DIRAC setup and beam condition, and for versions Mod1 and Mod2, modified for proton beam energy E_p = 450 GeV and intensity I_B. It is assumed, that at 450 GeV beam the setup would obtain 3000 spills (4.5s) per day.

Setup	E_p GeV	I_b p/s	Beam time s	Run time months	$\delta_{a_0^-}$ %
Present	24	$2.7 \cdot 10^{11}$	$1.2 \cdot 10^6$	14.5	43.
Present	24	$2.7 \cdot 10^{11}$	$6.0 \cdot 10^7$	715.6	5.
Mod1	450	$1.0 \cdot 10^{11}$	$5.8 \cdot 10^6$	14.3	5.
Mod2	450	$1.0 \cdot 10^{12}$	$7.4 \cdot 10^5$	1.9	5.

Taking into account both statistical and systematic errors, the one-dimensional $\pi^\mp K^\pm$ analysis in Q yields $n_A = 349 \pm 61(stat) \pm 9(syst) = 349 \pm 62(tot)$ atomic pairs (5.6 σ) for both combinations of charge and two-dimensional analysis in $(|Q_L|, Q_T)$ yields $n_A = 314 \pm 59(stat) \pm 10(syst) = 314 \pm 60(tot)$ atomic pairs (5.2 σ). This is the first statistically significant observation of the strange dimesonic πK atom.

Experimentally measured numbers of "atomic pairs" n_A and produced atoms N_A allow (see section 2) to obtain new estimation of $A_{\pi K}$ lifetime in ground state, based on two-dimensional analysis in $(|Q_L|, Q_T)$:

$$\tau = (3.8^{+3.3}_{-2.0}|_{stat}\ {}^{+1.0}_{-0.6}|_{syst})\ \mathrm{fs} = (3.8^{+3.5}_{-2.1}|_{tot})\ \mathrm{fs}\,, \tag{9}$$

which corresponds to isospin-odd πK scattering length estimation to be:

$$|a_0^-|M_\pi = 0.087^{+0.043}_{-0.024}|_{tot}\,. \tag{10}$$

This result has been used for estimation of time which is needed for measurement a_0^- with accuracy 5% [18]. Table 3 presents expected beam time and run time are needed for achievement of this accuracy for present (Nickel target only) and modified DIRAC setup. It is seen that experiment at SPS energy allows to measure S-wave pion-kaon scattering length difference with sufficient accuracy for checking theoretical predictions made by ChPT and LQCD.

5 Investigation of $\pi^+\pi^-$ atoms

DIRAC experiment collected data with Be-Pt target in 2012. These data allow to make observation of $A_{2\pi}$ in states with non-zero orbital momentum (long-lived atoms): $n_A^L = 436 \pm 61$ [19]. Lifetime of long-lived atoms ($\tau \geq 1.17 \cdot 10^{-11}$ s) is sensitive to energy splitting between ns and np atomic states.

It provides possibility to plan experiments for measurement of "Lamb shift like" effect in $\pi^+\pi^-$ system and new combination of S-wave pion-pion scattering lengths: $2 \cdot a_0^0 + a_0^2$.

6 Summary

In the DIRAC experiment at CERN, the dimesonic Coulomb bound states involving strangeness, the $\pi^- K^+$ and $\pi^+ K^-$ atoms, were observed for the first time with reliable statistics. The one-dimensional $\pi^\mp K^\pm$ analysis in Q yields $349 \pm 62(tot)$ atomic pairs (5.6 σ) for both combinations of charge. Analogously, a two-dimensional analysis in ($|Q_L|, Q_T$) was performed with the result of $314 \pm 60(tot)$ atomic pairs (5.2 σ).

DIRAC-like experiment at SPS energy provides possibility to check prediction of ChPT and LQCD for pion-kaon scattering lengths with accuracy at the level 5%.

Observation of "atomic pairs" from $\pi^+\pi^-$ atoms in long-lived states ($n_A^L = 436 \pm 61(tot)$) provides possibility to plan experiments for measurement of "Lamb shift like" effect in $\pi^+\pi^-$ system and new combination of S-wave pion-pion scattering lengths: $2 \cdot a_0^0 + a_0^2$.

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