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

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Abstract. Experiment DIRAC at CERN PS detects $349 \pm 62$ pairs from $\pi^- K^+$ and $\pi^+ K^-$ atoms and makes observation of exotic atoms consist of pion and kaon. It allows to measure a difference of S-wave pion-kaon scattering length with isospin $1/2$ and $3/2$: $|a_{1/2}^0 - a_{3/2}^0|$. Values of pion-kaon scattering lengths are predicted in a frame of ChPT and LQCD. Therefore investigation of $\pi^- K^+$ and $\pi^+ K^-$ atoms gives possibility to check these predictions for simplest hadron-hadron system with $s$-quark.

1 Introduction

$\pi K$-atom ($A_{\pi K}$) is a hydrogen-like atom consisting of $K^+$ ($K^-$) and $\pi^-$ ($\pi^+$) mesons with a Bohr radius of $a_B = 249$ fm, Bohr momentum of $p_B \approx 0.8$ MeV/c and a ground state Coulomb binding energy of $E_B = 2.9$ keV.

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

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

(1)

Here S-wave isospin-odd $\pi K$ scattering length $a_0^-$ = $\frac{1}{3}(a_{1/2}^0 - a_{3/2}^0)$ is defined in pure QCD for the quark masses $m_u = m_d$, $\alpha$ 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 ($m_u - m_d$).

Chiral Perturbation Theory (ChPT) describes QCD processes at low energies. ChPT in 1-loop approximation predicts S-wave pion-kaon scattering lengths [2, 3]:

$$a_{1/2}^0 = 0.19 \pm 0.2, \quad a_{3/2}^0 = -0.05 \pm 0.02, \quad a_{1/2}^0 - a_{3/2}^0 = 0.23 \pm 0.01$$

(2)

in units of inverse pion mass.

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

$$a_{1/2}^0 - a_{3/2}^0 = 0.267.$$

(3)

Scattering length difference also has been predicted with dispersion analysis, using Roy-Steiner equations and experimental data in GeV range [5]:

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

(4)

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In the framework of lattice QCD, predictions for $\pi K$ scattering length and their combination $a_0^-$ have been obtained: $a_0^{1/2} = 0.1725^{+0.0026}_{-0.0157}$, $a_0^{3/2} = -0.0574^{+0.0029}_{-0.0060}$ [6], $a_0^{1/2} = 0.183 \pm 0.039$, $a_0^{3/2} = -0.0602 \pm 0.0040$ [7], $a_0^- = \frac{1}{3} (a_0^{1/2} - a_0^{3/2}) = 0.0811 \pm 0.0143$ [8], $a_0^- = \frac{1}{3} (a_0^{1/2} - a_0^{3/2}) = 0.0745 \pm 0.0020$ [9].

Prediction of scattering length difference in (4) together with $\delta_K = 0.040 \pm 0.022$ [1] provides (1) an estimation of lifetime of $\Lambda_{\pi K}$ in ground state:

$$\tau = (3.5 \pm 0.4) \times 10^{-15}.$$  \hspace{1cm} (5)

There is differences in predictions of $a_0^{1/2} - a_0^{3/2}$ value, obtained with ChPT and Roy-Steiner equation [4, 5] from one side and LQCD [6, 9] from another side. It is needed to test predictions experimentally and accuracy of experimental measurement is to be at the level 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. The only experimental pion-kaon scattering length measurement has been done with estimation of $\pi K$ atom lifetime, using data collected in 2008-2010 with Nickel (Ni) target [10]:

$$|a_0^\pi| M_\pi = 0.107^{+0.093}_{-0.055}.$$  \hspace{1cm} (6)

Using all the data since 2007 and optimizing data handling and analysis, the observation of the $\pi K$ atom could be achieved for the first time with a significance of more than 5 standard deviations [11]. On the basis of the same data sample, $\pi K$ atom lifetime and $\pi K$ S-wave isospin-odd scattering length have been measured with improved accuracy [12].

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

A method of investigation for $\pi^+\pi^-$, $\pi K$ and other atoms, consisted of two oppositely charged mesons, has been proposed in [13]. Pairs of $K^+$ ($K^-$) and $\pi^-$ ($\pi^+$) 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% [14].

If at least one meson is generated from long-lived sources (electromagnetically or weakly decaying mesons or baryons: $\eta, \eta', K^0, \ldots$), 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 produced atoms is a breakup probability: $P_{\text{br}}(\tau) = n_A/N_A = n_A/(K \cdot N_C)$ [15, 16]. In Fig 1 dependence of $A_{\pi K}$ breakup probability is shown for two Ni target are used in experiment DIRAC for pair laboratory momentum range 5.1 ÷ 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 [17]. In 2004-2006 it has been modified in order to detect both $\pi^+\pi^-$ and $\pi K$ pairs [18]. New detectors for particle identification have been added: Cherenkov detectors with heavy gas and aerogel for identification of $K$-mesons among background of pions and protons, correspondingly. Taking into account kinematic of $\pi K$ “atomic pairs”, new detectors cover only internal parts of each arm (see Fig. 2). Aerogel Cherenkov detector is mounted only in positive particle arm, because a flux of antiprotons is small relative to a flux of $K^-$ mesons.

4 Selection $\pi K$ events

Analysis procedure selects events which have signals of detectors expected for $\pi^+ K^-$ and $\pi^- K^+$ pairs. Fig. 3a presents the distribution of selected events over the difference of the particle production times for $K^+$ mesons in the range (4.4–4.5) GeV/$c$. The distribution is fitted by the simulated distribution of $\pi^- K^+$, $\pi^+ \pi^-$, $p\pi^-$ and accidental pairs. Fig. 3b shows the fit for $K^+$ in the range (5.4–5.5) GeV/$c$. The contribution of misidentified pairs was estimated and accordingly subtracted [19]. Fraction of non-suppressed background pairs is calculated as function of momentum and used for estimation of systematic uncertainty (see below).

Fig. 4a illustrates the $Q_L$ distribution of potential $\pi^- K^+$ pairs requiring a ChF signal and $Q_T < 4$ MeV/$c$. The dominant peak on the left side is due to $p\pi^-$ pairs from $\Lambda$ decay. After requesting a ChA signal, the admixture of $p\pi^-$ pairs is decreased by a factor of 10 (Fig. 4b). By selecting proper TOFs between target and VH, background $p\pi^-$ and $\pi^+\pi^-$ pairs
Figure 2. General view of upgraded DIRAC setup (1 – target station; 2 – first shielding; 3 – micro drift chambers (MDC); 4 – scintillating fiber detector (SFD); 5 – ionization hodoscope (IH); 6 – second shielding; 7 – vacuum tube; 8 – spectrometer magnet; 9 – vacuum chamber; 10 – drift chambers (DC); 11 – vertical hodoscope (VH); 12 – horizontal hodoscope (HH); 13 – aerogel Cherenkov detector (ChA); 14 – heavy gas Cherenkov detector (ChF); 15 – nitrogen Cherenkov detector (ChN); 16 – preshower detector (PSh); 17 – muon detector (Mu).

is substantially suppressed (Fig. 4c). In the final distribution, the well-defined $\pi^- K^+$ Coulomb peak at $Q_L = 0$ emerges beside the strongly reduced peak from $\Lambda$ decays at $Q_L = -30$ MeV/c. The $Q_L$ distribution of potential $\pi^+ K^-$ pairs shows a similar behavior. Applying the ChF and TOF criteria provides a sufficient background rejection. Fig. 5 presents the $\pi^+ K^-$ Coulomb peak at $Q_L = 0$ and a second peak from $\bar{\Lambda}$ decays at $Q_L = 30$ MeV/c.

For the final analysis, the DIRAC procedure selects events fulfilling the following criteria:

$$Q_T < 4\text{MeV/c}, |Q_L| < 20\text{MeV/c}.$$  

5 Observation of $\pi^+ K^-$ and $\pi^- K^+$ atoms

Distributions of experimental data over relative momentum $Q$ and its projections $Q_L$ and $Q_T$ have been fitted by a sum of simulated distributions of “atomic”, “Coulomb” and “non-Coulomb” pairs [12]. 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 Pt (run 2007) and Ni (2008-2010) targets, detector planes and partitions.

Fig. 6a presents the experimental and simulated $Q$ distributions of $\pi^- K^+$ and $\pi^+ K^-$ pairs for the data obtained from the Pt target and Ni targets. One observes an excess of events above the sum of “Coulomb” and “non-Coulomb” pairs in the low $Q$ region, where atomic pairs are expected: these excess spectrum is shown in Fig. 6b together with the simulated distribution of atomic pairs. Comparing the experimental with the simulated distributions, demonstrates good agreement.
The numbers of atomic pairs, found in the $\pi^-K^+$ and $\pi^+K^-$ data, are $n_A(\pi^-K^+) = 243 \pm 51$ ($\chi^2/n = 36/37$, $n =$ number of degrees of freedom) and $n_A(\pi^+K^-) = 106 \pm 32$ ($\chi^2/n = 42/37$). Total number of “atomic pairs” is $n_A(\pi K) = 349 \pm 61$ ($\chi^2/n = 41/37$). Quality of $\pi^-K^+$ and $\pi^+K^-$ data fit, performed in assumption that “atomic pairs” are absent, is worse: $\chi^2/n = 73/38$.

Numbers of $\pi^+K^-$ and $\pi^-K^+$ “atomic pairs” obtained with analysis of one-dimensional distributions over $Q$ and $|Q_L|$ and two-dimensional ($|Q_L|, Q_T$) distribution are presented in
Figure 5. $Q_L$ distribution of $\pi^+K^-$ pairs after applying different criteria: absence of signals in CHF detector, proper TOFs between target and VH.

Figure 6. a) Distribution of $\pi^+K^-$ and $\pi^-K^+$ pairs over $Q$, 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. A sum of background distributions (“Coulomb” and “non-Coulomb”) is shown by a solid black line. b) Difference of experimental and background distributions is shown together with simulated distributions of “atomic pairs”.

Table 1 (Ni and Pt target together). The best statistical accuracy is 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 $\pi K$ 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 [20], 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 [10], 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 [19, 21]. 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.

Taking into account both statistical and systematic errors, the one-dimensional \( \pi^+K^\pm \) analysis in \( Q \) yields \( n_A = 349 \pm 61 \) (stat) \( \pm 9 \) (syst) \( = 349 \pm 62 \) (tot) “atomic pairs” (5.6 \( \sigma \)) 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 \( \sigma \)). This is the first statistically significant observation \( \pi K \) atom — the dimesonic Coulomb bound states involving strangeness.

### 6 Measurement of S-wave isospin-odd \( \pi K \) scattering length

Experimentally measured numbers of “atomic pairs” \( n_A \) and produced atoms \( N_A \) allow (see section 2) to obtain breakup probability \( P_{br} \).

Table 3 contains the \( P_{br} \) values obtained in the \( Q \) and \( (|Q_L|, Q_T) \) analyses with statistical uncertainties.

### Table 1. “Atomic pair” numbers \( n_A \) obtained by analyzing the 1-dimensional \( Q \) and \( |Q_L| \) distributions and the 2-dimensional \( (|Q_L|, Q_T) \) distribution. Only statistical errors are given.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>( \pi^-K^+ )</th>
<th>( \pi^+K^- )</th>
<th>( \pi^-K^+ ) and ( \pi^+K^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q )</td>
<td>( 243 \pm 51 ) (4.7 ( \sigma ))</td>
<td>( 106 \pm 32 ) (3.3 ( \sigma ))</td>
<td>( 349 \pm 61 ) (5.7 ( \sigma ))</td>
</tr>
<tr>
<td>(</td>
<td>Q_L</td>
<td>)</td>
<td>( 164 \pm 79 ) (2.1 ( \sigma ))</td>
</tr>
<tr>
<td>(</td>
<td>Q_L</td>
<td>, Q_T )</td>
<td>( 237 \pm 50 ) (4.7 ( \sigma ))</td>
</tr>
</tbody>
</table>

### 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 \( (|Q_L|, Q_T) \).

<table>
<thead>
<tr>
<th>Sources of systematic errors</th>
<th>( \sigma_{stat}^{Q} )</th>
<th>( \sigma_{stat}^{Q_L} )</th>
<th>( \sigma_{stat}^{Q_L, Q_T} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty in ( \Lambda ) width correction</td>
<td>0.8</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Uncertainty of multiple scattering in Ni (Pt) target</td>
<td>4.4</td>
<td>0.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Accuracy of SFD simulation</td>
<td>0.2</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Correction of Coulomb correlation function due to finite size production region</td>
<td>0.0</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Uncertainty in ( \pi K ) pair laboratory momentum spectrum</td>
<td>3.3</td>
<td>5.4</td>
<td>7.8</td>
</tr>
<tr>
<td>Uncertainty in laboratory momentum spectrum of background pairs</td>
<td>6.6</td>
<td>1.6</td>
<td>5.4</td>
</tr>
<tr>
<td>Total</td>
<td>8.6</td>
<td>6.4</td>
<td>10.1</td>
</tr>
</tbody>
</table>
Table 3. Experimental $P_{br}$ from $Q$ and ($|Q_L|$, $Q_T$) analyses. Only statistical uncertainties are cited.

<table>
<thead>
<tr>
<th>Data</th>
<th>RUN</th>
<th>Target ($\mu$m)</th>
<th>$P^{Q}_{br}$</th>
<th>$P^{Q,L,Q_T}_{br}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+K^-$</td>
<td>2007</td>
<td>Pt (25.7)</td>
<td>1.2 ± 1.3</td>
<td>0.27 ± 0.56</td>
</tr>
<tr>
<td>$\pi^+K^-$</td>
<td>2008</td>
<td>Ni (98)</td>
<td>0.53 ± 0.39</td>
<td>0.42 ± 0.38</td>
</tr>
<tr>
<td>$\pi^+K^-$</td>
<td>2009</td>
<td>Ni (108)</td>
<td>0.29 ± 0.20</td>
<td>0.33 ± 0.24</td>
</tr>
<tr>
<td>$\pi^+K^-$</td>
<td>2010</td>
<td>Ni (108)</td>
<td>0.33 ± 0.22</td>
<td>0.21 ± 0.20</td>
</tr>
<tr>
<td>$\pi^-K^+$</td>
<td>2007</td>
<td>Pt (25.7)</td>
<td>1.09 ± 0.52</td>
<td>1.44 ± 0.59</td>
</tr>
<tr>
<td>$\pi^-K^+$</td>
<td>2008</td>
<td>Ni (98)</td>
<td>0.32 ± 0.20</td>
<td>0.44 ± 0.22</td>
</tr>
<tr>
<td>$\pi^-K^+$</td>
<td>2009</td>
<td>Ni (108)</td>
<td>0.23 ± 0.16</td>
<td>0.16 ± 0.15</td>
</tr>
<tr>
<td>$\pi^-K^+$</td>
<td>2010</td>
<td>Ni (108)</td>
<td>0.41 ± 0.17</td>
<td>0.34 ± 0.16</td>
</tr>
<tr>
<td>$\pi^+K^-&amp;\pi^-K^+$</td>
<td>2007</td>
<td>Pt, 25.7</td>
<td>1.11 ± 0.48</td>
<td>0.83 ± 0.41</td>
</tr>
</tbody>
</table>

Sources of systematic uncertainties of breakup probability are mainly the same like for number of “atomic pairs” (see Table 2). There only one new source - uncertainty in the $P_{br}(\tau)$ relation.

Estimations of systematic errors, induced by different sources [12], are presented in Table 4. The total errors were calculated as the quadratic sum. The procedure of the $\pi K$ atom lifetime estimation, described below, includes all systematic errors, although their contributions are insignificant compared to the statistical errors.

Table 4. Estimated systematic errors of $P_{br}$ for data collected with Pt and Ni targets in $Q$ and ($|Q_L|$, $Q_T$) analyses.

| Source                                                | $Q$   | ($|Q_L|$, $Q_T$) |
|-------------------------------------------------------|-------|-----------------|
|                                                       | Pt    | Ni              | Pt    | Ni              |
| Uncertainty in $\Lambda$ width correction             | 0.011 | 0.0006          | 0.073 | 0.0006          |
| Uncertainty of multiple scattering in the target       | 0.0087| 0.0051          | 0.014 | 0.0036          |
| Accuracy of SFD simulation                             | 0.    | 0.0002          | 0.    | 0.0003          |
| Correction of the Coulomb correlation function on finite size production region | 0.0001| 0.0001          | 0.0002| 0.0000          |
| Uncertainty in $\pi K$ pair lab. momentum spectrum    | 0.089 | 0.0052          | 0.25  | 0.0050          |
| Uncertainty in the laboratory momentum spectrum of background pairs | 0.22  | 0.0011          | 0.21  | 0.0011          |
| Uncertainty in the $P_{br}(\tau)$ relation            | 0.01  | 0.0055          | 0.01  | 0.0055          |
| **Total**                                             | 0.24  | 0.0092          | 0.34  | 0.0084          |

For estimating the lifetime of $A_{\pi K}$ in the ground state, the maximum likelihood method [22] is applied [23]:

$$L(\tau) = \exp\left(-U^T G^{-1} U/2\right),$$  \(7\)

where $U_i = \Pi_i - P_{br,i}(\tau)$ is a vector of differences between measured $\Pi_i$ ($P_{br}$ in Table 3) and corresponding theoretical breakup probability $P_{br,i}(\tau)$ for a data sample $i$. The error matrix of $U$, named $G$, includes statistical ($\sigma_{\tau}$) as well as systematic uncertainties. Only the term corresponding to the uncertainty in the $P_{br}(\tau)$ relation is considered as correlated between the Ni and Pt data, which is a conservative approach and overestimates this error. The other systematic uncertainties do not exhibit a correlation between the data samples from the Ni and Pt targets. On the other hand, systematic uncertainties of the Ni data samples are correlated. The likelihood functions of the ($|Q_L|$, $Q_T$) and $Q$ analyses are shown in Fig. 7.
The total errors were calculated as the quadratic sum. The procedure of the \( \pi \) relation.

Lifetime estimation, described below, includes all systematic errors, although their contribution is insignificant compared to the statistical errors.

Sources of systematic uncertainties of breakup probability are mainly the same like for the corresponding theoretical breakup probability \( \pi \rightarrow K^+K^-\).

The likelihood functions of the \( (|Q_L|, Q_T) \) analysis (left) and \( Q \) analysis (right) are compared to the theoretical prediction (5).

**Figure 7.** Likelihood functions \( L(\tau) \) for \( (|Q_L|, Q_T) \) (left) and \( Q \) (right) analyses with \( Q_T < 4 \text{ MeV}/c \). The likelihood functions on the basis of both statistical and systematic errors (dashed green line) and on the basis of only statistical error (solid blue line) are presented. The vertical blue lines indicate the best estimate for \( \tau_{\text{tot}} \) and the corresponding confidence interval. The vertical red line is the theoretical prediction (5).

**Figure 8.** Ground state \( A_{\pi K} \) lifetime \( \tau_{\text{ls}} \) versus \( a_0^- \). Experimental results (blue lines) are compared to the theoretical prediction (red lines). \( (|Q_L|, Q_T) \) analysis (left) and \( Q \) analysis (right).

New estimation of \( A_{\pi K} \) lifetime in ground state, based on two-dimensional analysis in \( (|Q_L|, Q_T) \) [12]:

\[
\tau = (3.8^{+3.3}_{-2.0}\text{stat}^{+1.0}_{-0.6}\text{sys}) \text{ fs} = (3.8^{+3.5}_{-2.1}\text{tot}) \text{ fs},
\]

which corresponds (see Fig. 8(left)) to isospin-odd \( \pi K \) scattering length estimation to be:

\[
|a_0^-| M = 0.087^{+0.043}_{-0.024}\text{tot}.
\]

Estimation, based on \( Q \) analysis [12]:

\[
\tau = (5.5^{+4.9}_{-2.8}\text{stat}^{+0.9}_{-0.5}\text{sys}) \text{ fs} = (5.5^{+5.0}_{-2.8}\text{tot}) \text{ fs},
\]

provides (see Fig. 8(right)) the following value of the \( \pi K \) scattering length \( a_0^- \):

\[
|a_0^-| M = 0.072^{+0.031}_{-0.020}\text{tot}.
\]

Measured values are compatible with theoretical predictions, taking into account the experimental precision.
7 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 $\pi^\pm K^\mp$ analysis in $Q$ yields $349 \pm 62$ (tot) “atomic pairs” (5.6 $\sigma$) 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 $\sigma$).

The breakup probabilities for each atom type and each target are determined. By means of these probabilities, the lifetime of the $\pi K$ atom in the ground state is evaluated to be:

$$\tau_{\text{tot}} = (5.5^{+5.0}_{-2.8})_{\text{tot}} \cdot 10^{-15} \text{s},$$

and the S-wave isospin-odd $\pi K$ scattering length deduced:

$$\left| a_0 \right| = \frac{1}{3} \left| a_0^{1/2} - a_0^{3/2} \right| = (0.072^{+0.031}_{-0.020})_{\text{tot}} M^{-1}_\pi .$$

We are grateful to CERN for support and the PS team for the excellent performance of the accelerator. This work was funded by CERN, INFN (Italy), INCITE and MICINN (Spain), IFIN-HH (Romania), the Ministry of Education and Science and RFBR grant 01-02-17756-a (Russia), the Grant-in-Aid from JSPS and Sentanken-grant from Kyoto Sangyo University (Japan).

References

[19] V. Yazkov and M. Zhabitsky, DN 2013-06 (DN = DIRAC Note), cds.cern.ch/record/1628544
[21] A. Benelli and V. Yazkov, DN 2016-01, cds.cern.ch/record/2137645
[22] D. Drijard and M. Zhabitsky, DN 2008-07, cds.cern.ch/record/1367888
[23] V. Yazkov and M. Zhabitsky, DN 2016-06, cds.cern.ch/record/2252375