7 Study of Coulomb-bound πK-pairs

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in collaboration with:
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(DIRAC-II Collaboration)

The goal of the DIRAC experiment at CERN (PS212) is to measure the lifetime of electromagnetically bound $\pi^+\pi^-$ or $K^\pm\pi^\mp$ pairs (the so-called $\pi\pi$- and πK- "atoms"). Their mean lives are directly related to the isospin 0 and 2 s-wave scattering lengths (a_0 and a_2) for $\pi\pi$, and to the corresponding isospin 1/2 and 3/2 scattering lengths ($a_{1/2}$ and $a_{3/2}$) for πK. More precisely, the mean life is related to the absolute value of the difference between the two scattering lengths (1), a quantity that was calculated within the framework of Chiral Perturbation Theory (ChPT) with high precision, 1.5% for $|a_0 - a_2|$ (2), and 5.5% from Roy-Steiner dispersion-relations for $|a_{1/2} - a_{3/2}|$ (3). Thus a measurement of the mean life from DIRAC provides a valuable test of low-energy QCD concepts involving the u- and d-quarks for $\pi\pi$, and extending to the s-quark for πK. The expected mean life of πK-atoms is about 3.7 fs (1), with rather large uncertainties.

Results for $\pi\pi$-atoms have been published earlier by the DIRAC-I collaboration (4). A mean life of $2.91^{+0.49}_{-0.62}$ fs was measured, in good agreement with predictions from ChPT. We shall focus here on πK-atoms (DIRAC-II) in which we are mainly involved.

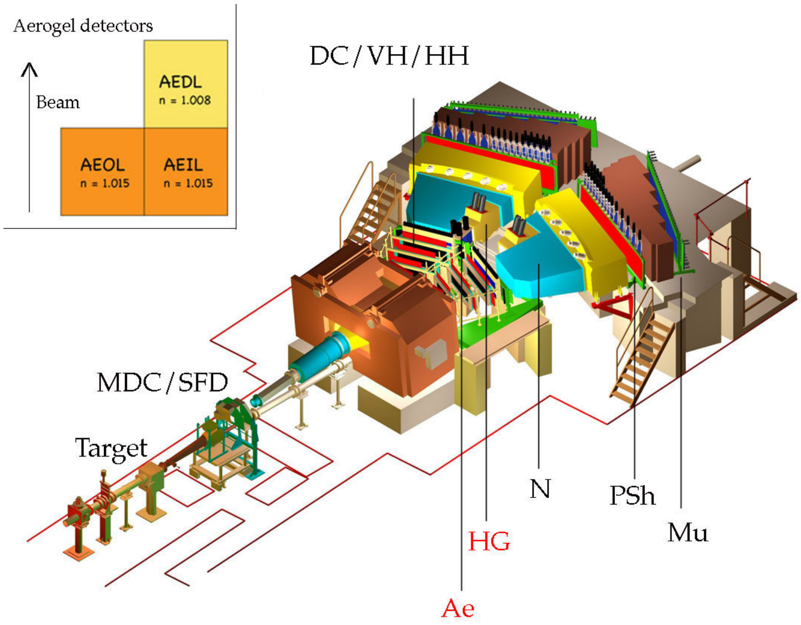

Figure 7.1: DIRAC-II spectrometer:

MDC	**microdrift chambers,**
SFD	**scintillator fibre detector,**
DC	**drift chambers,**
VH, HH	**vertical and horizontal scintillation hodoscopes,**
PSh	**preshower,**
Mu	**muon counters,**
Ae	**aerogel,**
HG	**heavy gas and**
N	**nitrogen Čerenkov counters.**

The inset shows the arrangement of the three aerogel modules.

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A sketch of the DIRAC-II spectrometer is shown in Fig. 7.1. The 24 GeV/c proton beam from the PS impinges on a thin Pt- (or Ni-) target. The secondary particles emerging from the target in the forward direction are analyzed in a double-arm magnetic spectrometer. Positive particles are deflected into the left arm, negative ones into the right arm. Electrons and positrons are vetoed by N_2-Čerenkov detectors and muons by their signals in scintillation counters behind the steel absorbers. Particle identification is performed by the heavy gas (C_4F_{10}) and aerogel Čerenkov counters. The former detects pions (but not kaons), while the latter also detects kaons (but not protons).

Our group has developed and built a large volume (37ℓ) aerogel Čerenkov counter in the left arm (positive charges) for kaon detection and proton suppression (5), and the heavy gas system (6). The aerogel detector consists of three independent modules (inset of Fig. 7.1). Two of them (AEIL close to the proton beam and AEOL at larger angles) have refractive index $n = 1.015$ and are used for kaons between 4 and 5.5 GeV/c. At small angles the momenta increase up to 8 GeV/c and hence AEDL, with the lower index $n = 1.008$, is used to suppress fast protons that also fire AEIL.

The measurement of the mean life is as follows: Atoms produced in the forward direction are ionized while crossing the target, leading to "atomic" $\pi^{\pm}K^{\mp}$-pairs with very small relative momenta between the kaons and the pions (typically $<$ 3 MeV/c in the c.m.s system). Since ionization competes with annihilation into $K^0\pi^0$ (or $\overline{K}^0\pi^0$), the number of atomic pairs grows with increasing lifetime. Unbound πK-pairs ("Coulomb-pairs") which interact electromagnetically are also produced. The number of produced atoms is related to the number of Coulomb-pairs (7), For relative momenta below 3 MeV/c the ratio of the number of produced atoms to that

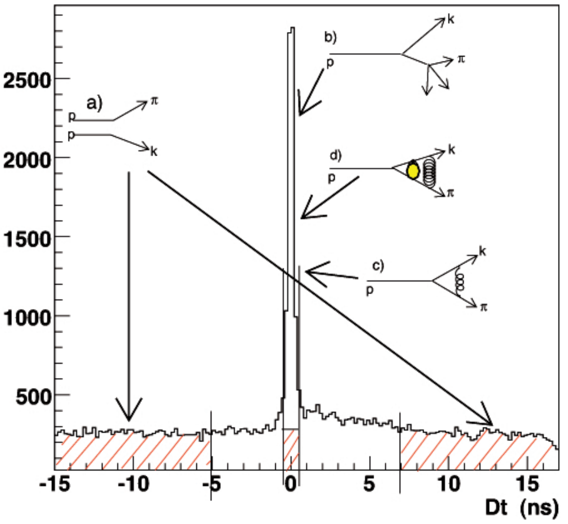

Figure 7.2: Distribution of the $\pi - K$ time difference for (a) accidentals, (b) non-Coulomb pairs, (c) Coulomb-pairs, and (d) πK-atoms.

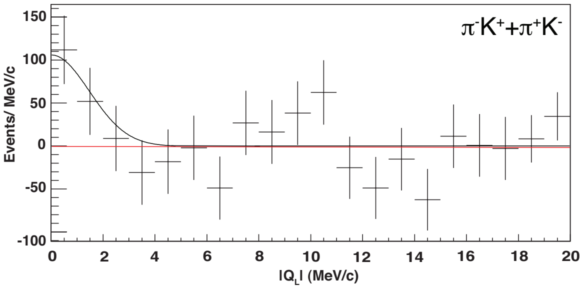

Figure 7.3: Residuals between data and the fitted background for π^-K^+ and π^+K^- from the 2007 data. A Gaussian fit has been applied (solid line) to illustrate the distribution of atomic-pairs.

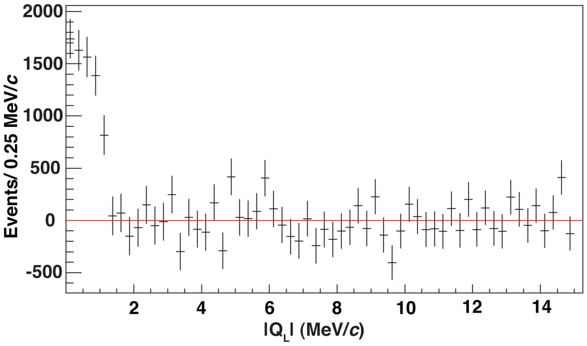

Figure 7.4: Residuals between data and the fitted background for $\pi^+\pi^-$ (from ref. [9]).

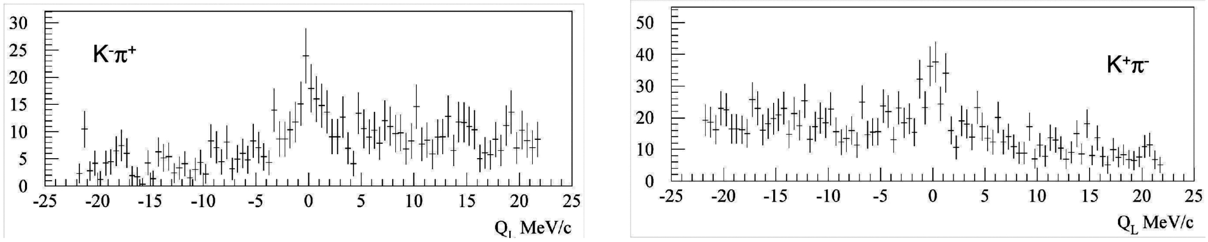

Figure 7.5: Q_L distribution for selected π^+K^- and π^-K^+ events. The peak at small $|Q_L|$ is due to Coulomb- and atomic pairs (see text).

of Coulomb-pairs is around 60%. Detection efficiencies are taken into account by Monte Carlo simulation. The background stems from non-Coulomb pairs due to K and π mesons from long-lived resonances (and therefore do not interact), and from accidentals (pairs produced by two different proton interactions). Figure 7.2 shows a distribution of the time difference between particles in the two arms of the spectrometer.

The DIRAC collaboration observed πK-atoms for the first time with the data collected in 2007 (Figs. 7.3 and 7.4). For comparison we also show the results for $\pi^+\pi^-$-atoms from the same data runs. We have detected 173 ± 54 πK atomic pairs (8), thus with a statistical significance of 3.2σ. However, the evidence for πK-atoms was strengthened by the simultaneous observation of Coulomb-pairs from which the fraction of expected *bound* pairs could be calculated (7). The latter was in excellent agreement with the number of observed atoms. This result led to a lower limit for the mean life of πK-atoms of 0.8 fs in the 1s-state, at a confidence level of 90%, which could be translated into an upper limit of $|a_{1/2} - a_{3/2}| <$ 0.58 m_π^{-1}. Details can be found in ref. (8; 9; 10).

For the 2007 results we had used only the detectors downstream of the magnet. The kaon selection is described in detail in ref. (8; 9). Two planes of scintillator fibers (SFD, see Fig. 7.1) and 16 planes of micro drift chambers (MDC) are now available to determine the interaction point in the target with better precision. We can thus select events with relative transverse momentum smaller than 4 MeV/c, thus reducing the background by typically a factor of 4.

Figure 7.5 shows the distribution of the relative longitudinal momentum Q_L for πK-pairs for a sample of the data, using the SFD planes. The enhancement at low $|Q_L|$ is due to Coulomb- (and atomic) pairs. The background for larger $|Q_L|$ is substantially lower than for data without SFD information (8).

In the 2007 runs ADCs for the aerogel detectors were not available. ADC and TDC information from the three aerogel modules is now recorded. To determine the light yield and detection efficiency for kaons we first selected a pure pion beam in the left arm by applying time-of-flight cuts, and also requiring a signal in the heavy gas counter. The ADC/TDC response was then analyzed as a function of pion momentum and used to estimate the response to protons. The prediction was compared to data from a pure proton beam in the left arm, applying a time-of-flight cut, requiring no signal in the heavy gas counter, and a π^-p invariant mass consistent with the decay of a Λ-hyperon. Prediction and measurements were found to be in very good agreement. Hence the detection efficiency for kaons with the aerogel and the contamination from protons could be estimated reliably.

Figure 7.6 shows the light yield for kaons and protons from the "heavy" aerogel (AEOL) in the relevant momentum range between 4.0 and 5.5 GeV/c. For example, kaons can be identified with an efficiency of 0.95 by requiring at least 2 photoelectrons, while the contamination from protons is 0.05. The results for the AEIL are similar (Fig. 7.7). Above 5.5 GeV/c we also used the information from the "light" aerogel (AEDL) for which we obtained an average kaon efficiency of 0.95 above 5 GeV/c, while the proton contamination rose from 0.15 at 5 GeV/c to a worrying $\simeq$ 100% above 7 GeV/c, due to the low light yield of this detector. However, a computer simulation shows that even a proton contamination at this level is not problematic. Figure 7.8 shows the $|Q_L|$ distribution for simulated $\pi^- p$ events, assuming in the reconstruction that the proton is in fact a kaon. No enhancement is observed around $Q_L = 0$, and therefore the proton contamination is automatically taken into account when subtracting the background.

We collected more data in 2009. The Zurich group is currently analyzing the 2008 data sample using the new SFD detectors (provided by our Japanese collaborators), and is also implementing the corresponding Monte Carlo simulation. The SFD should improve the transverse momentum resolution from 3 MeV/c to 1 MeV/c. Data taking for DIRAC-II has been approved at least until the end of 2010 by the CERN committees, at which time we should achieve a significance of 5 – 6 standard deviations on the evidence for πK-atoms and, correspondingly, an accuracy of 40% on the lifetime (or 20% on the scattering lengths). This is a significant improvement on current knowledge, but somewhat more modest than expected, mainly due to a one year beam magnet breakdown, and the low proton beam flux that was finally delivered.

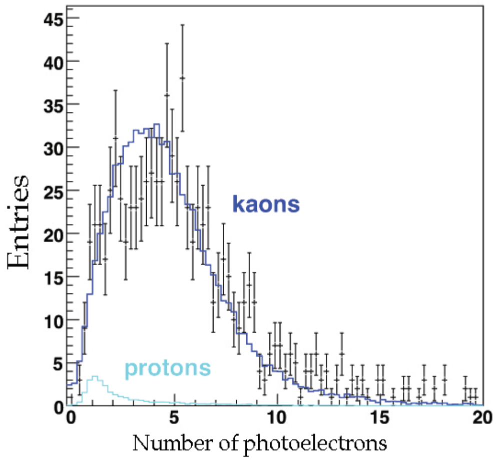

Figure 7.6:
Light yield in photoelectrons from the aerogel Čerenkov counters AEOL for kaons and protons.

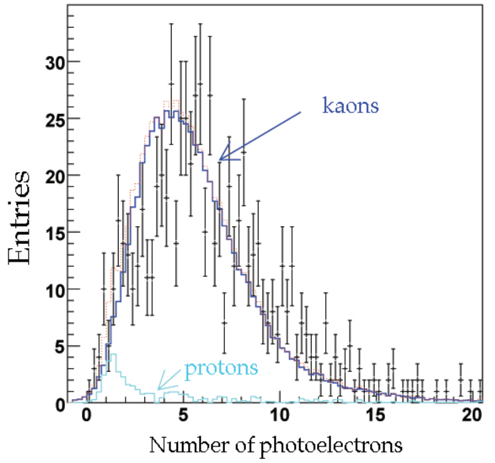

Figure 7.7: As in Fig. 7.6 for the AEIL counters

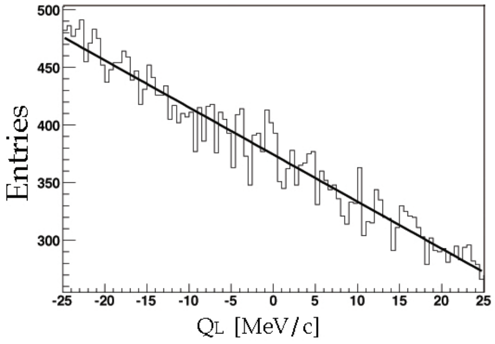

Figure 7.8:
Distribution of the longitudinal momentum difference Q_L for $p\pi^-$ events assumed to be $K^+\pi^-$.

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