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Evidence for πK atoms with DIRAC

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Electromagnetically bound $\pi^{\pm}K^{\mp}$-pairs (πK-atoms) have been observed by the DIRAC-II experiment at the CERN-PS. The πK-atoms were produced by the 24 GeV/c proton beam impinging on a thin Pt-target. The $\pi^{\pm}$- and $K^{\mp}$-mesons from the atom dissociation were analyzed in a two-arm magnetic spectrometer. An enhancement was observed at low relative momentum, corresponding to the production of 173 ± 54 πK-atoms. From these first data a lower limit for the mean life of 0.8 fs was derived at the 90% confidence level. The mean life being related to the S-wave πK-scattering lengths a_1 and a_3 (isospin 1/2 and 3/2), one then obtains an upper limit for the difference $|a_1 - a_3|$ of 0.58 m_{π}^{-1} at the 90% confidence level.

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Electromagnetically bound $\pi^{\mp}K^{\pm}$-pairs ($\pi^{\mp}K^{\pm}$-atoms) have been observed for the first time in 2008 by our DIRAC-II Collaboration at CERN [1]. The $\pi^{+}K^{-}$-atom is unstable and decays through the strong force into $\pi^{0}\overline{K}^{0}$ (while $\pi^{-}K^{+}$-atoms decay into $\pi^{0}K^{0}$). The mean life τ, which we intend to measure, is related to the S-wave πK-scattering lengths a_1 and a_3 in the isospin 1/2 and 3/2 states, respectively. The πK-scattering length is of interest to test chiral perturbation theories extended to the s-quark. A mean life $\tau \sim 3.7$ fs has been predicted [2].

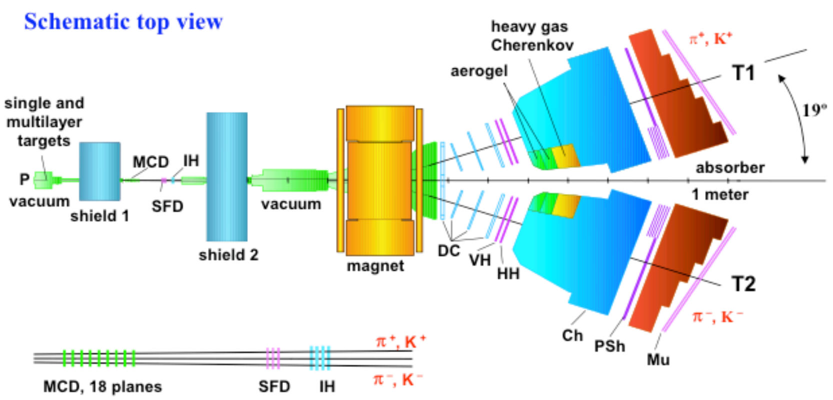

Figure 1: Sketch of the updated DIRAC-II spectrometer, showing the locations of the Čerenkov counters to identify electrons, pions and kaons. MDC = microdrift chambers, SFD = scintillator fibre detector, IH = ionization hodoscope, DC = drift chambers, VH, HH = vertical and horizontal scintillation hodoscopes, PSh = preshower, Mu = muon counters.

The DIRAC-I collaboration has measured the $\pi\pi$ S-wave scattering length [3]. A sketch of the modified spectrometer (DIRAC-II) to collect the πK (and more $\pi\pi$) data is shown in fig. 1. The 24 GeV/c proton beam from the CERN-PS impinges on a 26 μm Pt-target. The proton beam then passes through a vacuum pipe and is absorbed by the beam dump. The secondary particles emerging from the target are analyzed in a double-arm magnetic spectrometer measuring the momentum vectors of two oppositely charged hadrons. Positive particles are deflected into the left arm, negative ones into the right arm. Electrons and positrons are vetoed by the N_2-Čerenkov detectors and muons by their signals in scintillation counters behind the steel absorbers. To distinguish kaons from pions and to suppress protons we use a novel aerogel Čerenkov counter in the left arm (positive charges) and a C_4F_{10}-gas Čerenkov counter for pion detection. The signal from πK-atoms is observed for kaon and pion pairs with very small relative momentum (typically $|Q_L| < 3$ MeV/c in the c.m.s system).

An aerogel detector in the right arm (negative charges) is not necessary since the antiproton flux is negligible compared to that of negative kaons, while protons in the left arm are much more frequent than positive kaons. The aerogel detector consists of three independent modules [4, 5]. Two of them (total volume of 24ℓ) have refractive index $n = 1.015$ for kaons between 4 and 5.5 GeV/c, and the third one (13ℓ) has the lower index $n = 1.008$ for 5.5 to 8 GeV/c kaons and kaon-proton separation. The loss due to light absorption is compensated by using a wavelength shifter and by increasing the radiator thickness in the center of the detector (pyramid geometry).

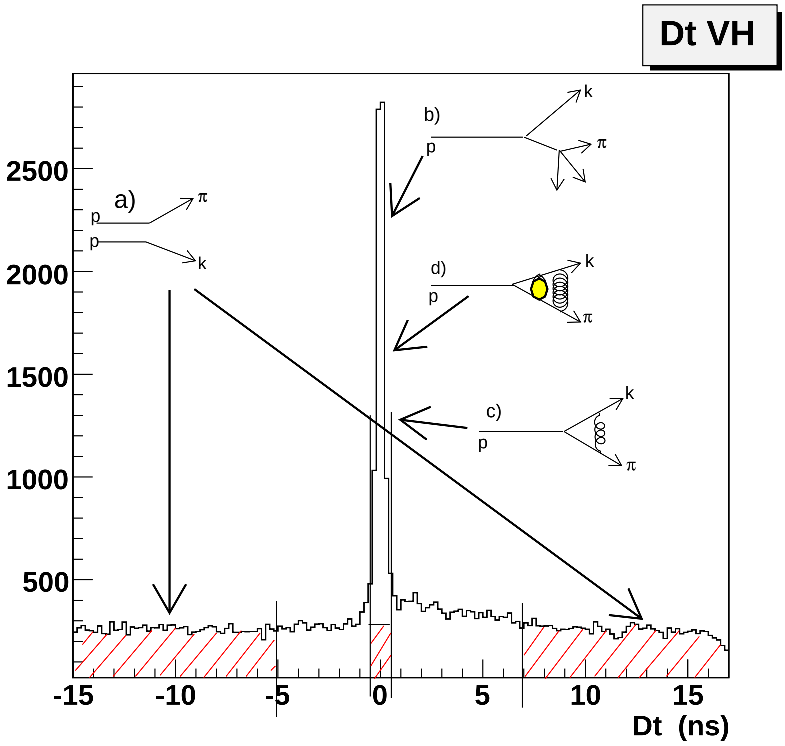

Figure 2: Time difference between the Vertical Hodoscopes for the $\pi^{\pm}K^{\mp}$ final states.

Four mechanisms contribute to the production of $\pi^{\pm}K^{\mp}$ final states as is shown in fig.2. Accidental pairs (a) are due to particles produced on different interactions between protons and the target, non-Coulomb-pairs (b) are associated with the production of long-lived intermediate states. On the other hand, $\pi^{\pm}K^{\mp}$-pairs which interact electromagnetically form correlated Coulomb-pairs (c), or atomic pairs (d). The latter atoms, while traveling through the target, can either decay, be (de)-excited or break up into $\pi^{\pm}K^{\mp}$-pairs which emerge from the target with very low relative momentum.

The variable of interest is the relative momentum Q of the $\pi^{\mp}K^{\pm}$-pairs in their center-of-mass systems, in particular the longitudinal component Q_L which is not affected by multiple scattering. In the transverse plane, the resolution on the relative momentum Q_T (typically 3 MeV/c) is dominated by multiple scattering, while the resolution on the longitudinal component Q_L ($<$ 1 MeV/c) is not affected. We use therefore only Q_L.

For the analysis of the first data reported here and in ref. [1] we use only detectors downstream

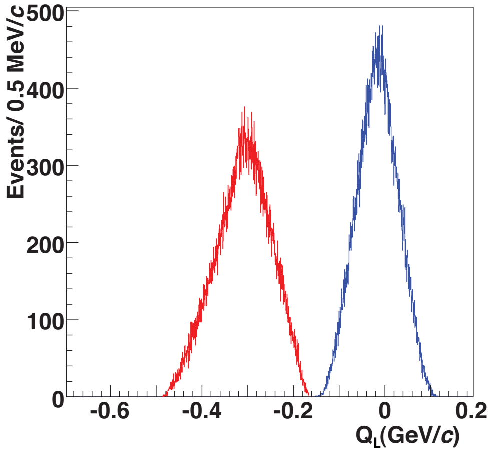

Figure 3: Q_L distribution of $\pi^- K^+$ events in blue and in red $\pi^+\pi^-$ events reconstructed as $\pi^- K^+$ events.

of the dipole magnet. The trajectories are determined by the drift chambers, the pattern recognition starting from the coordinates in the last plane and extrapolating back to the target. For prompt pairs the time difference between the positive and negative spectrometer arm lies within 1 ns. Accidental pairs are removed using the time information from the vertical hodoscopes. Electrons or muons are also removed, and a loose preselection of oppositely charged particles is performed. Pions, kaons and protons below 2.5 GeV/c can be separated by time-of-flight. For the $\pi^- K^+$ analysis the aerogel detector is used in addition to remove protons in the positive arm, while for the $\pi^+ K^-$ analysis the time difference between the negative and the positive arm has to be negative to remove protons faking pions.

There are two possible final states that could be misunderstood for πK : $\pi^+\pi^-$ where the π^+ is misidentified as a K^+, and the $p\pi^-$ final state where the proton is taken as a K^+. Both these two channels are not dangerous for our analysis results, since the Q_L distributions calculated with the wrong particle hypothesis have a peak shifted from 0 MeV/c that doesn't overlap with our region of study, in fig 3 is shown the shift of 300 MeV/c in the distribution of $\pi^+\pi^-$ events reconstructed as $\pi^- K^+$ event with respect to the correctly identify $\pi^- K^+$ events.

The prompt pairs are composed of the following three types: atomic-pairs, Coulomb-pairs, and non-Coulomb and accidentals pairs. We assume that the background due to non-Coulomb pairs can be described by the Q_L-distribution of accidentals, following a similar analysis for $\pi^+\pi^-$-atoms [3]. Coulomb pairs have to be simulated and non-Coulomb pairs have been approximated with a straight line. Fig 4 shows the $\pi^- K^+$ and $\pi^+ K^-$ data events from the Dirac experiment with superimposed the amount resulting from the background fit ($|Q_L| > 3$ MeV/c) of Non Coulomb and accidentals events (c1) of Coulomb Correlated events (c2) and the sum of the two background distributions (c3=c1+c2).

Since the shapes of both contributions are known, one can extrapolate into the $|Q_L| < 3$ MeV/c signal region. The difference (residuals) between the data and the sum of both contributions is plotted in fig. 5. Above $|Q_L| = 3$ MeV/c the residuals are consistent with zero, while the enhancement at low relative momentum is the evidence for πK-atoms. We obtain 173 ± 54 detected atomic pairs with a statistical significance of 3.2σ. The systematic uncertainty is estimated to be around 5%,

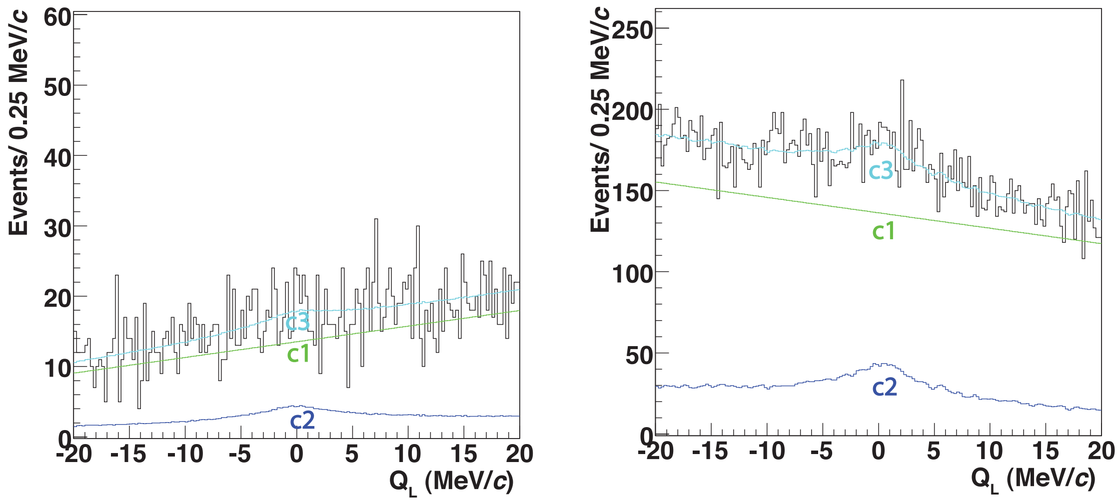

Figure 4: Background fit and signal extraction for $\pi^- K^+$ (right) and $\pi^+ K^-$ (left) events.

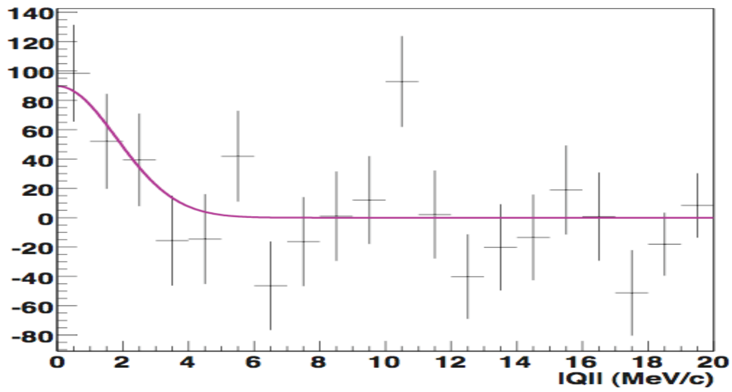

Figure 5: Residuals between data and the fitted background for $\pi^- K^+$ and $\pi^+ K^-$. A Gaussian fit has been applied (solid line) to illustrate the distribution of atomic-pairs.

much smaller than the statistical one.

The evidence for the observation of πK-atoms is strengthened by the observation of Coulomb-pairs (see fig. 6) which, a fortiori, implies that atoms have also been produced. This can be seen as follows: non-Coulomb pairs have a similar Q_L-distribution as accidentals. Hence dividing the normalized distribution for prompt pairs by the one for accidentals one obtains the correlation function R describing Coulomb-pairs. The function R, shown in fig. 6 as a function of $|Q_L|$, is clearly increasing with decreasing momentum, proving that Coulomb-pairs have been observed.

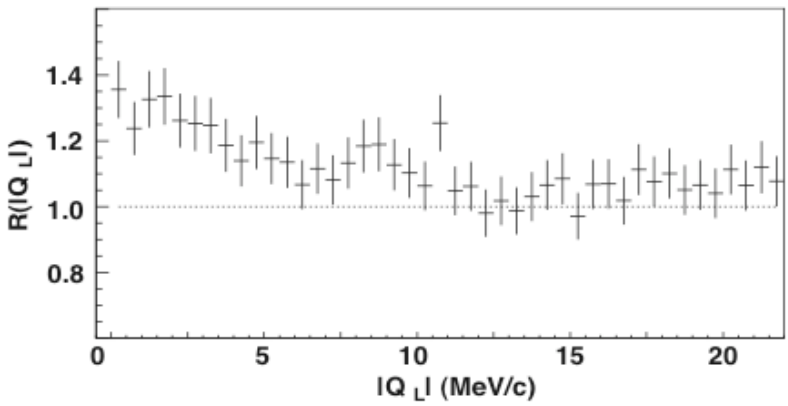

Figure 6: Correlation function R as a function of $|Q_L|$ for πK-pairs. The deviation from the horizontal dotted line proves the existence of πK Coulomb-pairs.

The ratio of the number of produced atoms to the number of Coulomb-pairs with small relative momenta can be calculated [6, 7]. This number needs to be corrected by Monte-Carlo simulation to account for the acceptance of the apparatus and all cuts. The breakup probability relates the number of atoms to the number of atomic pairs. A calculation of the breakup probability as a function of mean life has been performed using the Born approximation [8]. For the predicted mean life of 3.7 fs [2] the breakup probability is 53% . One then obtains from the number of produced atoms the predicted number of observed atomic pairs, 147 ± 36, in good agreement with the experimental result above.

Conversely, one can use the number of observed atomic-pairs and the number of Coulomb-pairs below $|Q_L| < 3$ MeV/c to calculate the breakup probability: 64 ± 25 %. This leads to a lower limit for the mean life of πK-atoms of $\tau(1s) = 0.8$ fs at a confidence level of 90%. This result can be translated into an upper limit $|a_1 - a_3| < 0.58\ m_\pi^{-1}$ at the 90% confidence level.

The choice of Pt as production target for the 2007 data was justified by the high breakup probability so that of πK-atoms could be observed. More data is being collected with a 98 μm Ni-target, for which the breakup probability is lower (∼35% see ref. [8]) but still rapidly rising around the predicted mean life of 3.7 fs. This will allow a more accurate measurement of τ. The ultimate goal is to measure the mean life of πK-atoms with a precision of about 20%, leading to a 10% uncertainty in the difference of scattering lengths $|a_1 - a_3|$.

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