First observation of $\pi^- K^+$ and $\pi^+ K^-$ atoms, their lifetime measurement and πK scattering lengths evaluation

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Contents

- Theoretical status of πK scattering lengths
- Published results on πK atoms
- Method of πK atom observation and investigation
- DIRAC setup
- Observation of πK atoms
- πK atoms with 450 GeV beam

Theoretical status of πK scattering lengths

πK scattering lengths

I . ChPT predicts s-wave scattering lengths:

$L^{(2)}$, $L^{(4)}$ and 1-loop

$$a_0^{1/2} = 0.19 \pm 0.02,\ a_0^{3/2} = -0.05 \pm 0.02$$

$$a_0^{1/2} - a_0^{3/2} = 0.24 \pm 0.03$$

V. Bernard, N. Kaiser, U. Meissner - 1991

$$a_0^{1/2} - a_0^{3/2} = 0.23 \pm 0.01$$

A. Roessl - 1999

$L^{(2)}$, $L^{(4)}$, $L^{(6)}$ and 2-loop

$$a_0^{1/2} - a_0^{3/2} = 0.267$$

J. Bijnens, P. Dhonte, P. Talavera - April 2004

II . Roy-Steiner equations:

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

P. Büttiker et al. - 2004

πK scattering lengths in LQCD

III . S-wave πK scattering has also been studied extensively in the framework of lattice QCD

Recently predictions for πK scattering have been obtained:

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

S.R. Beane et al, Phys. Rev. D77 (2008) 094507

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

C.B. Lang et al., Phys. Rev. D86 (2012) 054508

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

K. Sasaki et al., Phys. Rev. D89 (2014) 054502

Published results on on πK atoms

DIRAC data	Observed events	$\tau_{1s}(10^{-15}s)$ value stat syst tot	Reference
2007	173 ± 54 (3.2σ)	> 0.8 at $CL = 90\%$	PL B 674 (2009) 11
2008-10	178 ± 49 (3.6σ)	$2.5^{+3.0+0.3}_{-1.8-0.1}$ $\begin{bmatrix} +3.0 \\ -0.18 \end{bmatrix}$	PL B 735 (2014) 288

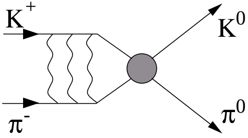
Experimental data on the πK low-energy phases are absent.

$\pi^- K^+$ and $\pi^+ K^-$ atoms lifetime

πK-atom ($A_{\pi K}$) is a hydrogen-like atom consisting of $K^\pm$ and $\pi^\mp$ mesons:

$$E_B = -2.9\, keV,\ r_B = 248\, fm, p_B \approx 0.8\, MeV/c$$

The πK-atom lifetime (ground state 1S), $\tau = \frac{1}{\Gamma}$ is dominated by the annihilation process into $\pi^0 K^0$:



$$A_{K^+\pi^-} \to \pi^0 K^0,\ A_{\pi^+K^-} \to \pi^0 \bar{K}^0$$

$$\Gamma_{1S,\pi^0 K^0} = R_K \mid a_0^{1/2} - a_0^{3/2} \mid^2 \text{ with } \frac{\Delta R}{R} \approx 2\%$$

J. Schweizer - 2004

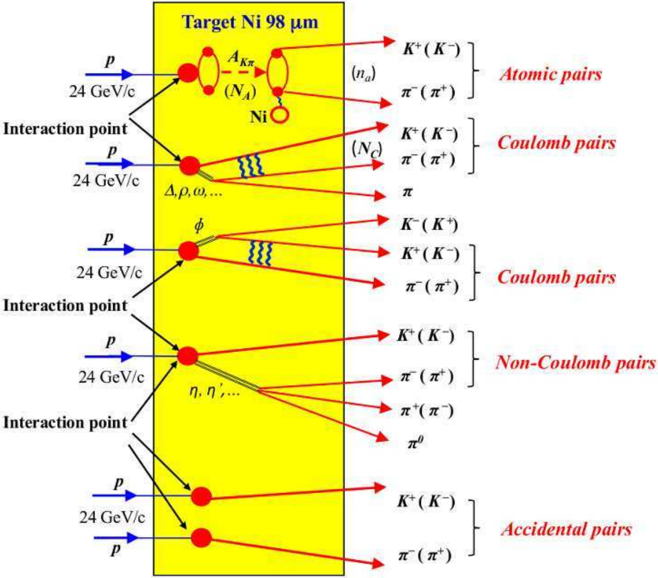
From Roy-Steiner equations:

$$a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015 \to \tau = (3.7 \pm 0.4)10^{-15} s$$

$$\text{If} \quad \frac{\Delta\Gamma}{\Gamma} = 10\% \quad \Rightarrow \quad \frac{\Delta|a_0^{1/2} - a_0^{3/2}|}{|a_0^{1/2} - a_0^{3/2}|} = 5\%$$

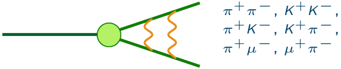
Method of πK atom observation and investigation

Method of and πK atom observation

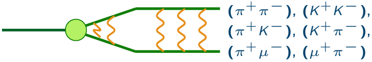


Coulomb pairs and atoms

For the charged pairs from the short-lived sources and small relative momentum Q there is Coulomb interaction in the final state. This interaction increases the production yield of the free pairs with Q decreasing and creates atoms.



Coulomb pairs



Atoms

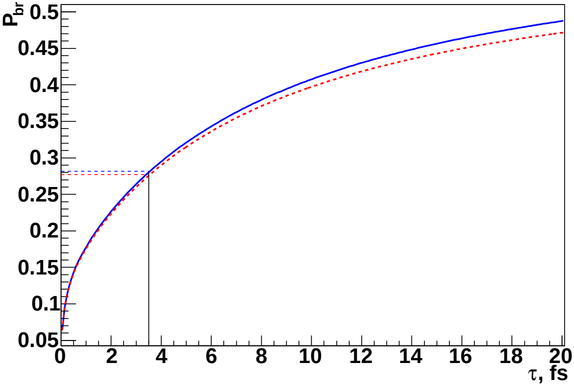
There is precise ratio between the number of produced Coulomb pairs (N_C) with small Q and the number of atoms (N_A) produced simultaneously with these Coulomb pairs:

$$N_A = K(Q_0) \cdot N_C \ (Q \leq Q_0), \ \frac{\delta K(Q_0)}{K(Q_0)} \leq 10^{-2}$$

n_A - atomic pairs number, $P_{br} = \frac{n_A}{N_A}$

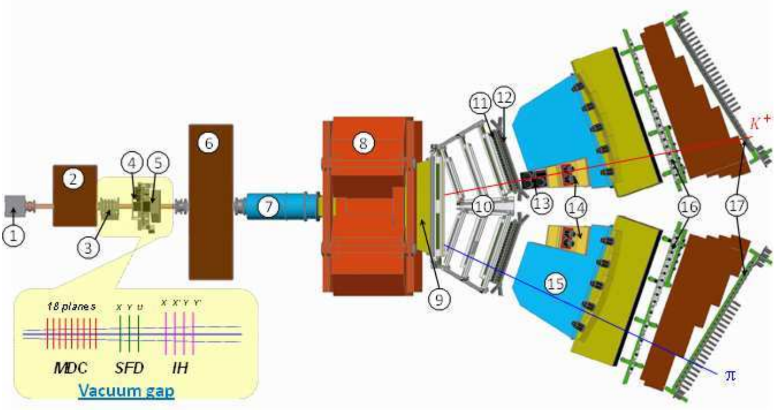
Break-up probability

Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on πK atom lifetime for Nickel target with thicknesses $108\mu m$ and $98\mu m$



DIRAC setup

Experimental setup



1 Target station with Ni foil; 2 First shielding; 3 Micro Drift Chambers; 4 Scintillating Fiber Detector; 5 Ionization Hodoscope; 6 Second Shielding; 7 Vacuum Tube; 8 Spectrometer Magnet; 9 Vacuum Chamber; 10 Drift Chambers; 11 Vertical Hodoscope; 12 Horizontal Hodoscope; 13 Aerogel Čerenkov; 14 Heavy Gas Čerenkov; 15 Nitrogen Čerenkov; 16 Preshower; 17 Muon Detector

Setup resolutions

SFD			
Coordinate precision	$\sigma_X = 60\mu m$	$\sigma_Y = 60\mu m$	$\sigma_W = 120\mu m$
Time precision	$\sigma^t_X = 380ps$	$\sigma^t_Y = 512ps$	$\sigma^t_W = 522ps$

DC	
Coordinate	$\sigma = 85\mu m$

VH	
Time precision	$\sigma = 100ps$

Spectrometer		
Relative resolution on the particle momentum in L.S.		$3 \cdot 10^{-3}$
Precision on Q-projections	$\sigma_{Q_X} = \sigma_{Q_Y} = 0.5\ MeV/c$	$\sigma_{Q_L} = 0.5\ MeV/c\ (\pi\pi)$ $\sigma_{Q_L} = 0.9\ MeV/c\ (\pi K)$

Trigger efficiency 98%	for pairs with $Q_L < 28\ MeV/c$ $Q_X < 6\ MeV/c$ $Q_Y < 4\ MeV/c$

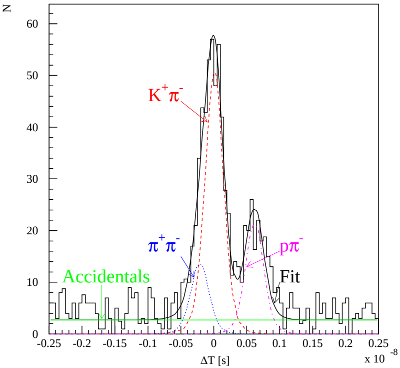
Experimental conditions

Primary proton beam	$24\ GeV/c$
Beam intensity	$(10.5 \div 12) \cdot 10^{10}\ proton/spill$
Single count of one IH plane	$(5 \div 6) \cdot 10^{6}\ particle/spill$
Spill duration	$450\ ms$

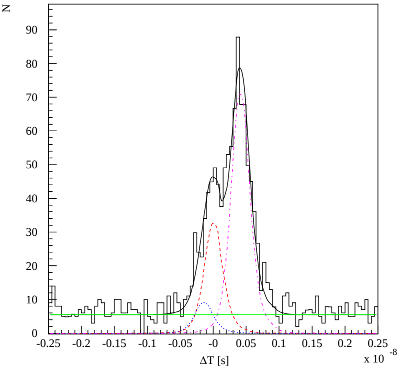
Ni target		
Purity	99.98%	
Target thickness (year)	$98 \pm 1\ \mu m$ (2008)	$108 \pm 1\ \mu m$ $(2009 - 2010)$
Radiation thickness	$6.7 \cdot 10^{-3}\ X_0$	$7.4 \cdot 10^{-3}\ X_0$
Probability of inelastic proton interaction	$6.4 \cdot 10^{-4}$	$7.1 \cdot 10^{-4}$

Observation of πK atoms

Measured difference of K^+ and π^- generation time

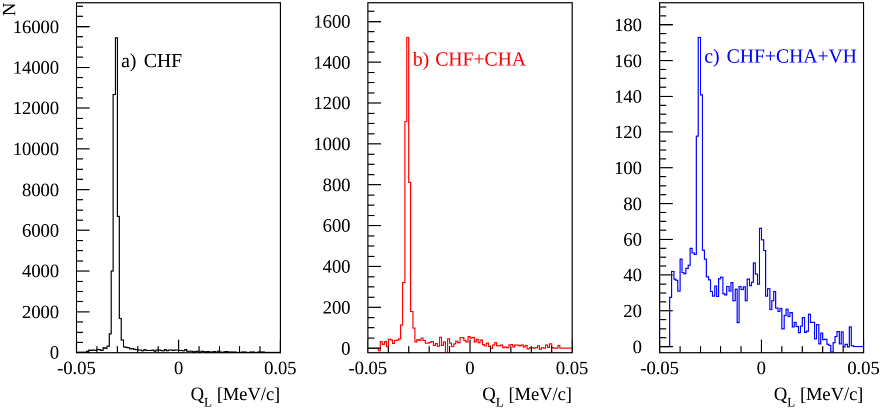


Momentum of positive particle in a range $4.4 \div 4.5$ GeV/c

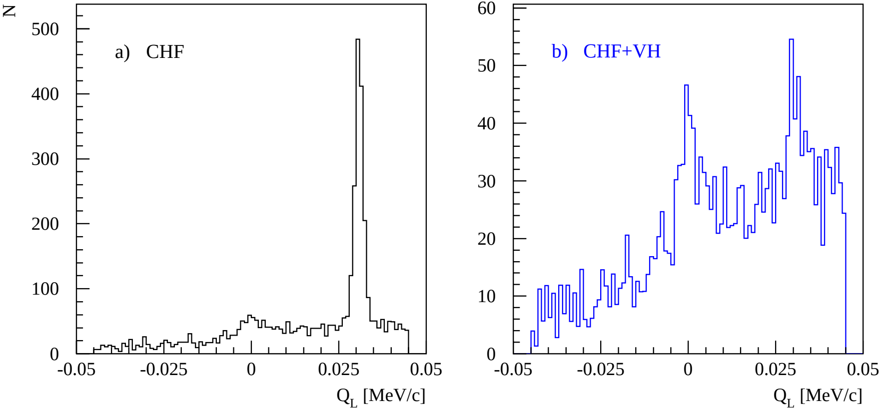


Momentum of positive particle in a range $5.4 \div 5.5$ GeV/c

Background suppression for $\pi^- K^+$

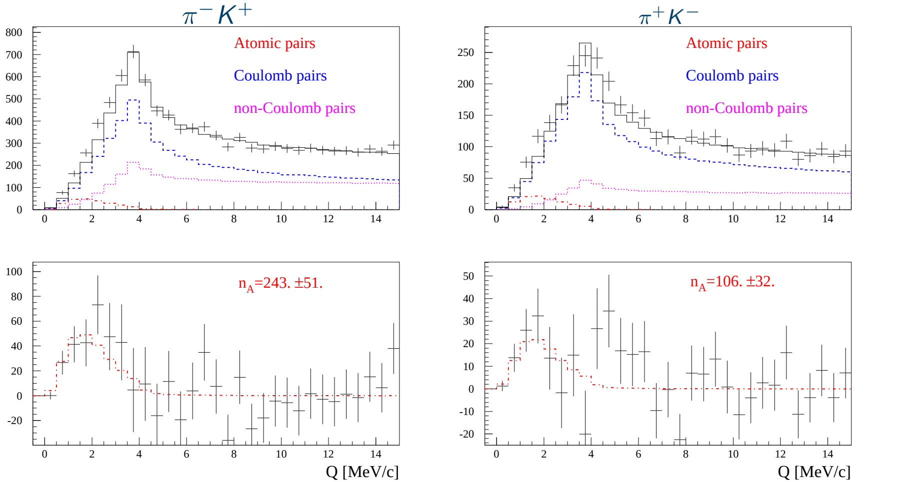


Background suppression for $\pi^+ K^-$



$\pi^- K^+$ and $\pi^+ K^-$ atoms - run 2007-2010

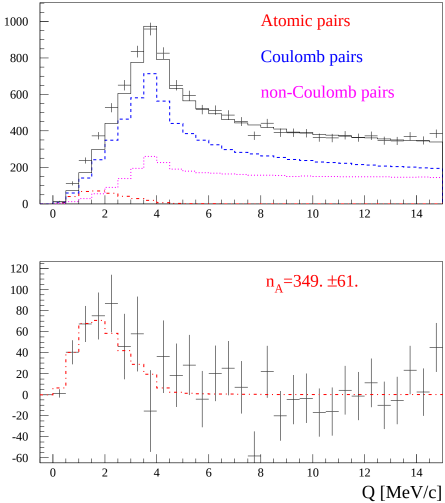
Statistics with Platinum (2007) and Nickel (2008-2010) targets



Criterion $Q_T < 4 MeV/c$. $\chi^2/ndf = 36/37$.
In absense of "atomic pairs" $\chi^2/ndf = 56/38$

Criterion $Q_T < 4 MeV/c$. $\chi^2/ndf = 42/37$.
In absense of "atomic pairs" $\chi^2/ndf = 53/38$

Statistics with Platinum (2007) and Nickel (2008-2010) targets



Criterion $Q_T < 4MeV/c$. $\chi^2/ndf = 41/37$. In absense of "atomic pairs" $\chi^2/ndf = 73/38$

Statistics πK atomic pairs

Analysis	$\pi^- K^+$	$\pi^+ K^-$	$\pi^- K^+$ and $\pi^+ K^-$
Q	243 ± 51 (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)

Systematic errors

Sources of systematic errors	σ_Q^{syst}	$\sigma_{Q_L}^{syst}$	$\sigma_{\lvert Q_L \rvert, Q_T}^{syst}$
Uncertainty in Λ width correction	0.8	3.0	2.0
Uncertainty of multiple scattering in Ni target	4.4	0.7	2.7
Accuracy of SFD simulation	0.2	0.0	0.1
Correction of Coulomb correlation function on 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

Observation of πK atoms

Analysis with Q_L, Q_T:

$$n_A = 314 \pm 59(stat) \pm 10(syst) = 314 \pm 60(tot)$$

5.2 standard deviations

Analysis with Q:

$$n_A = 349 \pm 61(stat) \pm 9(syst) = 349 \pm 62(tot)$$

5.6 standard deviations

CERN-EP-2016-128 ; arXiv:1605.06103.
Submitted to Phys. Rev. Lett.

Break-up probability of πK atoms

Year	Target	Q	Q_L	$\lvert Q_L \rvert, Q_T$
		$\pi^- K^+$		
2007	Pt 26 μ	1.09 ± 0.52	1.42 ± 0.95	1.44 ± 0.59
2008	Ni 98 μ	0.32 ± 0.20	0.41 ± 0.34	0.44 ± 0.22
2009	Ni 108 μ	0.23 ± 0.16	0.04 ± 0.22	0.16 ± 0.15
2010	Ni 108 μ	0.41 ± 0.17	0.15 ± 0.20	0.33 ± 0.16
		$\pi^+ K^-$		
2007	Pt 26 μ	1.2 ± 1.2	0.9 ± 1.6	0.27 ± 0.56
2008	Ni 98 μ	0.52 ± 0.39	0.50 ± 0.62	0.42 ± 0.38
2009	Ni 108 μ	0.29 ± 0.20	0.49 ± 0.37	0.33 ± 0.24
2010	Ni 108 μ	0.33 ± 0.22	-0.13 ± 0.20	0.21 ± 0.20

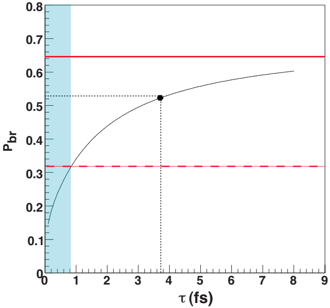
Systematic errors for break-up probability in Nickel target

Sources of systematic errors	Nickel target		
	σ_Q^{syst}	$\sigma_{Q_L}^{syst}$	$\sigma_{\lvert Q_L\rvert,Q_T}^{syst}$
Uncertainty in Λ width correction	0.0006	0.0013	0.0006
Uncertainty of multiple scattering in Ni target	0.0051	0.0006	0.0036
Accuracy of SFD simulation	0.0002	0.0001	0.0003
Correction of Coulomb correlation function on finite size production region	0.0001	0.0000	0.0000
Uncertainty in πK pair laboratory momentum spectrum	0.0052	0.0031	0.0050
Uncertainty in laboratory momentum spectrum of background pairs	0.0011	0.0010	0.0011
Total	0.0074	0.0036	0.0063

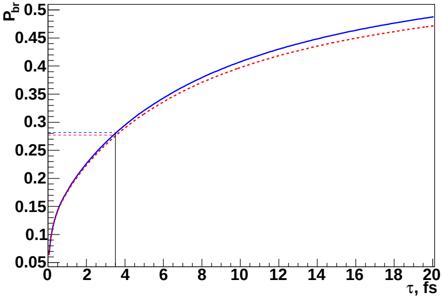
Systematic errors for break-up probability in Platinum target

Sources of systematic errors	Platinum target		
	σ_{Q}^{syst}	$\sigma_{Q_L}^{syst}$	$\sigma_{\lvert Q_L \rvert, Q_T}^{syst}$
Uncertainty in Λ width correction	0.011	0.099	0.0732
Uncertainty of multiple scattering in Ni target	0.0087	0.0086	0.0141
Accuracy of SFD simulation	0.	0.	0.
Correction of Coulomb correlation function on finite size production region	0.0001	0.0002	0.0002
Uncertainty in πK pair laboratory momentum spectrum	0.089	0.27	0.25
Uncertainty in laboratory momentum spectrum of background pairs	0.22	0.068	0.21
Total	0.24	0.29	0.34

Lifetime evaluation



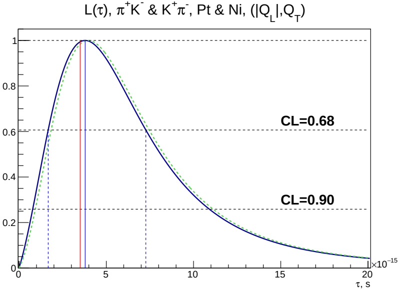
Probability of πK atom breakup in Platinum target vs the atom lifetime



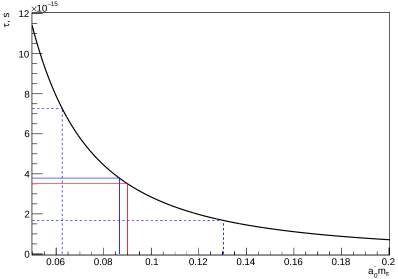
Probability of πK atom breakup in Nickel target vs the atom lifetime

πK atom lifetime estimation

Analysis with Q_L, Q_T: preliminary, to be published.



Likelihood function for πK atom lifetime measurement



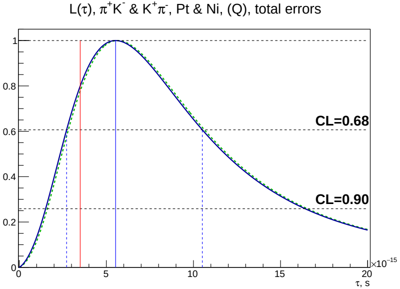
Relation between measured value πK atom lifetime (τ) and a S-wave isospin-odd πK scattering length $|a_0^-|$

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

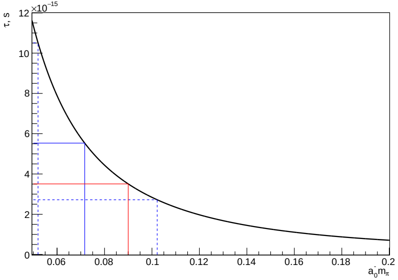
$$|a_0^-|M_\pi = 0.087^{+0.043}_{-0.024}$$

πK atom lifetime estimation

Analysis with Q: preliminary, to be published.



Likelihood function for πK atom lifetime measurement



Relation between measured value πK atom lifetime (τ) and a S-wave isospin-odd πK scattering length $|a_0^-|$

$$\tau = (5.5^{+4.9}_{-2.8}|_{stat}\ ^{+0.9}_{-0.5}|_{syst})\ fs = (5.5^{+5.0}_{-2.8}|_{tot})\ fs$$

$$|a_0^-|M_\pi = 0.072^{+0.031}_{-0.020}$$

Production of $\pi^+\pi^-$ and πK atoms at 450 GeV/c proton beam

Increasing of statistic with 450 GeV/c proton beam

The yield w of charged particles, and $\pi^+\pi^-$-,π^+K^-- and π^-K^+- atoms into DIRAC setup acceptance.

θ_{lab}	5.7°	4°	2°	0°
E_p	24 GeV	450 GeV	450 GeV	450 GeV
Yield charged particles				
W_{ch}	0.022	0.14	0.50	2.9
W_{ch}^N	1	6.4	22.7	132
Yield of $\pi^+\pi^-$ atoms				
$W_A \times 10^9$	1.94	34.	69.	89.
W_A^N	1.	17.3	35.4	45.9
$(W_A/W_{ch})^N$	1.	2.4	1.2	0.27
Yield of π^+K^- atoms				
$W_A \times 10^9$	0.217	8.1	16.3	23
W_A^N	1.	37.5	75.	106.
$(W_A/W_{ch})^N$	1.	10.6	5.8	1.2
Yield of π^-K^+ atoms				
$W_A \times 10^9$	0.52	8.5	19.	30.
W_A^N	1.	16.4	37.6	57.4
$(W_A/W_{ch})^N$	1.	4.9	3.0	0.66

Accuracy of a_0^- measurement with 450 GeV beam

On the base of experimental data, estimation of time needed for measurement a_0^- with statistical accuracy $\delta_{a_0^-}$ for present DIRAC setup and beam condition (Nickel target only); Mod1 is for DIRAC setup at $E_p = 450$ GeV beam (small modification due to another geometry of secondary particle beam); Mod2 is for essentially modified DIRAC setup at 450 GeV beam with higher intensity (I_B). It is assumed that at 450 GeV beam setup would obtain 3000 spills (4.5s) per day.

Setup	E_p GeV	I_b p/s	θ_{lab}	Solid angle *sr*	Beam time s	Run time months	$\delta_{a_0^-}$ %
Present	24	$2.7 \cdot 10^{11}$	5.7	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{6}$	14.5	43.
Present	24	$2.7 \cdot 10^{11}$	5.7	$1.2 \cdot 10^{-3}$	$6.0 \cdot 10^{7}$	715.6	5.
Mod1	450	$1.0 \cdot 10^{11}$	4.0	$0.6 \cdot 10^{-3}$	$5.8 \cdot 10^{6}$	14.3	5.
Mod2	450	$1.0 \cdot 10^{12}$	4.0	$0.6 \cdot 10^{-3}$	$7.4 \cdot 10^{5}$	1.9	5.

Work under LOI for experiment at 450 Gev proton beam is started.

Conclusion

- In the experiment DIRAC at CERN, the dimesonic Coulomb bound states involving strangeness, the $\pi^- K^+$ and $\pi^+ K^-$ atoms have been observed with reliable statistics: 349 ± 62 events ($5.6\ \sigma$).
- Value of πK atom lifetime preliminary has been expracted to be $\tau = (3.8^{+3.5}_{-2.1}|_{tot})\ fs$. It provides a measurement of the S-wave isospin-odd πK scattering length $|a_0^-| = (0.087^{+0.043}_{-0.024}) \cdot M_\pi^{-1}$.
- Simulation, based on results of experiment DIRAC, shoes that a S-wave isospin-odd πK scattering length $|a_0^-|$ could be measured with accuracy 5% in a reasonable time, using 450 GeV proton beam.

Thank you for your attention!

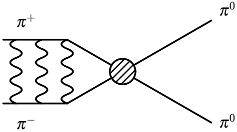
Supplementary slides

Pionium lifetime

Pionium ($A_{2\pi}$) is a hydrogen-like atom consisting of π^+ and π^- mesons:

$$E_B = -1.86\, keV,\ r_B = 387\, fm,\ p_B \approx 0.5\, MeV/c$$

The lifetime of $\pi^+\pi^-$ atoms is dominated by the annihilation process into $\pi^0\pi^0$:



$$\Gamma = \frac{1}{\tau} = \Gamma_{2\pi_0} + \Gamma_{2\gamma} \text{ with } \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi_0}} \approx 4 \times 10^{-3}$$

$$\Gamma_{1S,2\pi^0} = R|\, a_0 - a_2\,|^2 \text{ with } \frac{\Delta R}{R} \approx 1.2\%$$

$$\tau = (2.9 \pm 0.1) \times 10^{-15} s$$

Gasser et al. - 2001

a_0 and a_2 are the $\pi\pi$ S-wave scattering lengths for isospin $I = 0$ and $I = 2$.

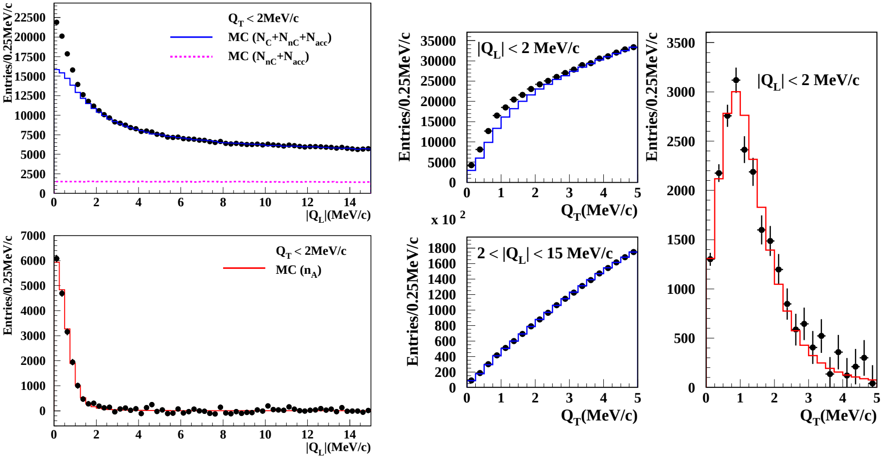
Published results on $\pi\pi$ scattering lengths

DIRAC data	$\tau_{1s}(10^{-15}s)$ value stat syst theo* tot	$\mid a_0 - a_2 \mid$ value stat syst theo* tot	Reference
2001	$2.91^{+0.45+0.19}_{-0.38-0.49}\begin{bmatrix}+0.49\\-0.62\end{bmatrix}$	$0.264^{+0.017+0.022}_{-0.020-0.009}\begin{bmatrix}+0.033\\-0.020\end{bmatrix}$	PL B 619 (2005) 50
2001-03	$3.15^{+0.20+0.20}_{-0.19-0.18}\begin{bmatrix}+0.28\\-0.26\end{bmatrix}$	$0.2533^{+0.0078+0.0072}_{-0.0080-0.0077}\begin{bmatrix}+0.0106\\-0.0111\end{bmatrix}$	PL B 704 (2011) 24

* theoretical uncertainty included in systematic error

NA48	K-decay	$a_0 - a_2$ value stat syst theo tot	Reference
2009	$K_{3\pi}$	$0.2571 \pm 0.0048 \pm 0.0029 \pm 0.0088$	EPJ C64 (2009) 589
2010	$K_{e4}\&K_{3\pi}$	$0.2639 \pm 0.0020 \pm 0.0015$	EPJ C70 (2010) 635

$\pi^+\pi^-$ atoms - runs 2001-2003



Method of long-lived $\pi^+\pi^-$ atom observation and investigation

Properties of long-lived $\pi^+\pi^-$ atoms

Decay length (cm) of $A_{2\pi}$ with different principal quantum number n and orbital momentum l for $\gamma = 16$.

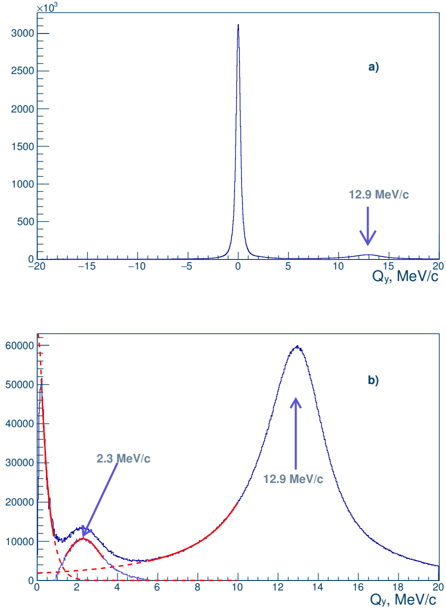
l	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$
0	$1.39 \cdot 10^{-3}$	$1.11 \cdot 10^{-2}$	$3.76 \cdot 10^{-2}$	$8.91 \cdot 10^{-2}$	$1.74 \cdot 10^{-1}$
1		5.6	19	43	84

Fraction of atoms with non-zero orbital momentum ($\epsilon_n(Be)$) on the exit of Be target (100 μm) and $\epsilon_n(Pt)$ in the entry of Pt foil (10 cm downstream) for $\gamma = 16$.

	$n=2$	$n=3$	$n=4$	$n=5$
$\epsilon_n(Be) \times 10^2$	$2.48 \pm O(10^{-3})$	1.54 ± 0.01	0.86 ± 0.03	0.56 ± 0.06
$\epsilon_n(Pt) \times 10^2$	$0.52 \pm O(10^{-4})$	$1.01 \pm O(10^{-3})$	0.78 ± 0.03	0.54 ± 0.06

$$\epsilon_{n\geq 2}(Be) = (7.11 \pm 0.77) \cdot 10^{-2},\ \epsilon_{n\geq 2}(Pt) = (4.59 \pm 0.76) \cdot 10^{-2}\,.$$

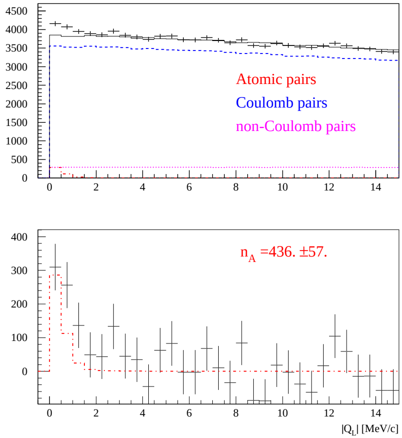
Observation of long-lived $\pi^+\pi^-$ atoms



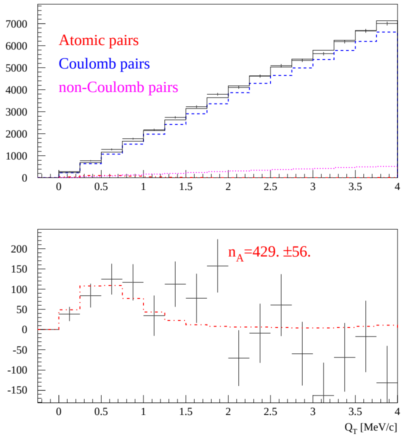
Distribution of e^+e^- pairs generated in the Be target (before permanent magnet), Pt foil (after main part of permanent magnet field) and in upstream detector region (after permanent magnet field).

$$Q'_T = \sqrt{Q_X^2 + (Q_Y - 2.3\,\mathrm{MeV}/c)^2}$$

Run 2012, statistics with low and medium background. Two-dimensional distribution over $\mid Q_L \mid$, Q'_T have been fitted with $\chi^2/ndf = 138/140$. Projections to $\mid Q_L \mid$ and Q'_T are presented.



$Q'_T < 2$ MeV$/c$.



$\mid Q_L \mid < 2$ MeV$/c$.

Statistics of "atomic pairs" from long-lived atoms

Q'_T cut (MeV/c)	n_A^L	$n_A^{L,\ tot}$	Back-ground	χ^2/n
Fit over $\|Q_L\|$, Q_T				
2.0	436 ± 57	488 ± 64	16790	138/140
Fit over $\|Q_L\|$				
0.5	152 ± 29	467 ± 88	971	29/27
1.0	349 ± 53	489 ± 75	3692	19/27
1.5	386 ± 78	454 ± 91	9302	22/27
2.0	442 ± 105	495 ± 117	16774	22/27
Analysis with "Coulomb pairs" generated at Platinum target				
2.0	$(-0.8 \pm 13.) \times 10^3$			238/140

Observation of long-lived atom

Systematic errors of number of long-lived "atomic pairs"

Sources of systematic errors	σ^{syst}
Uncertainty in correction on Λ-width	4.4
Uncertainty of Platinum foil thickness	22.
Total	23.

$$n_A^L = 436 \pm 57(stat.) \pm 23(syst.) = 436 \pm 61$$

Expected number $\rightarrow 653 \pm 110\,(453 \div 845)$

B.Adeva et al., Phys. Lett. B 751 (2015) 12

Experimental conditions

Secondary particles channel (relative to the proton beam)	5.7^o
Angular divergence in vertical and horizontal planes	$\pm 1^o$
Solid angle	$1.2 \cdot 10^{-3}\ sr$
Dipole magnet	$B_{max} = 1.65\ T,\ BL = 2.3\ Tm$

Time resolution [ps]								
	VH	IH				SFD		
plane	1	1	2	3	4	X	Y	W
2008	112	713	728	718	798	379	508	518
2010	113	907	987	997	1037	382	517	527