Investigation of $\pi^+\pi^-$, $K^+\pi^-$ and π^+K^- atoms for pion-pion and pion-kaon scattering length measurements

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Low-energy QCD precise predictions

$\pi\pi$ scattering lengths

In ChPT the effective Lagrangian, which describes the $\pi\pi$ interaction, is an expansion in (even) terms:

$$L_{eff} = \underset{(tree)}{L^{(2)}} + \underset{(1-loop)}{L^{(4)}} + \underset{(2-loop)}{L^{(6)}} + \cdots$$

Colangelo et al. in 2001, using ChPT (2-loop)& Roy equations:

$$\left.\begin{aligned} a_0 &= 0.220 \pm 2.3\% \\ a_2 &= -0.0444 \pm 2.3\% \end{aligned}\right\} a_0 - a_2 = 0.265 \pm 1.5\%$$

These results (precision) depend on the low-energy constants (LEC) l_3 and l_4. Lattice gauge calculations from 2006 provided values for these l_3 and l_4.

Because l_3 and l_4 are sensitive to the quark condensate, precision measurements of a_0, a_2 are a way to study the structure of the QCD vacuum.

Lattice calculations of $\bar{l}_3$, $\bar{l}_4$

- 2006: l_3, l_4 first lattice calculations
- 2012: 10 collaborations: 3 USA, 5 Europe, 2 Japan
- J. Gasser, H. Leutwyler: Model calculation (1985)
  $\bar{l}_3 = 2.6 \pm 2.5$, $\Delta\bar{l}_3/\bar{l}_3 \approx 1$
- Lattice calculations in near future will obtain
  $\Delta\bar{l}_3/\bar{l}_3 \approx 0.1$ or $\Delta\bar{l}_3 \approx 0.2 - 0.3$
- To check the predicted values of l_3 the experimental relative errors of $\pi\pi$-scattering lengths and their combinations must be at the level $(0.2 - 0.3)\%$

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

$$a_{1/2} - a_{3/2} = 0.267$$

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

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

Recently predictions for πK scattering have been obtained:

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

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

What new will be known if πK scattering lengths will be measured?

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!

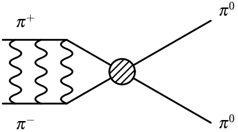
Experimental data on the πK low-energy phases are absent.

Pionium lifetime

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

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

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



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

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

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

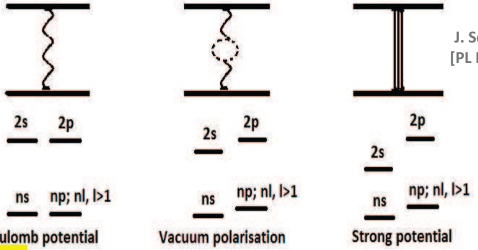
Gasser et al. - 2001

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

$$\frac{\Delta\tau}{\tau} = 9\% \quad \Rightarrow \quad \frac{\Delta|a_0 - a_2|}{|a_0 - a_2|} = 4.3\%$$

$A_{2\pi}$ Energy Levels

For Coulomb potential, E depends only on n



J. Schweizer [PL B (2004)]

Notation:

$E_{2s} - E_{2p} = \Delta_{2s-2p}$

$\Delta^{vac}_{2s-2p} = -0.111\text{eV}$ $\quad \Delta^{str}_{2s-2p} = -0.47 \pm 0.01\text{eV}$ $\quad$ higher order QED $\Delta^{em}_{2s-2p} = -0.012\text{eV}$

$$\Rightarrow \Delta^{vac+str+em}_{2s-2p} = -0.59 \pm 0.01\text{eV}$$

$$\Delta^{str}_{2s-2p} = -\frac{\alpha^3 m_\pi}{8}\frac{1}{6}\left(2a_0 + a_2\right) + \cdots$$

G.V.Efimov et al. Sov.J.Nucl.Phys. (1986)

$$\Delta^{str}_{ns-np} = -\frac{\Delta^{str}_{2s-2p}}{n^3} \cdot 8$$

CONCLUSION: one parameter ($2a_0+a_2$) allows to calculate all Δ^{str}_{ns-np} values

Dependence of $A_{2\pi}$ lifetime on electric field E strength

$$N_A = N_A(0)\cdot e^{-\frac{t}{\tau_{2p}}} \qquad N_A = N_A(0)\cdot e^{-\frac{t}{\tau_{eff}}}$$

$$\tau_{eff} = \frac{\tau_{2p}}{1+\frac{|\xi|^2}{4}\frac{\tau_{2p}}{\tau_{2s}}} = \frac{\tau_{2p}}{1+120|\xi|^2}$$

where: $|\xi|^2 \approx \frac{|\vec{E}|^2}{(E_{2p}-E_{2s})^2}$

$B_{Lab} = 2$ Tesla

$$\begin{cases} \gamma = 20, & |\xi| = 0.025 \Rightarrow \tau_{eff} = \frac{\tau_{2p}}{1.3} \\ \gamma = 40, & |\xi| = 0.05 \Rightarrow \tau_{eff} = \frac{\tau_{2p}}{2.25} \end{cases}$$

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

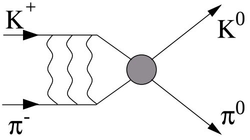
NA48	K-decay	$a_0 - a_2$ value stat syst theo tot	Reference
2009	$K_{3\pi}$	$0.2571 \pm 0.0048 \pm 0.0029 \pm 0.0088$	EPJ C64 (2009) 589
2010	$K_{e4} \& K_{3\pi}$	$0.2639 \pm 0.0020 \pm 0.0015$	EPJ C70 (2010) 635

$K^+\pi^-$ and π^+K^- atoms lifetime

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

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

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



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

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

J. Schweizer - 2004

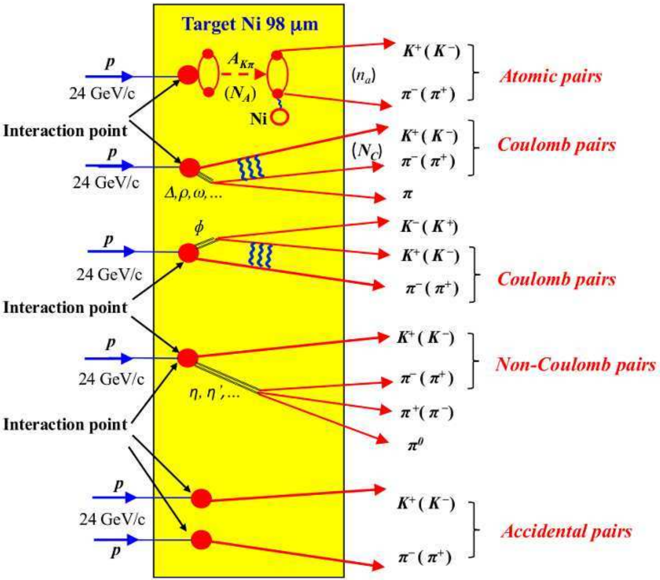
From Roy-Steiner equations:

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

$$\text{If} \quad \frac{\Delta\Gamma}{\Gamma} = 20\% \quad \Rightarrow \quad \frac{\Delta|a_{1/2}-a_{3/2}|}{|a_{1/2}-a_{3/2}|} = 10\%$$

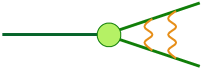
Method of $\pi^+\pi^-$ and πK atom observation and investigation

Method of and πK atom observation and investigation



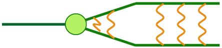
Coulomb pairs and atoms

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



$\pi^+\pi^-$, K^+K^-,
π^+K^-, $K^+\pi^-$,
$\pi^+\mu^-$, $\mu^+\pi^-$

Coulomb pairs



$(\pi^+\pi^-)$, (K^+K^-),
(π^+K^-), $(K^+\pi^-)$,
$(\pi^+\mu^-)$, $(\mu^+\pi^-)$

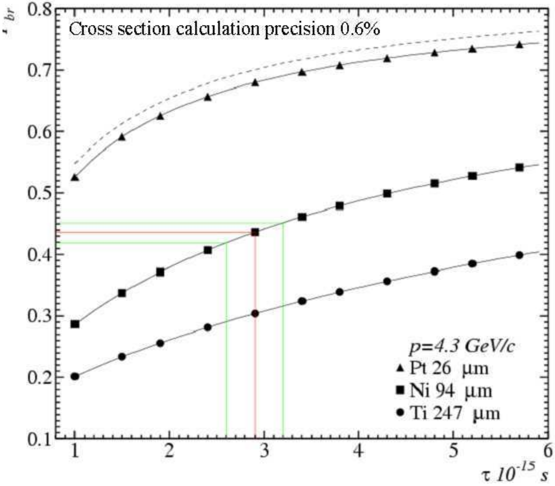
Atoms

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, $P_{br} = \frac{n_A}{N_A}$

Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on pionium lifetime τ

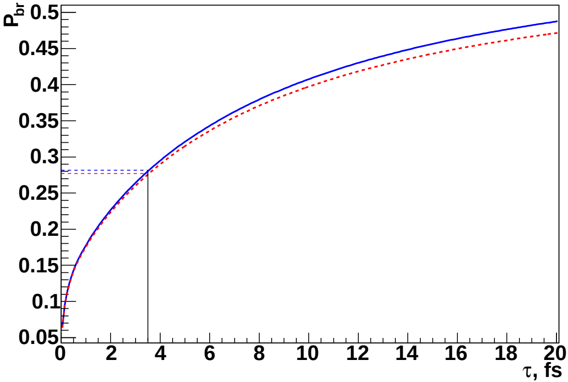


All targets have the same thickness in radiation lengths $6.7 \cdot 10^{-3} X_0$.

There is an optimal target material for a given lifetime.

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 $98\mu m$



Method to observe long-lived atoms

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

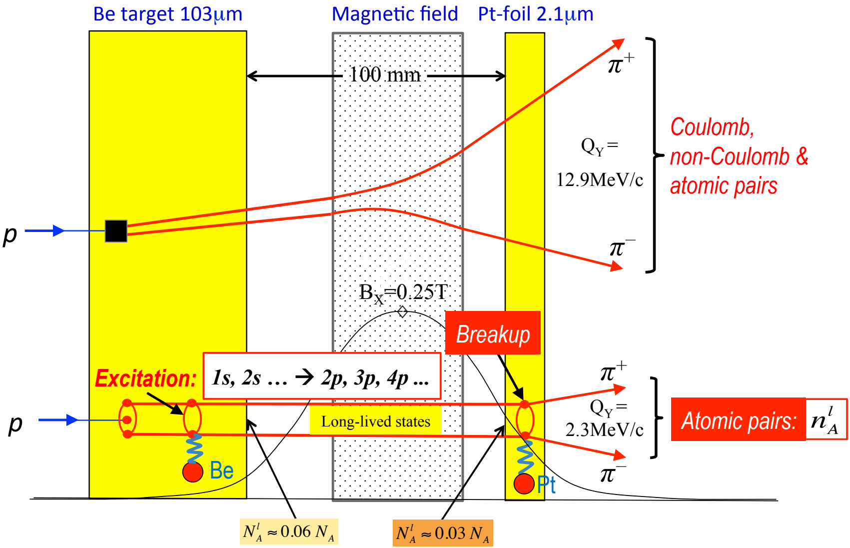
l	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
0	$1.39 \cdot 10^{-3}$	$1.11 \cdot 10^{-2}$	$3.76 \cdot 10^{-2}$	$8.91 \cdot 10^{-2}$	$1.74 \cdot 10^{-1}$
1		5.6	19	43	84

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

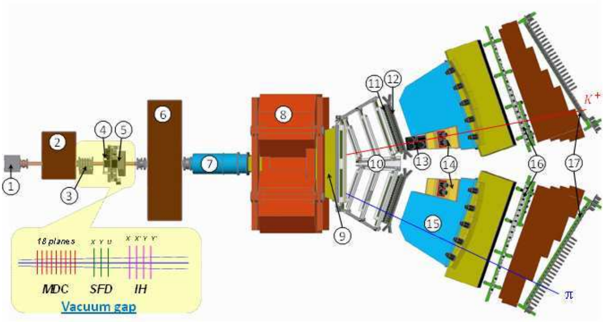
$$\epsilon_{n\geq 2}(Be) = (7.11 \pm 0.77) \cdot 10^{-2},\ \epsilon_{n\geq 2}(Pt) = (4.59 \pm 0.76) \cdot 10^{-2}\,.$$

Method to observe long-lived atoms



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

Experimental conditions

SFD			
Coordinate precision	$\sigma_X = 60\mu m$	$\sigma_Y = 60\mu m$	$\sigma_W = 120\mu m$
Time precision	$\sigma_X^t = 380ps$	$\sigma_Y^t = 512ps$	$\sigma_W^t = 522ps$

DC	
Coordinate	$\sigma = 85\mu m$

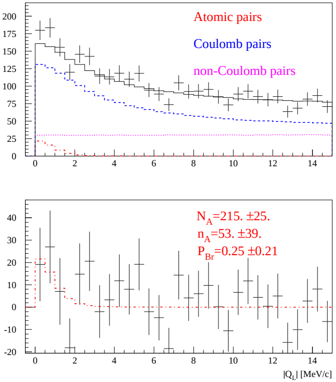
VH	
Time precision	$\sigma = 100ps$

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

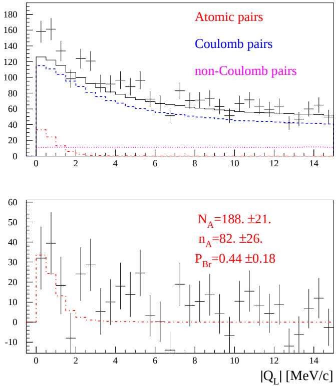
Trigger efficiency 98%	for pairs with $Q_L < 28\ MeV/c$ $Q_X < 6\ MeV/c$ $Q_Y < 4\ MeV/c$

Status of πK atom investigation

Run 2008-2010, statistics with low and medium background (2/3 of all statistics). Point-like production for all particles.

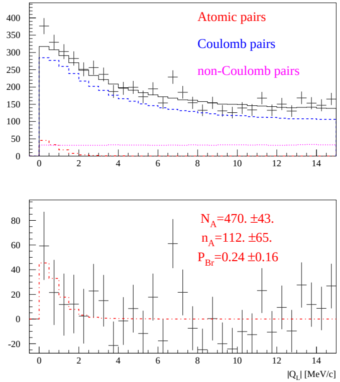


$| Q_L |$ distribution analysis on $| Q_L |$ for $Q_T < 4MeV/c$. $\chi^2/ndf = 44/37$

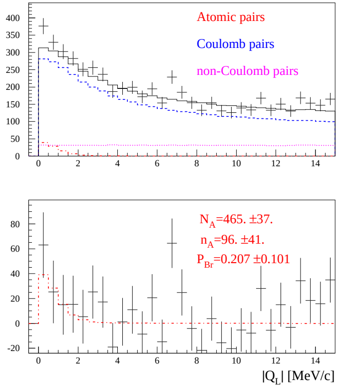


$| Q_L |$ distribution analysis on $| Q_L |$ and Q_T for $Q_T < 4MeV/c$. $\chi^2/ndf = 130/117$

Run 2008-2010, statistics with low and medium background (2/3 of all statistics). Point-like production for all particles.



$|Q_L|$ distribution analysis on $|Q_L|$ for $Q_T < 4MeV/c$. $\chi^2/ndf = 41/37$



$|Q_L|$ distribution analysis on $|Q_L|$ and Q_T for $Q_T < 4MeV/c$. $\chi^2/ndf = 142/117$

Break-up probability of πK atoms

Year	N_A	n_A	P_{br}
$K^+\pi^-$ over Q_T, Q_L			
2008	132 ± 16	14 ± 19	0.11 ± 0.15
2009	169 ± 24	33 ± 26	0.20 ± 0.17
2010	164 ± 23	49 ± 26	0.30 ± 0.19
All	465 ± 37	96 ± 41	0.21 ± 0.10
π^+K^- over Q_T, Q_L			
2008	51 ± 11	21 ± 13	0.41 ± 0.33
2009	78 ± 13	26 ± 16	0.34 ± 0.24
2010	60 ± 12	35 ± 16	0.58 ± 0.36
All	188 ± 21	82 ± 26	0.44 ± 0.18

$$n_A^{K^+\pi^-} + n_A^{\pi^+K^-} = 178 \pm 49$$

Systematic errors

Systematic errors in P_{br} common to all data collected from 2008 to 2010

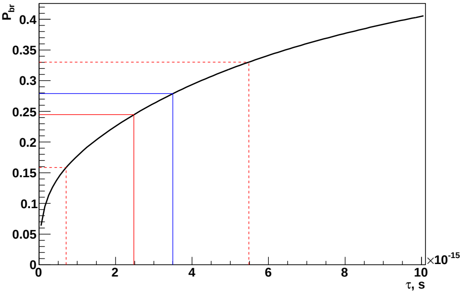
Sources of systematic errors	$\sigma^{syst}_{Q_L,Q_T}$	$\sigma^{syst}_{Q_L}$
Uncertainty in correction on Λ-width	0.0039	0.0071
Uncertainty of multiple scattering in the Nickel target	0.0032	0.00054
Accuracy of SFD detector response simulation	0.00075	0.00029
Correction of Coulomb correlation function on finite size of production region	0.000058	0.000058
Uncertainty in a dependence $P_{br}(\tau)$	0.0050	0.0050
Accuracy of a target thickness measurement	0.00030	< 0.00030

Systematic errors

Systematic errors in P_{br} specific to the data samples collected in 2008, 2009 and 2010

Year	$\sigma^{syst}_{\pi K}$	σ^{syst}_{backgr}
$K^+\pi^-$ over Q_T, Q_L		
2008	0.0028	0.0015
2009	0.0044	0.0025
2010	0.0036	0.0022
$K^+\pi^-$ over Q_L		
2008	0.0030	0.0028
2009	0.0053	0.0044
2010	0.0046	0.0036
π^+K^- over Q_T, Q_L		
2008	0.0072	0.0067
2009	0.0048	0.0028
2010	0.0017	0.0043
π^+K^- over Q_L		
2008	0.0093	0.0072
2009	0.0047	0.0048
2010	0.0021	0.0017

πK atom lifetime estimation



Analysis with Q_L, Q_T:

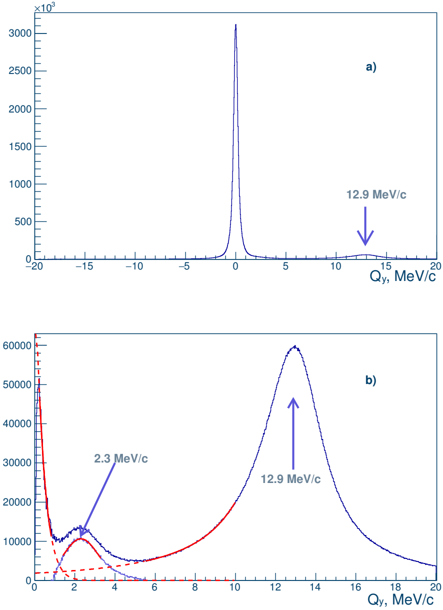
$$\tau = (2.5^{+3.0}_{-1.8}|_{stat}\ {}^{+0.3}_{-0.1}|_{syst})\ fs = (2.5^{+3.0}_{-1.8}|_{tot})\ fs$$

$$|a_0^-|M_\pi = 0.107^{+0.093}_{-0.035} = 0.11^{+0.09}_{-0.04}$$ Phys.Lett. B 735 (2014) 288

Analysis with Q_L:

$$\tau = (2.4^{+5.4}_{-2.2}|_{stat}\ {}^{+0.5}_{-0.1}|_{syst})\ fs = (2.4^{+5.5}_{-2.2}|_{tot})\ fs$$

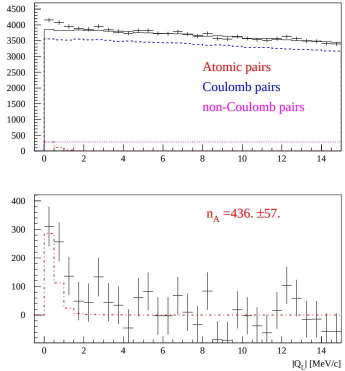
The first observation of long-lived $\pi^+\pi^-$ atoms



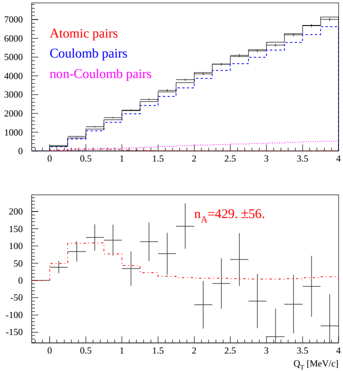
Distribution of e^+e^- pairs generated in the Be target (before permanent magnet), Pt foil (after main part of permanent magnet field) and in upstream detector region (after permanent magnet field).

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

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



$Q'_T < 2$ MeV/c.



$|Q_L| < 2$ 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 $\rightarrow 653 \pm 110\,(453 \div 845)$

Increasing of statistic with 450 GeV/c proton beam

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

θ_{lab}	5.7°	4°	2°	0°
E_p	24 GeV/c	450 GeV/c	450 GeV/c	450 GeV/c
The yield of $\pi^+\pi^-$ atoms				
W_A	$1.25\cdot10^{-9}$	$1.9\cdot10^{-8}$	$3.5\cdot10^{-8}$	$4.5\cdot10^{-8}$
W_A^N	1	15	28	36
W_A/W_π	$5.7\cdot10^{-8}$	$1.4\cdot10^{-7}$	$7.0\cdot10^{-8}$	$1.6\cdot10^{-8}$
$(W_A/W_\pi)^N$	1	2.4	1.2	0.27
The yield of π^+K^- atoms				
W_A	$1.3\cdot10^{-11}$	$8.8\cdot10^{-10}$	$1.7\cdot10^{-9}$	$2.0\cdot10^{-9}$
W_A^N	1	67	131	154
W_A/W_π	$5.9\cdot10^{-10}$	$6.3\cdot10^{-9}$	$3.4\cdot10^{-9}$	$6.9\cdot10^{-10}$
$(W_A/W_\pi)^N$	1	11	5.8	1.2
The yield of $K^+\pi^-$ atoms				
W_A	$3.1\cdot10^{-11}$	$9.7\cdot10^{-10}$	$2.1\cdot10^{-9}$	$2.7\cdot10^{-9}$
W_A^N	1	31	68	87
W_A/W_π	$1.4\cdot10^{-9}$	$6.9\cdot10^{-9}$	$4.2\cdot10^{-9}$	$9.3\cdot10^{-10}$
$(W_A/W_\pi)^N$	1	4.9	3.0	0.66

Conclusion

- The analysis of πK pairs statistic with low and medium background, collected from 2008 to 2010, allows to evaluate the number of atomic πK pairs (178 ± 49) as well as the number of produced πK atoms (653 ± 42) and thus the breakup (ionisation) probability.
- Value of πK atom lifetime has been expracted to be $\tau = (2.5^{+3.0}_{-1.8})\, fs$. It provides a measurement of the S-wave isospin-odd πK scattering length $|a_0^-| = (0.11^{+0.09}_{-0.04}) \cdot M_\pi^{-1}$.
- Analysis of data collected in 2012 with Be-Pt target allows to make observation of "atomic pairs" from $\pi^+\pi^-$ atoms in long-lived states: $n_A^L = 436 \pm 61$. It provides possibility to plan experiments for measurement of "Lamb shift like" effect in $\pi^+\pi^-$ system.

Thank you for your attention!

Supplementary slides

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	$6.4\cdot 10^{-4}$	$7.1\cdot 10^{-4}$

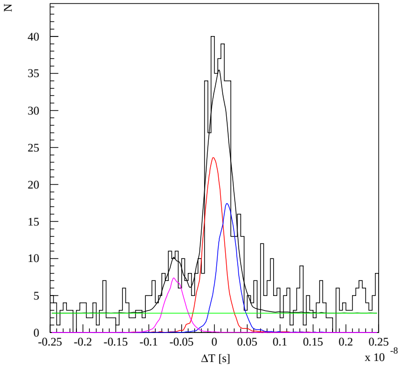
Experimental conditions

Secondary particles channel (relative to the proton beam)	5.4^o
Angular divergence in vertical and horizontal planes	$\pm 1^o$
Solid angle	$1.2 \cdot 10^{-3}\ sr$
Dipole magnet	$B_{max} = 1.65\ T, BL = 2.2\ Tm$

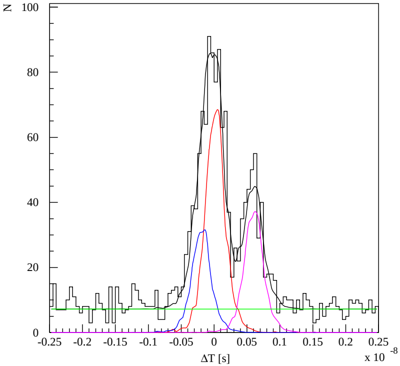
Time resolution [ps]								
	VH	IH				SFD		
plane	1	1	2	3	4	X	Y	W
2008	112	713	728	718	798	379	508	518
2010	113	907	987	997	1037	382	517	527

Admixtures in distributions of π^+K^- and π^-K^+ pairs

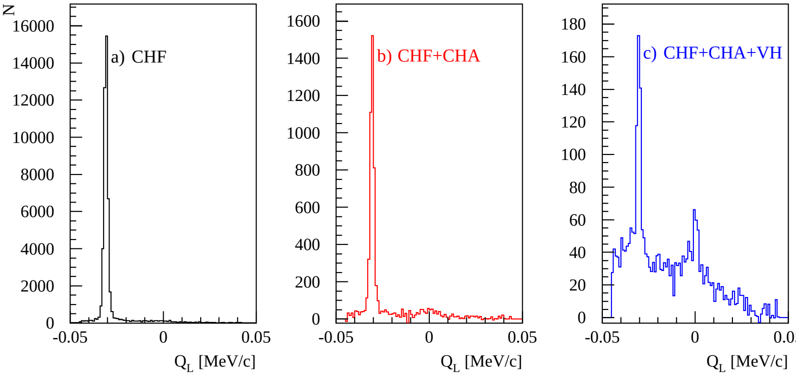
π^+K^-



π^-K^+



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



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