Frascati Physics Series Vol. XLVI (2007), pp. 000-000
HADRON07: XII Int. Conf. on Hadron Spectroscopy – Frascati, October 8-13, 2007
Plenary/Parallel Session *pick one*

MEASUREMENT OF THE $\pi^+\pi^-$ ATOM LIFETIME AT DIRAC

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Abstract

The measurement of the $\pi^+\pi^-$ atom lifetime with 10% precision provides, in a model independent way, the difference between the S-wave $\pi\pi$ scattering lengths for isospin 0 and 2, $|a_0 - a_2|$, with 5% accuracy. The scattering lengths a_0 and a_2 have been calculated in Chiral Perturbation Theory (ChPT) with a precision better than 2.5%. Therefore, such a measurement will be a sensitive check of the understanding of chiral symmetry breaking in QCD.

1 Introduction

Pionium or $A_{2\pi}$ is a hydrogen-like atom consisting of π^+ and π^- mesons. The $\pi^+\pi^-$ atom decays by strong interaction mainly into $\pi^0\pi^0$. The branching ratio of the alternative decay mode $A_{2\pi} \to 2\gamma$ is at the level of $4 \cdot 10^{-3}$. There is a relation [1] between the width of $A_{2\pi}$ decay $\Gamma_{2\pi^0}$ and $\pi\pi$ scattering lengths for isospin 0 and 2: $\Gamma_{2\pi^0} = C \cdot |a_0 - a_2|^2$.

The scattering lengths a_0 and a_2 have been calculated in Chiral Perturbation Theory (ChPT) with a precision better than 2.5% [2]: $a_0 = 0.220 \pm 0.005$, $a_2 = -0.0444 \pm 0.0010$ and $a_0 - a_2 = 0.265 \pm 0.004$.

ChPT at next-to-leading order in isospin breaking provides correction to decay width $\Gamma_{2\pi^0}^{NLO} = \Gamma_{2\pi^0}(1 + \delta_\Gamma), \delta_\Gamma = (5.8 \pm 1.2)\%$. Using this correction the lifetime of $\pi^+\pi^-$ atoms is predicted [3] to be $\tau = (2.9 \pm 0.1) \cdot 10^{-15}$ s.

The goal of the DIRAC experiment at CERN (PS212) is to measure the pionium lifetime with 10% precision. Such a measurement provides in a model independent way the difference between the S-wave $\pi\pi$ scattering $|a_0 - a_2|$, with 5% accuracy. Therefore, such a measurement will be a sensitive check of the understanding of chiral symmetry breaking in QCD.

2 Method of lifetime measurement

The $A_{2\pi}$ are produced by Coulomb interaction in the final state of $\pi^+\pi^-$ pairs generated in proton-target interactions from fragmentation and strong decay ("short-lived" sources). For this cases the region of production being small as compared to the Bohr radius of the atom and, neglecting strong final state interaction, the cross section σ_A^n for production of atoms with principal quantum number n is proportional to the inclusive production cross section for pion pairs from "short lived" sources without Coulomb correlation (σ_s^0) [4]:

$$\frac{d\sigma_A^n}{d\vec{p_A}} = (2\pi)^2 \frac{E_A}{M_A} |\Psi_n^C(\vec{r^*} = 0)|^2 \frac{d^2\sigma_s^0}{d\vec{p_+} d\vec{p_-}}, \tag{1}$$

with $\vec{p_A}$, E_A and M_A the momentum, energy and mass of the atom in the lab frame, respectively, and $\vec{p_+}$, $\vec{p_-}$ the momenta of the charged pions, and $|\Psi_n^C(\vec{r^*} = 0)|^2$ is the square of the Coulomb atomic wave function for zero distance $\vec{r^*}$ between them in the pair c.m. system.

Also $\pi^+\pi^-$ pairs from short-lived sources are generated in free state. Such pairs ("Coulomb pairs") are affected by Coulomb interaction, too. The number of produced atoms (N_A) is proportional to the number of "Coulomb pairs" (N^C) with low relative momenta ($N_A = K \cdot N^C$). The coefficient K is precisely calculable. And there are $\pi^+\pi^-$ pairs from long-lived sources (electromagnetically or weakly decaying mesons or baryons: $\eta, K_s^0, \ldots$). Such pairs, not affected by final state interaction, are named "non-Coulomb pairs".

Another type of background is "accidental pairs" consisted of pions generated in two different proton-nucleus. They are also not affected by final state interaction.

After production $A_{2\pi}$ travel through the target and some of them are broken up due to their interaction with matter: "atomic pairs" are produced, characterized by small pair c.m. relative momenta $Q < 3$ MeV/c. These pairs are detected in the DIRAC setup. Other atoms annihilate into $\pi^0\pi^0$. Using experimentally measured number of "Coulomb" pairs it is possible to measure breakup probability $P_{\rm br}(\tau) = n_A/N_A = n_A/(K \cdot N_C)$.

The dependence of $P_{\rm br}$ on the lifetime τ is determined by the solution of differential transport equations [5]. In fig. 1 the lifetime dependence of $P_{\rm br}$ is presented for three different targets used in the DIRAC experiment. The nickel target provides the best statistical accuracy for the same running time.

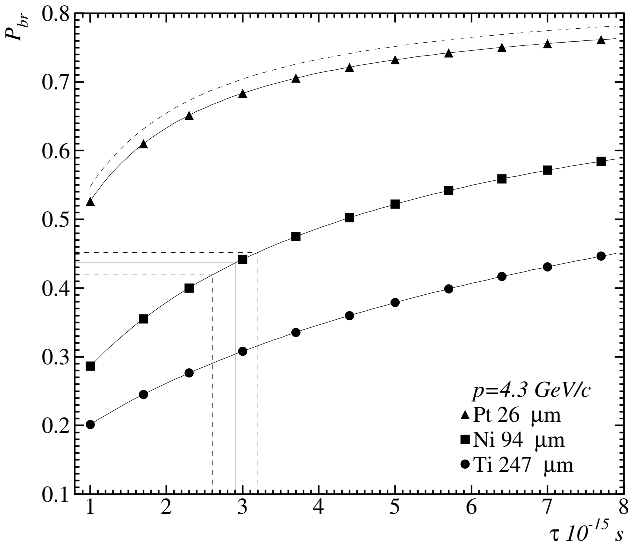

Figure 1: *Dependence of the breakup probability* $P_{\rm br}$ *on* $A_{2\pi}$ *lifetime for three targets used in the DIRAC experiment: platinum of 26* μm*, nickel of 94* μm *and titanium of 247* μm *thickness.*

3 Experimental setup

The purpose of the DIRAC setup (Fig. 2) is to detect $\pi^+\pi^-$ pairs with small relative momenta [6]. This setup is located at the CERN T8 beam area (East Hall). It became operational at the end of 1998 and uses the 24 GeV proton beam from PS accelerator. During some periods in 2002 and 2003 there was 20 GeV proton beam.

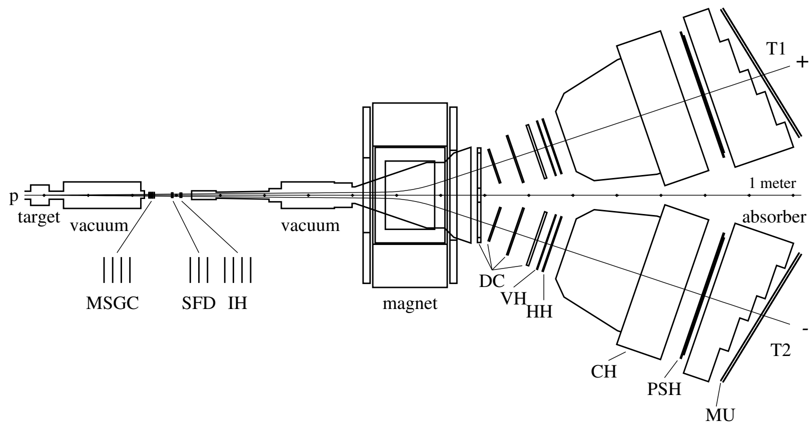

Figure 2: *DIRAC setup. MSGC are microstrip gas chambers, SFD is a scintillating fiber detector and IH is a scintillation ionization hodoscope. Downstream the spectrometer magnet there are two identical arms T1 and T2. Each arm consists of drift chambers (DC), vertical (VH) and horizontal (HH) scintillation hodoscopes, threshold Cherenkov counters (CH), shower detectors (PSH) and scintillation muon detectors (MU)*

4 Analysis

Experimental data collected in 2001, 2002, 2003 years was processed using measurement of drift chambers and X- and Y- planes of scintillation fiber detector. An experimental distribution of events dN/dQ over relative momentum Q is obtained (see fig.3a). Events which fit criterion $Q_T < 4$ MeV/c are selected. This distribution is a mixture of “atomic”, “Coulomb” and “non-Coulomb” pairs. Admixture of “accidental” pairs is excluded using time measurements with vertical scintillation hodoscope.

The spectrometer including the target is fully simulated by GEANT-DIRAC [7], a GEANT3-based simulation code. The detector and trigger system response simulation are implemented in the DIRAC analysis code ARIANE [8]. The different event types are simulated according to the underlying physics.

Atoms are generated in S-states according to eq.1 using measured laboratory momentum distributions for pairs from short-lived sources. The "atomic" pairs are generated according to evolution of the atom while propagating through the target.

"Coulomb" pairs are generated according to $A_C(Q) \cdot Q^2$ using measured laboratory momentum distributions for short-lived pairs. The term Q^2 describes phase space modified by Coulomb interaction (Gamov-Sommerfeld factor) $A_C(Q) = (2\pi m_\pi \alpha/Q)/(1 - exp(-2\pi m_\pi \alpha/Q))$.

"Non-Coulomb" pairs, where at least one pion originates from the decay of a long-lived source do not undergo any final state interactions. Thus they are generated according to Q^2 using momentum distributions for long-lived sources (difference obtained from FRITIOF-6).

These simulated data sets are reconstructed with exactly the same procedures and cuts as used for experimental data.

Experimental distribution dN/dQ is fitted by a sum of simulated distribution of "atomic", "Coulomb" and "non-Coulomb" pairs. Contributions for each kind of pairs are free parameters of the fit. The result of fit is shown in fig.3.

Simulation shows that different projection of Q have different sensitivity to the systematic effects. Therefore the same analysis was repeated for distribution over absolute value of longitudinal projection $|Q_L|$ of relative momentum Q on the total pair momentum in the laboratory system (see fig.4).

5 Systematic errors

At the analysis of experimental data the next sources of systematic errors have been investigated:

1. The error in an estimation of multiple scattering in detectors and elements of the setup of experiment DIRAC.

2. An admixture of non-identified K^+K^- $p\overline{p}$ pairs.

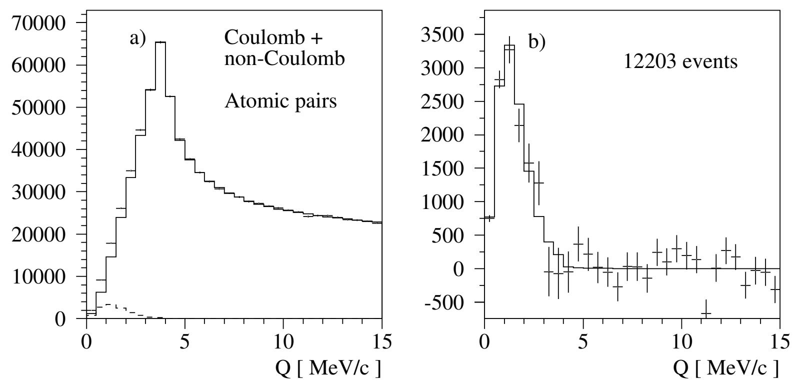

Figure 3: *a) Experimental distribution over Q (points with error bars); sum of distributions "Coulomb" and "non-Coulomb" pairs (solid) and "atomic" pairs (dashed). b) The difference of experimental distribution and a sum of background ("Coulomb" and "non-Coulomb") pairs (points with error bars) and simulated distribution of "atomic" pairs (solid).*

3. Final size of production region. Cross section of atom production eq.1 is calculated in approximation of point-like sources of pions. However there are correction due to finite size of production region and strong interaction in the final state [9].

4. Finite double-track resolution of fiber detector.

5. Presence of hits from background particles.

6. Accuracy of trigger system simulation.

Systematic errors are investigated for analysis of distributions over Q, $|Q_L|$ and two dimensional distribution over $(|Q_L|, Q_T)$. The values of statistical error, estimation of separate systematic errors and total systematic error are presented in tab.1. It is seen that the best analysis could be done using two dimensional distribution.

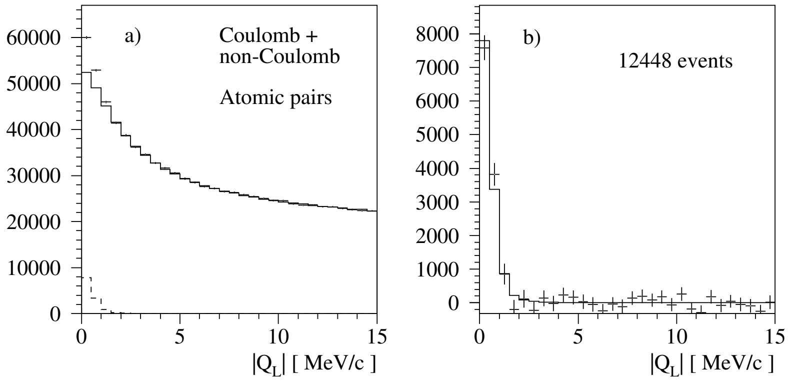

Figure 4: *a) Experimental distribution over $|Q_L|$ (points with error bars); sum of distributions "Coulomb" and "non-Coulomb" pairs (solid) and "atomic" pairs (dashed). b) The difference of experimental distribution and a sum of background ("Coulomb" and "non-Coulomb") pairs (points with error bars) and simulated distribution of "atomic" pairs (solid).*

6 Conclusion

Unfortunately these data have been analyzed very recently. Therefore collaboration is not ready to present final values of breakup probability and lifetime for $\pi^+\pi^-$ atom.

On the basis of breakup probability errors it is possible to expect that statistical error of lifetime τ is at the level $8.7 \div 12.2\%$ and systematic error of τ is at the level $3.3 \div 6.0\%$.

Therefore analysis of data collected in years 2001, 2002 and 2003 allows DIRAC experiment to achieve at least statistical accuracy better than 10%.

7 Acknowledgments

I would like to thank V. Brekhovskikh (IHEP) and M. Zhabitsky (JINR) for their help in preparing of presentation, all members of DIRAC collaboration

Table 1: *Estimation of relative errors of breakup probability for analysis with 3 variables.*

Error	δ_Q	$\delta_{\vert Q_L \vert}$	$\delta_{\vert Q_L \vert, Q_T}$
Statistical	0.031	0.044	0.031
Multiple scattering	0.018	0.008	0.014
Heavy particles admixture	0.001	0.008	0.001
Finite size effects	$^{+0.}_{-0.006}$	$^{+0.}_{-0.004}$	$^{+0.}_{-0.005}$
Double track resolution	0.009	0.001	0.003
Background particles	0.002	0.003	0.002
Trigger simulation	0.002	0.002	0.003
Total systematic	$^{+0.021}_{-0.022}$	0.012	$^{+0.015}_{-0.016}$

for there contribution to our joint research, and organizers of HADRON07 for invitation to make this report.

References

1. S.M. Bilenky *et al.*, Sov. J. Nucl. Phys. **10** (1969), p. 469.

2. G. Colangelo, *et al.*, Nucl. Phys. B **603** (2001), p. 125.

3. J. Gasser, *et al.*, Phys. Rev. D **64** (2001) 016008.

4. L.L. Nemenov, Sov. J. Nucl. Phys. **41** (1985), p. 629.

5. L.G. Afanasyev and A.V. Tarasov, Phys. At. Nucl. **59** (1996), p. 2130.

6. B. Adeva *et al.*, Nucl. Instrum. Methods A **515** (2003), p. 467.

7. O Gortchakov *et al.*, User guide (http://gortchak.home.cern.ch/gortchak/geant-dirac/montecarlo/instruction/instruct26.html)

8. D. Drijard *et al.*, The DIRAC offline user's guide (http://dirac.web.cern.ch/DIRAC/Userguide.html).

9. R. Lednicky, DIRAC note **2004-06** (nucl-th/0501065).