EXPERIMENTAL INVESTIGATION OF $\pi^+\pi^-$ ATOMS

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on behalf of DIRAC Collaboration

The goal of the DIRAC experiment is to measure the $\pi^+\pi^-$ atom lifetime of order $3 \cdot 10^{-15}$ s with 10% precision. This measurement will provide 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. Low energy QCD — chiral perturbation theory — predicts nowadays scattering lengths with the accuracy of 2%. Therefore, such a measurement will be a sensitive check of the understanding of chiral symmetry breaking of QCD by giving an indication about the value of the quark condensate, an order parameter of QCD. A statistics of 5000 $\pi^+\pi^-$ atoms collected. This sample provides a statistical accuracy for the lifetime measurement at the 20% level.

Introduction

Pionium or $A_{2\pi}$ is a hydrogen-like atom consisting of π^+ and π^- mesons. The lifetime of this atom is inversely proportional to the squared difference between the S-wave $\pi\pi$ scattering lengths for isospin 0 and 2, $|a_0 - a_2|$. This value is predicted by chiral perturbation theory (ChPT), and a measurement of the $\pi^+\pi^-$ atom lifetime provides a possibility to check predictions of ChPT in a model-independent way.

1. Present status of $\pi\pi$ scattering length investigation.

In chiral perturbation theory (ChPT) the 2-loop calculation, exploiting Roy equations, leads to a precise prediction for $|a_0 - a_2|$ at the level of 1.5%: $|a_0 - a_2| = 0.265 \pm 0.004$ [1].

Experimental data on $\pi\pi$ scattering lengths can be obtained in an indirect way via the following indirect processes:

(1) K_{e4} decay, $K^+ \Rightarrow \pi^+\pi^- e^+ \nu_e$, using a model-independent analysis. The most resent result obtained from 4×10^5 K_{e4} decays have been

collected in the experiment E865 (BNL). The analysis yields the S-wave $\pi\pi$ scattering length $a_0 = 0.216 \pm 0.013(\text{stat}) \pm 0.004(\text{syst}) \pm 0.005(\text{theor})$ [2].

(2) $\pi N \to \pi\pi N$ reaction. The latest measurement gives a value $a_0 = 0.204 \pm 0.014(\text{stat}) \pm 0.008(\text{syst})$ [3]. In this case the experimental procedure is not strictly unambiguous, since the contribution of non-OPE components (Δ, N^*) can effect the reliability of the result [3].

2. Theoretical motivation

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 exists a relation [4,5] between $\Gamma_{2\pi^0}$ and $\pi\pi$ scattering lengths: $\Gamma_{2\pi^0} = C \cdot |a_0 - a_2|^2$.

ChPT at next-to-leading order in isospin breaking provides correction to decay width $\Gamma^{NLO}_{2\pi^0} = \Gamma_{2\pi^0}(1+\delta_\Gamma), \delta_\Gamma = (5.8 \pm 1.2)\%$. Using this correction the lifetime of $\pi^+\pi^-$ atoms is predicted to be [6]:

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

A measurement of the atom lifetime with an accuracy of 10% allows to determine the corresponding $\pi\pi$ scattering length difference with 5% accuracy.

3. 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 [7,8]. The cross section for production with quantum numbers (n, l, m) is given by:

$$\frac{d\sigma^A_{nlm}}{d\vec{P}} = (2\pi)^3 \frac{E}{M} |\Psi^{(C)}_{nlm}|^2 \frac{d\sigma^0_s}{d\vec{p}d\vec{q}},\ \vec{p} = \vec{q}$$

Here $\Psi^{(C)}_{nlm}$ is the Coulomb wave function of the atom at origin, whereas $d\sigma^0_s/(d\vec{p}d\vec{q})$ is the cross section for $\pi^+\pi^-$ pair production from short-lived sources, without taking into account Coulomb interaction in the final state. Pairs from short-lived sources (direct processes, $\rho, \omega, \ldots$) are produced in a small volume ($r \sim 10$ fm) whose extensions is much less than the Bohr radius of $A_{2\pi}$ (387 fm). Such pairs are affected by the Coulomb interaction in the final state. 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, characterised by small pair c.m. relative momenta $Q < 3$ MeV/c. These pairs are detected in the DIRAC setup. Other atoms annihilate into $\pi^0\pi^0$. The amount of broken up atoms n_A depends on the lifetime which defines the decay rate. Therefore, the breakup probability is a function of the $A_{2\pi}$ lifetime.

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 atom (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.

The aim of DIRAC (DImeson Relativistic Atom Complex) is to measure the $A_{2\pi}$ breakup probability $P_{\rm br}(\tau)$. $P_{\rm br}(\tau)$ is the ratio between the observed number of "atomic pairs" and the number of produced $\pi^+\pi^-$ atoms which is calculated from the measured number of "Coulomb pairs" and the coefficient K.

The dependence of $P_{\rm br}$ on the lifetime τ is determined by the solution of differential transport equations [9].

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.

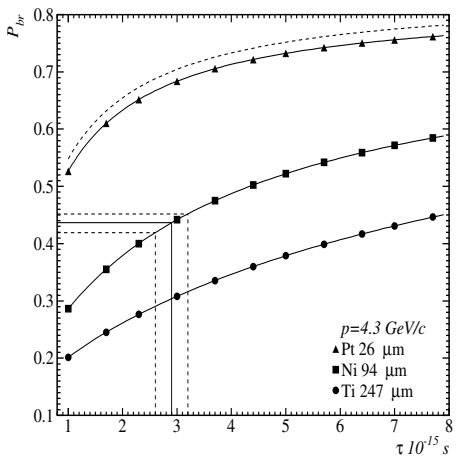

Figure 1. Dependence of the breakup probability $P_{\rm br}$ on $A_{2\pi}$ lifetime for three targets used in the DIRAC experiment: platinum of 26 μm, nickel of 94 μm and titanium of 247 μm thickness.

4. Experimental setup

The purpose of the DIRAC setup [10] is to detect $\pi^+\pi^-$ pairs with small relative momenta(see Fig. 2). 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.

In Table 1 the main setup features are summarised. The setup resolution is shown for the projections of the relative c.m. momentum Q: Q_L is a projection along the total pair momentum in the laboratory system, Q_X and Q_Y are the X- and Y- projections of the transverse component of Q.

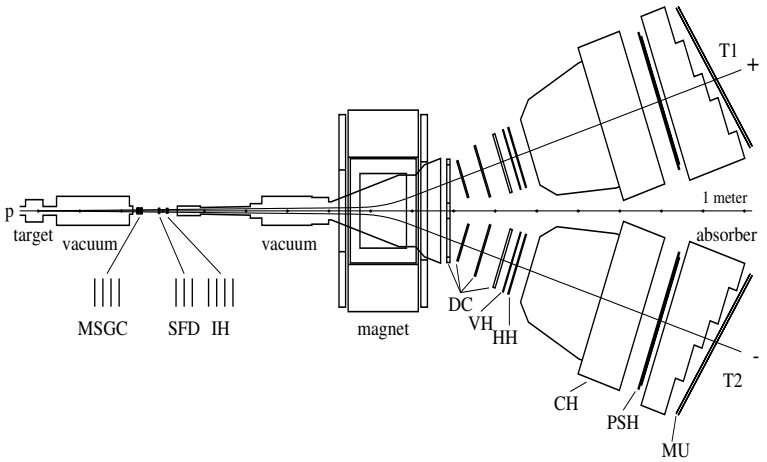

Figure 2. DIRAC setup. MSGC are microstrip gas chambers, SFD is a scintillating fibre detector and IH is a scintillation ionization hodoscope. Downstream the spectrometer magnet there are two identical arms T1 and T2. Each arm consists of drift chambers (DC), vertical (VH) and horizontal (HH) scintillation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

Table 1. Setup features.

Angle of channel to proton beam	5.7°
Channel aperture	$1.2 \cdot 10^{-3}$ sr
Magnet bending power	2.3 T·m
Momentum range	$1.2 \leq p_\pi \leq 7$ GeV/c
Resolution on relative momentum projections	$\sigma_{Q_X} = \sigma_{Q_Y} = 0.4$ MeV/c $\sigma_{Q_L} = 0.6$ MeV/c

5. Experimental data

The setup detects pairs of oppositely charged particles. Fig. 3 shows the event distribution over time difference between positive and negative particles. The peak in the central part contains pairs of particles which are generated in the same proton–nucleus interaction ("real pairs"). In addition to "Coulomb" and "atomic" pairs, "real pairs" include also pairs from long-lived sources ($\eta, K_s^0, \ldots$). Such pairs, not affected by final state interaction, are named "non-Coulomb pairs". The wings of the distribution are formed by "accidental pairs" consisting of particles from different proton–nucleus interactions and so not affected by final state interaction. Therefore, the Q distribution over of "non-Coulomb" and "accidental" pairs are assumed to be identical. At least it should be the case for small relative momenta, where the influence of energy conservation is negligible. In DIRAC only events with small relative momenta are used. Admixture of "accidental pairs" under the central peak is subtracted by using the widths of the intervals Δt_1, Δt_2 and Δt_3.

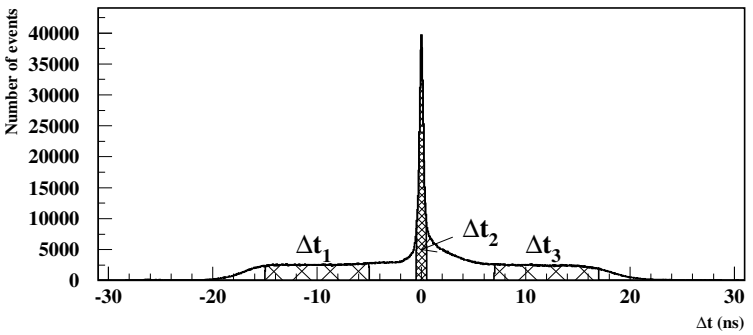

Figure 3. Distribution of events over time difference measured by vertical scintillation hodoscope (time of negative particle is subtracted from time of positive one). Regions Δt_1 and Δt_3 contain pure "accidental pairs" and Δt_2 one contains a mixture of "real" and "accidental" pairs.

Eq. 1 shows the experimental correlation function $R(Q)$. This function consists of two parts. One part is a constant $N \cdot f$ as the result of dividing the distribution of "non-Coulomb pairs" ($dN^{NC}_{\rm real}/dQ$) by the distribution of "accidental pairs". Here N is a normalisation parameter and f the fraction of "non-Coulomb pairs".

$$R(Q) = \frac{\frac{dN_{\rm real}}{dQ}}{\frac{dN_{\rm acc}}{dQ}} = \frac{\frac{dN^{NC}_{\rm real}}{dQ} + \frac{dN^{C}_{\rm real}}{dQ}}{\frac{dN_{\rm acc}}{dQ}} = N \cdot [f + A_C(Q)] \qquad (1)$$

The second part of $R(Q)$ is Q-dependent: the number of "Coulomb pairs" ($dN^C_{\rm real}/dQ$) with very small Q is increased by Coulomb interaction. It should be emphasised that the Coulomb factor $A_C(Q)$ (Eq. 1) is smeared compared to the theoretical one due to multiple scattering in the target and finite setup resolution.

The experimental relative momentum distributions for "real" and "accidental" pairs are shown in Fig. 4. These data were collected with nickel target in 2001.

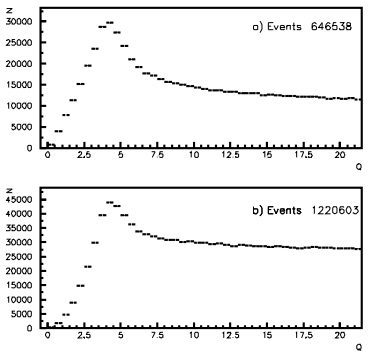

Figure 4. Experimental distributions of $\pi^+\pi^-$ pairs over relative momentum Q for "real" pairs (a) and "accidental pairs" (b).

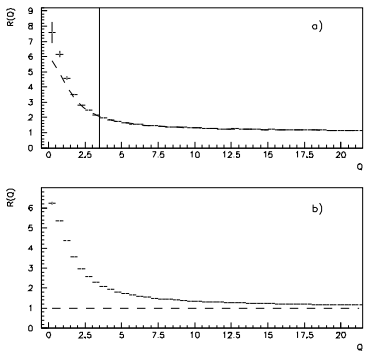

Figure 5. (a) The experimental correlation function (points with error bars) is fitted by a correlation function (smooth curve) approximated in $Q > 3.5$ MeV/c. The excess for $Q < 3.5$ MeV/c occurs due to "atomic pairs". (b) The approximated correlation function is the sum of correlation functions for "Coulomb" (points) and "non-Coulomb" (dashed line) pairs.

Fig. 5 shows the experimental correlation function (Eq. 1). In the region $Q > 3.5$ MeV/c this function was fitted by an approximated correlation function which takes into account "non-Coulomb pairs" (constant term) as well as "Coulomb pairs" (Q-dependent term), the multiple scattering in the target and also the setup resolution. The fraction of "non-Coulomb pairs" f is a free parameter in the fit procedure (Eq. 1). There is a good agreement between the experimental and approximated correlation functions for $Q > 2.5$ MeV/c. On the other hand in the region $Q < 2.5$ MeV/c the experimental points lie higher than the approximation function describing "free pairs" only. This excess is the signal of "atomic pairs".

To calculate the number of "atomic pairs" the approximated correlation function has been transformed to a Q-distribution by multiplying it with the distribution of "accidental pairs" (Eq. 1). Differences of experimental and approximated distributions are shown in Fig. 6 for data collected in 1999, 2000, 2001 and in 15 days of 2002.

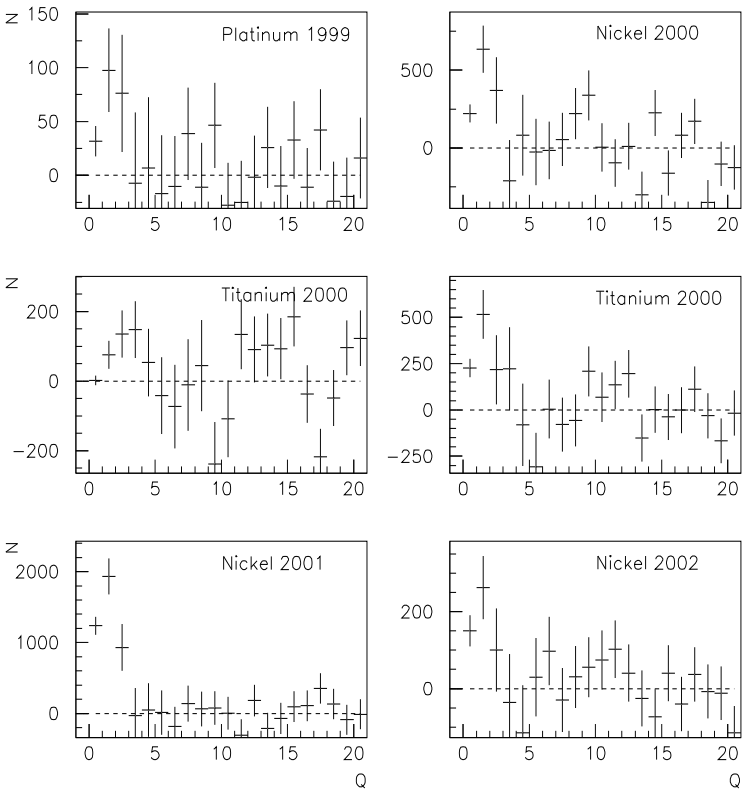

Figure 6. Signals of "atomic pairs" in the region $Q < 3$ MeV/c are obtained with different targets. For 2002 only data collected in 15 days are analysed.

The overall statistics of "atomic pairs" is presented in Table 2 for two Q. Taking into account data collected before the end of 2001 it is possible to achieve statistical accuracy for the lifetime measurement at the 20% level.

Conclusions

The DIRAC collaboration has built up a double arm spectrometer providing resolution of 1 MeV/c for low relative pair momentum Q. The capability

Table 2. Number of "atomic pairs" detected.

Sample	Target		Triggers	n_A	n_A
	Matter	thickness μm	10^6	$Q < 2$ MeV/c	$Q < 3$ MeV/c
Pt 1999	Platinum	26	55.7	130 ± 43 (3σ)	207 ± 77 (2.7σ)
Ni 2000	Nickel	94	896	920 ± 170 (5.4σ)	1335 ± 300 (4σ)
Ti 2000+01	Titanium	244	910	1170 ± 190 (6.2σ)	1495 ± 340 (4.4σ)
Ni 2001	Nickel	98	647	2686 ± 310 (8.7σ)	3500 ± 510 (6.9σ)
Ni 2002	Nickel	98	77	400 ± 100 (4σ)	545 ± 170 (3.2σ)

to detect $\pi^+\pi^-$ atoms has been demonstrated.

Preliminary results have been achieved by analysing a sample of 5000 atoms. The statistical accuracy in the lifetime determination reaches 20%. Data collected in 2002 allow us to increase the statistical accuracy up to 15%.

In order to study systematic errors, dedicated measurements with a multi-layer nickel target are planned to be performed toward the end of the 2002 run period and in 2003.

References

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