FIRST MEASUREMENT OF THE $\pi^+\pi^-$ ATOM LIFETIME

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The goal of the DIRAC experiment at CERN (PS212) is to measure the $\pi^+\pi^-$ atom lifetime. Based on part of the collected data we present a first result on the lifetime, $\tau = \left[2.91 \,^{+0.49}_{-0.62}\right] \times 10^{-15}$ s, and discuss the major systematic errors. This lifetime corresponds to $|a_0 - a_2| = 0.264 \,^{+0.033}_{-0.020}\, m_\pi^{-1}$.

Keywords: Exotic atoms; Pion scattering; Chiral symmetries.

1. Introduction

The pion is the lightest hadron. Concepts of low-energy QCD are therefore most sensitively constrained by the pion properties and the pion-pion interaction. The $\pi^+\pi^-$ atom provides a tool to study these interactions with high precision. The strong $\pi\pi$-interaction leads to a shift ϵ of the atomic binding energy with respect to pure Coulomb binding and to a finite lifetime (τ) due to the charge exchange process $\pi^+\pi^- \to \pi^0\pi^0$. Because in the atom the two pions scatter off each other at very low relative c.m. momentum Q (typically $Q \leq 2$ MeV/c) and in well definded quantum states (zero orbital momentum), shift and lifetime are directly related to the S-wave scattering lengths for Isospin I = 0,2 by $\epsilon_{n.S} \propto 2a_0 + a_2$ and $\tau_{n,S}^{-1} \propto |a_0 - a_2|^2$[1]. More specifically

$$\tau_{1S}^{-1} = \frac{2p}{9}\alpha^3 \left|a_0 - a_2\right|^2 (1+\delta) \qquad (1)$$

with α the fine-structure constant and p the π^0 momentum in the atomic rest frame. The term δ accounts for QED and QCD corrections and is a known quantity ($\delta = (5.8 \pm 1.2) \times 10^{-2}$) ensuring a 1% accuracy for Eq. (1) [2].

DIRAC has measured the lifetime of the atom in its ground state for the first time [3]. We present the measurement and discuss the most important systematic errors and their evolution since the publication.

The experiment uses a double-arm spectrometer with high resolution for low-Q $\pi^+\pi^-$-pairs[a], originating from collisions of 24 GeV/c protons of the CERN PS with a typically 94 μm thick Ni foil. Figure 1 shows the set-up.

The pions produced in proton-Ni collisions may emerge as low-Q $\pi^+\pi^-$-pairs, which undergo Coulomb final state interaction (CC *background*) and exhibit an enhancement at low Q with respect to phase space. The enhancement can be calculated for "point-like" sources [4]. For very low Q the Coulomb final state interaction also leads to *atom formation* in S-states. The number of atoms and the number of CC background events with $Q \leq 2$ MeV/c are therefore linked theoretically, $N_{AT}/N_{CC} = k_{theo} = 0.675$. The atom, while traveling through the target collides with target atoms and may become excited or ionized. $\pi^+\pi^-$-pairs from atom break-up (*"atomic pairs"*) may be detected in the spectrometer and be identified as such due to their low-Q feature [5]. With the help of theory of atomic collisions and transport equations a relation between break-up probability and lifetime is estab-

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[a] typically $\sigma_{Q_x} \approx \sigma_{Q_y} \approx \sigma_{Q_L} \approx 0.5$ MeV/c with Q_x, Q_y the transverse and Q_L the longitudinal components of Q with respect to the flight direction of the $\pi^+\pi^-$-pair.

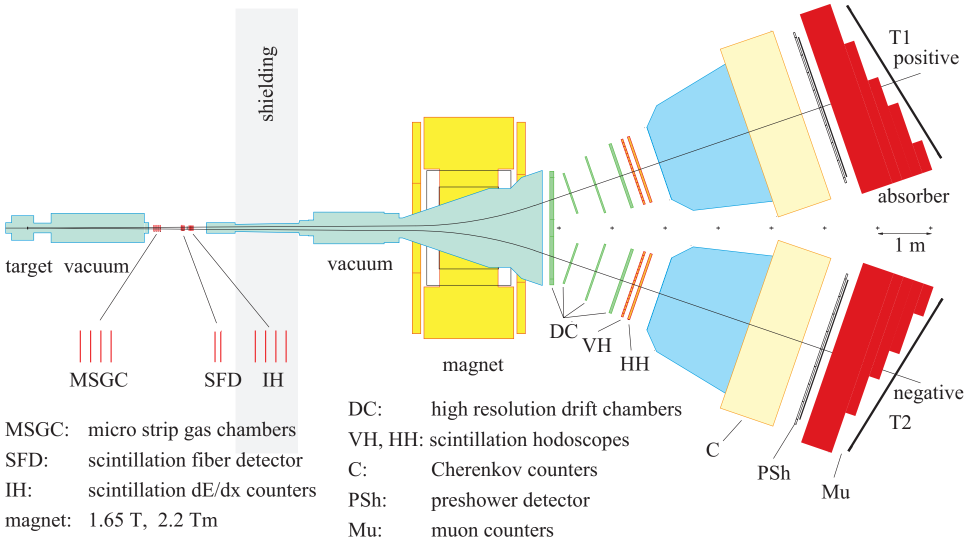

Fig. 1. Schematic top view of the DIRAC spectrometer.

lished, with an accuracy on the 1% level [6,7,8].

Background from non-correlated $\pi^+\pi^-$-pairs is due to pions from two proton interactions (*accidental*) or to pions, that emerge from long-lived intermediate resonances (NC *background*).

2. The Measurement

An extensive description of the DIRAC set-up, data selection, tracking, Monte Carlo procedures, signal extraction, a first high statistics demonstration of the feasibility of the lifetime measurement and the lifetime measurement, based on the Ni data of 2001, have been published in [9,3]. Since its start-up, DIRAC has accumulated about 15'000 atomic pairs. The data used for this work were taken with two Ni foils, one of 94μm thickness (76% of the $\pi^+\pi^-$ data), and one of 98 μm thickness (24% of the data).

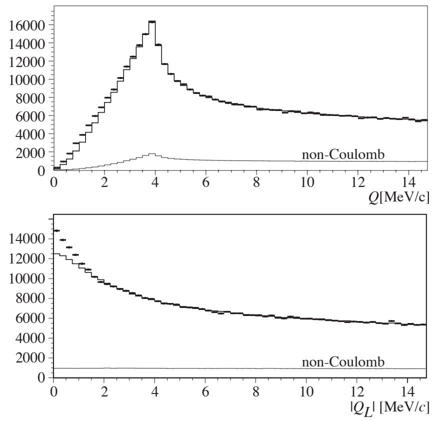

Fig. 2. Measured Q and Q_L distributions and combined CC and NC background. NC-background is also shown separately.

Figure 2 shows the measured distributions in Q and Q_L. They correspond to events where the time difference of the positive and negative arm of the spectrometer was less than 1 ns, and where the accidental background component is already subtracted. The spike in the Q-distribution is due to a cut in the transverse Q component, $Q_T \leq 4$ MeV/c. Also shown are the simulated CC- and NC backgrounds. They were fitted in regions outside of the signal for atomic pairs. The Coulomb enhancement is clearly seen in the Q_L-distribution. After subtraction of the background the expected signal of atomic pairs is obtained and shown in Fig. 3.

As a result we obtain $n_A = 6560 \pm 295$ atomic pairs, and $n_{CC} = 106114 \pm 1061$ CC

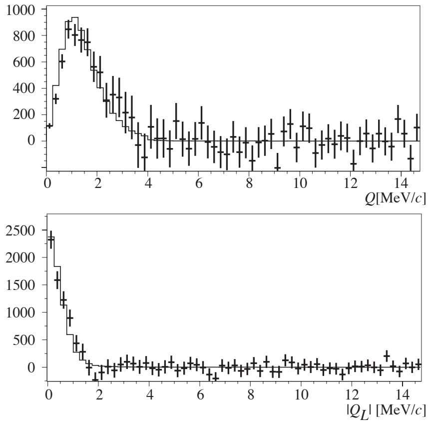

Fig. 3. Measured distributions after background subtraction, corresponding to atomic pairs. Also shown is the shape of the simulated atomic pair distribution.

Table 1. Summary of systematic effects on the measurement of the break-up probability P_{br}. Extreme values have been transformed into σ assuming uniform distributions.

source	extreme values	σ
CC-background	± 0.012	± 0.007
signal shape	± 0.004	± 0.002
mult. scattering	$^{+0.01}_{-0.02}$	$^{+0.006}_{-0.013}$
K^+K^- and $\bar{p}p$	$^{+0.00}_{-0.04}$	$^{+0}_{-0.023}$
finite size	$^{+0.00}_{-0.03}$	$^{+0}_{-0.017}$
Total	.	$^{+0.009}_{-0.032}$

background events with $Q \leq 4\text{MeV}/c$. With the acceptance correction for the atomic pairs for this Q cut as well as for initially produced CC background events with $Q \leq 2\text{MeV}/c$, and the theoretical k_{theo}, we obtain an overall conversion factor $k = 0.1383$, and the break-up probability becomes $P_{br} = n_A/(k \times n_{CC}) = 0.447 \pm 0.023_{stat}$. Since the 94 μm thick Ni-target was only pure to 98.4% we have to apply a correction to P_{br} of 0.005, which leads to

$$P_{br} = 0.452 \pm 0.023_{stat} \qquad (2)$$

3. Systematic errors

Table 1 gives the systematic errors as published in [3]. The major systematic errors are due to multiple scattering, corrections of the Coulomb correlation due to non-pint like interactions and unrecognized admixtures of K^+K^- and $p\bar{p}$ pairs. The latter two contributions will be measured soon. The contribution of multiple scattering was estimated on the basis of a possible +5% and -10% maximum uncertainty in multiple scattering in general, as in our momentum range no measurements existed that were better than 5%. Meanwhile we have analyzed a dedicated measurement on multiple scattering on all major scatterers in our spectrometer in detail and found agreement with GEANT Moliere description on the 1% level, except for highly inhomogeneous detector materials (SFD, MSGC). Wether the incorrectly simulated detectors cause a shift in the break-up probability has yet to be verified. Given the 1% accuracy of our multiple scattering measurement the associated systematic error, however, is reduced to ±0.002, and the over-all systematic error becomes $^{+0.008}_{-0.030}$.

On a less quantitative level we expect the atomic pair line shape uncertainty to be correlated with the amount of K^+K^- and $p\bar{p}$ pair admixtures. Furthermore studies have shown that the CC background uncertainty depends on the degree of accuracy the single particle momentum distributions are known and applied in the simulations.

4. Results

The relation between lifetime and break-up probability from section 1 is displayed in Fig. 4. Equally shown there is the measured break-up probability with statistical and additionally systematic errors. We deduce a lifetime of

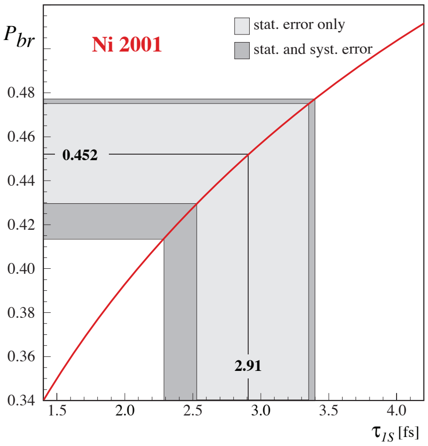

Fig. 4. Break-up probability P_{br} as a function of the lifetime of the atomic ground state τ_{1S} for the combined 94 and 98 μm thick Ni targets. The experimentally determined P_{br} with statistical and total errors translates into a value of the lifetime with corresponding errors.

$$\begin{aligned} \tau_{1S} &= \left[2.91 \;{}^{+0.45}_{-0.38}\}_{stat} \;{}^{+0.19}_{-0.49}\}_{syst}\right] 10^{-15} \text{ s} \\ &= \left[2.91 \;{}^{+0.49}_{-0.62}\right] 10^{-15} \text{ s}. \end{aligned} \tag{3}$$

The errors are not symmetric because the $P_{br} - \tau$ relation is not linear, and because finite size corrections and heavy particle admixtures lead to possible smaller values of P_{br}. The accuracy achieved for the lifetime is about +17%, almost entirely due to statistics and −21%, due to statistics and systematics in roughly equal parts. The two main systematic errors (particle admixtures and finite size correction) will be studied in more detail in the future program of DIRAC. The improvement on the systematic error due to multiple scattering leads to an insignificant improvement on the overall lifetime accuracy, $\tau_{1S} = \left[2.91 \;{}^{+0.47}_{-0.59}\right] 10^{-15}$ s.

Using Eq. (1), the above lifetime corresponds to $|a_0 - a_2| = 0.264 \;{}^{+0.033}_{-0.020}\; m_\pi^{-1}$, in good agreement with the theoretical prediction of chiral perturbation theory [10].

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