Pion-Pion Scattering Lengths from $\pi^+\pi^-$ Atom with the DIRAC experiment

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Abstract. The DIRAC experiment at CERN is presently measuring the lifetime of the pionium atom, a bound state of a π^+ and π^- meson. The isospin 0 and 2 scattering length difference will be determined unambiguously once the value of the lifetime is known. In what follows we describe the present status of the experiment, the experimental goals and the first results.

MOTIVATION

The goal of the DIRAC experiment is to find the difference of isospin 0 and 2 pion-pion *S*-wave scattering lengths a_0 and a_2 by measuring the lifetime of the $\pi^+\pi^-$ bound state ($A_{2\pi}$). The principal decay of such a state is into two neutral pions ($BR = 99.6\%$). The lifetime and difference of scattering lengths are related through [1][2]:

$$\Gamma_{\pi^0\pi^0} = 1/\tau_{A_{2\pi}} = \frac{2}{9}\alpha^3 p^* \cdot (a_0 - a_2)^2(1+\delta_\Gamma), \tag{1}$$

where α is the fine structure constant, and $p^* = (M^2_{\pi^+} - M^2_{\pi^0} - M^2_{\pi^+}\alpha^2/4)^{1/2}$ and $\delta_\Gamma = (5.8 \pm 1.2) \cdot 10^{-2}$. The Chiral Perturbation theory (ChPT) currently predicts $|a_0 - a_2| = 0.265 \pm 0.004\,[m_\pi^{-1}]$ yielding the $A_{2\pi}$ lifetime of $\tau_{A_{2\pi}} = 2.9 \pm 0.1\, fs$ [2].

DIRAC's goal is to determine the pionium lifetime with a precision of $0.3\, fs$. Once the lifetime is known, the determination of the scattering lengths will follow from (1).

Our scattering length measurement is model-independent in a sense that we are detecting pion pairs at close to 0 relative momenta, and, hence, do not need to rely on the precise knowledge of the scattering matrix at higher momenta.

DESCRIPTION OF THE SETUP

DIRAC's experimental setup is located on the 24 GeV PS beamline at CERN. Secondary particles resulting from collisions between proton beam and a thin target (of the order of $100\,\mu m$ in thickness) are registered by 3 coordinate detectors. Charged secondaries are subsequently separated by the 1.65 Tesla magnet into the positive and negative arm, where they traverse another set of coordinate detectors, time-of-flight and identification counters.(See Ref. [3] for more details.)

The spectrometer has an excellent time and momentum resolution allowing us to measure low relative momenta (chosen to be recorded on tape by the multilevel trigger system described in detail Ref. [4]) at high laboratory momenta.

SIGNAL AND BACKGROUND

Coherent $\pi^+\pi^-$ pairs originating from proton-target collisions may sometimes form a $\pi^+\pi^-$ bound state. After evolving in the target material pionium atoms either annihilate or dissociate. Dissociated atoms constitute the signal for the DIRAC experiment.

The background events are formed by two types of pion pairs: Coulomb-correlated and non-correlated ones. Coulomb correlated pairs are similar in nature to the pionium atoms, with the exception that the interactions between the former are characterized by a continuous, rather than a discrete, energy spectrum, as is the case for the latter. Non-correlated pairs are formed by the *incoherent* pion pairs.

The breakup probability is defined as a ratio of the number of pionium atoms n_A that have dissociated in the target over the number of the initially produced pionium atoms $N_{A2\pi}$: $P_{br} = n_A/N_{A2\pi}$. When combined with the relationship between the number of atoms and the Coulomb pairs $N_{A2\pi} = 0.615 \cdot N_c(Q < 2\,MeV/c)$ [5][6], the expression for the breakup probability becomes

$$P_{br} = n_A/(0.615 \cdot N_c(Q < 2\,MeV/c)). \tag{2}$$

Hence, if the number of Coulomb pairs with relative momenta below $2\,MeV/c$ and number dissociated atomic pairs is known, the breakup probability is determined unambiguously. The $A_{2\pi}$ lifetime is then found from the breakup probability vs. lifetime relationship calculated using Glauber and Born approximations [7][8][9].

SINGLE LAYER TARGET SIGNAL EXTRACTION

We analyzed the results of the 2001 run with the single layer $98\,\mu m$ Ni target. Before proceeding with the signal extraction we applied the following set of cuts: (a) prompt events selected by imposing a narrow time window of -0.5 to $0.5\,ns$, (b) fast protons, electrons and muons coming from the upstream region were rejected, (c) only the pion pairs with relative momenta $Q_{trans} = (Q_x^2 + Q_y^2)^{1/2} < 4\,MeV/c$ and $|Q_l| < 22\,MeV/c$ were taken.

The background was constructed using Monte Carlo methods. Both Q_l and Q_{tot} background spectra were fitted to the *signal-free regions of the measured data*, i.e. those with $Q_l > 2\,MeV$ and $Q_{tot} > 4\,MeV$. Multiplication of the Coulomb-correlated and non-correlated data by the fit parameters in the *entire relative momentum range* gives us the overall background in the -0.5 to $0.5\,ns$ time interval. Subtracting the background from the experimental data yields the signal (shown in Fig. 1).

6800 ± 400 atomic pairs were found in 2001. We note that the solid-shaded histograms on the bottom two plots corresponding to the simulated and subsequently reconstructed atomic pairs replicate well the extracted signal. Additionally, the flatness and the 0 mean value of the signal-free parts of the distributions indicate the accuracy of the simulated background.

Due to the sizable effects of multiple scattering [10] and, to a lesser extent, the effects of the detector response, the proportionality constant 0.615 in Eq. 2 has a value different from the model-based 0.615. A dedicated multiple scattering measurement to quantify this effect is under way.

Once the breakup probability is determined with sufficient accuracy, the pionium lifetime may be obtained from the functional dependence as described at the end of the previous section.

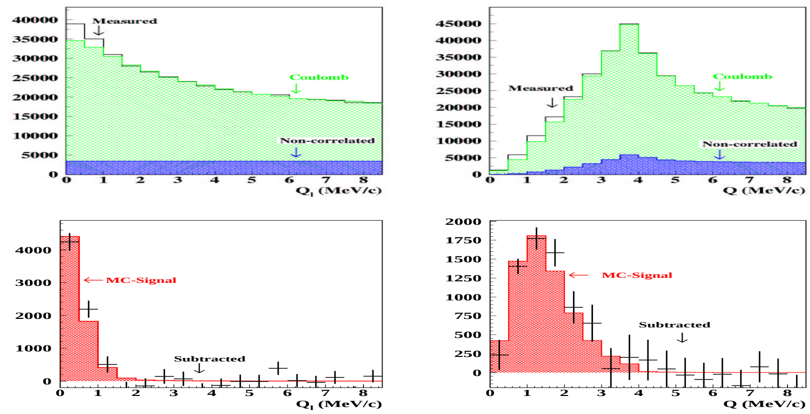

FIGURE 1. Top row: relative momenta distributions of the experimental data and background. Bottom row: signal resulting from subtracting the background from the experimental data.

COMBINED METHOD OF SINGLE AND MULTILAYER TARGET MEASUREMENTS

We have an additional way to measure the pionium lifetime at our disposal. In the 2002 run we have introduced a segmented Ni target consisting of 12 planes with 1 mm gap between each [10]. The combined thickness of all planes is approximately equal to that of the single layer 98 μm Ni target.

Single and multilayer target event distributions are identical in all but one respects: the multilayer target yields a *lower number* of dissociated pairs due to the annihilations in the interlayer gaps. Hence, without resorting to a Monte Carlo simulation we can at once obtain the single/multilayer signal difference (Fig. 2). We observe that the subtraction yields a flat spread of relative momenta in the signal-free regions ($Q_l > 2\,MeV$ and $Q_{tot} > 4\,MeV$) centered around 0 indicating that the backgrounds for both targets are indeed identical. **The signal difference between the two targets is found to be 825 $\pm$ 239 events** and its shape again accurately replicates that of the modeled atomic pairs.

The signal extraction from both targets individually is accomplished in the same way as described in the previous section. The ratio of the atomic pair signals from each target is equal to the ratio of breakup probabilities [11]. $A_{2\pi}$ lifetime is then found from the latter and the functional dependence similar to the one described in section 3.

The single/multilayer target method offers the following advantages: (a) As evidenced by Fig. 2 the signal shape can be determined relying only on the experimental data. (b) It allows us to bypass the procedure of finding the number of pionium atoms through the Coulomb-correlated background (Eq. 2). (c) We will be able to obtain a “pure” background distribution and use it as a cross-check of the Monte Carlo-generated background: $N_{bckgrnd} = \varepsilon \cdot N^{exp}_{multi} - N^{exp}_{single}$, where ε is the ratio of atomic pair signals from the single layer over the multilayer target, respectively [10].

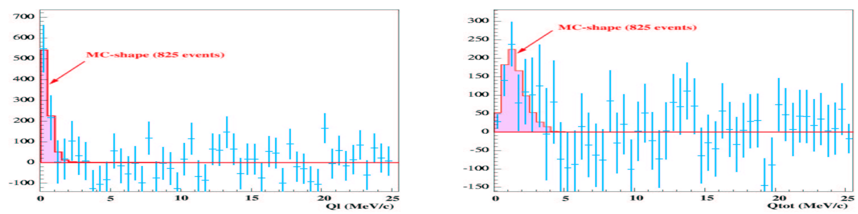

FIGURE 2. Signal resulting from subtracting normalized single from multilayer relative momenta distributions.

SUMMARY AND OUTLOOK

The DIRAC experiment has observed and quantified the atomic pair signal, which will be used in determining the $A_{2\pi}$ lifetime and pion-pion scattering length difference. Our Monte Carlo-simulated background was found to be consistent with the normalization in Q_{tot} and Q_l and the extracted signal to be in good agreement with the simulated atomic pairs.

In 2003 we are planning to get a better handle on multiple scattering by performing a dedicated measurement to determine it with a 1% accuracy in order to improve on the current 5% value. More multilayer and single layer data taking is planned to improve on the statistical accuracy in obtaining the $A_{2\pi}$ lifetime.

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