Determination of Pion Scattering Lengths from $\pi^+\pi^-$ Atom with the DIRAC Experiment

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Total number of institutions: 19
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Motivation

- Measurement of the difference of $I = 0$ and $2$, $S$-wave scattering lengths will provide a crucial test of the theoretical predictions, such as the Chiral Perturbation theory.

- DIRAC will find $|a_0 - a_2|$ by measuring the lifetime of the $\pi^+\pi^- (A_{2\pi})$ bound state ($1/\tau \propto |a_0 - a_2|^2$).

- Our method is model-independent.
Introduction

- DIRAC uses a 24 GeV proton beam striking a thin target.
- Coherent $\pi^+$’s and $\pi^-$’s resulting from proton-target collisions may form a $\pi^+\pi^-$ bound state.
- As it travels through the target, the pionium atom may:
  1. Annihilate via $\pi^+\pi^- \rightarrow \pi^0\pi^0$ ($BR = 99.6\%$).
  2. Break up by colliding with target atoms.
Lifetime and Scattering Lengths

- Lifetime measurement yields the difference between the $a_0$ and $a_2$ scattering lengths ($I = 0, 2$) through:

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

- Chiral Perturbation theory predicts (e.g., Colangelo et al., 2001):

$$
\Delta = |a_0 - a_2| = 0.265 [m^{-1}_\pi] \quad \tau = 2.9 \text{ fs}
$$

- DIRAC’s goal: Measure lifetime (thereby finding $|a_0 - a_2|$) with precision of:

$$
\sigma_\tau = 0.2 - 0.3 \text{ fs}
$$
Experimental Setup
**Trigger**

- **Current full trigger:** \( T_1 \cdot (DNA + RNA) \cdot T_4 \). Overall reduction factor: 1000. Overall efficiency: 95%.
  - **T1:** Selects events with one track per arm.
  - **DNA+RNA:** Neural network triggers selecting events with relative momenta: \( Q_x < 3 \text{ MeV}, Q_x < 10 \text{ MeV}, Q_l < 30 \text{ MeV} \).
  - **T4:** Selects events satisfying \( Q_x < 3 \text{ MeV} \) and \( Q_l < 30 \text{ MeV} \).
Offline Tracking

- Track reconstruction:
  1. Downstream tracks reconstructed in DC’s.
  2. Upstream part of the tracks adjusted with the Kalman filter procedure.

- Track reconstruction challenging since looking for very low relative momenta at high *lab* momenta.

- Need to have a high relative momentum resolution. In fact:
  \[
  \sigma_{Q_x} < 0.4 \text{ MeV/c}, \sigma_{Q_y} < 0.4 \text{ MeV/c}, \sigma_{Q_l} < 0.6 \text{ MeV/c}.
  \]
Signal and Background

- Background:
  - **Coulomb-correlated** pairs: formed by coherent $\pi^+$ and $\pi^-$ having a Coulomb final state interaction.
  - **Non-correlated** pairs: formed by incoherent $\pi^+\pi^-$ pairs.

- Signal: detected pion pairs, called **atomic pairs**, coming from $A_{2\pi}$ breakups. ($A_{2\pi}$ atoms are essentially Coulomb pairs that formed a bound state.)
Signal and Background Are Interrelated

\[ \pi^+\pi^- \text{ Pairs} \rightarrow \text{Coulomb final state int.} \rightarrow \text{Coulomb Pairs (CC)} \rightarrow \text{Atomic formation} \rightarrow A_{2\pii} \]

Gamow-Sakharov:
\[ \frac{dN^{CC}}{dQ} = \frac{2\pi P_B / Q}{1 - e^{-2\pi A / Q}} \frac{dN^{\pi\pi}}{dQ} \]

Nemenov:
\[ N_{A_{2\pii}} = 0.615 \times N_{CC} (Q < 2\text{MeV}) \]
Signal Layer Target Signal Extraction (Cuts)

- Prompt events: $\Delta t_{VH} \in [-0.5 \, \text{ns}, 0.5 \, \text{ns}]$.

- Reject electrons with the Cherenkov detector.

- Reject muons with the muon counter.

- Eliminate fast protons with the $P_+ < 4\text{GeV}/c$ cut.

- Pion pair relative momenta cuts:

  $$Q_{\text{trans}} = \sqrt{Q_x^2 + Q_y^2} < 4 \, \text{MeV}/c, \quad |Q_l| < 22 \, \text{MeV}/c$$
Signal Layer Target Signal Extraction (Cuts)

- Generate **Coulomb-correlated** and **non-correlated** background inside target. Non-correlated background produced according to: \( dN_{nc}/dQ_{tot} \propto Q_{tot}^2 \). Coulomb background: \( dN_{cc}/dQ \propto A_c(Q)Q^2 \).

- **Reconstruct** tracks offline.

- **Fit** MC-produced \( Q_l \) and \( Q_{tot} \) background to the signal-free regions of the measured data: \( Q_l > 2 \text{ MeV} \) and \( Q_{tot} > 4 \text{ MeV} \).

- **Subtract** thus obtained background from measured data in the entire \( Q_l \) and \( Q_{tot} \) range.
Single Layer Target Signal Extraction (1)

2001 Run

\[ n_A = 6800 \pm 400 \text{(stat err)} \]
Single Layer Target Signal Extraction (2)

- Breakup probability:
  \[ P_{br} \equiv \frac{n_A}{N_A} \]

  with
  \[ n_A = \text{number of dissociated atoms} \]
  \[ N_A = \text{number of initially produced atoms}. \]

- Since \( N_A = 0.615 \cdot N_{cc}(Q < 2\ MeV/c) \), then
  \[ P_{br} = \frac{n_A}{0.615 \cdot N_{cc}(Q < 2\ MeV/c)} \]

- And get the lifetime (L. Afanasyev, L. Tarasov, D. Trautmann).

- BUT the formula above is an idealization due to...

![Lifetime plot](image.png)
Multiple Scattering Effects

At production:

\[ \frac{N_A}{N_{cc}} (Q < 2\text{MeV}) = 0.615 \]

- Atomic pair signal (very low relative momenta) is washed out by multiple scattering.

- In fact, \( N_A = K_{eff} \cdot N_{cc}(Q < 2\text{MeV/c}) \) with \( K_{eff} \neq 0.615 \). Need to find \( K_{eff} \) by measuring MS very accurately.

After Target:

\[ \frac{N_A}{N_{cc}} (Q < 2\text{MeV}) = ?? \]
Comparison of the single and multilayer targets:

- Same amount of multiple scattering.
- Same Coulomb and non-correlated pair (background) yield.
- Same number of produced $A_{2\pi}$, but **lower number of dissociated pairs**.
Signals from Single and Multilayer Targets (1)

- Subtract experimental single layer $Q_l$ and $Q_{tot}$ distributions from multilayer ones. Result: Atomic pair signal difference between the two targets.

2002 Run
Signals from Single and Multilayer Targets (2)

- Individual atomic pair signals from the single and multilayer targets can be found in a standard way using MC.

- From the ratio of single/multilayer target signals get $A_{2\pi}$ lifetime:

$$\epsilon = \frac{N_A^{single}}{N_A^{multi}} = \frac{P^{br}_{single}}{P^{br}_{multi}}$$

![Graph showing the ratio of single/multilayer breakup probability vs. $A_{2\pi}$ lifetime (ns)]
Signals from Single and Multilayer Targets (2)

- Purely experimental determination of the signal shape with the subtraction method.
- Allows us to determine lifetime without $N_{cc} \rightarrow N_A$
  
  $(N_A = K_{eff} \cdot N_{cc}(Q < 2 \text{ MeV/c}))$ procedure.
- Can obtain “pure” background distribution to use as a cross-check of the MC-generated background:

$$N_{bkwrd} = \epsilon \cdot N_{exp}^{\text{multi}} - N_{exp}^{\text{single}}$$
Summary and Outlook

- **Good spectrometer resolution** allows us to accurately measure very low relative momenta at high energies.

- MC simulation of the **background is consistent** with normalization in $Q$ and $Q_I$.

- **Extracted signal** is in good agreement with the one from simulated atomic pairs.

- In 2003 we **will collect more single and multilayer data** to obtain $A_{2\pi}$ lifetime, signal shape and background.

- **Need to get a good handle on multiple scattering**, now known with 3% precision. Dedicated measurement is planned to determine it to within 1% accuracy.