Pionium Lifetime in DIRAC

Analysis of the 2001, 2002 and 2003 data

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What is new in this method?

GEM/MSGC built at the Santiago de Compostela University

Spatial resolution ~50um
**QT resolution ~0.1MeV/c** (in QL is 0.55MeV/c)
Systematics due to upstream multiple scattering reduced to almost zero.
20 and 24 GeV/c proton beams at PS accelerator.
94 and 98 um Ni targets

**22200** pion pairs from pionium ionization
Breakup probability versus pionium lifetime

The relation between the $P_{br}$ and the lifetime is known with a precision better than a 1%.
**Breakup probability**

\[
P_{Br} = \frac{n_A}{N_A} = \frac{1}{K^{th}} \frac{n_A}{N_C} \quad P_{Br} = \frac{N_{AT}(\Omega)}{N_{CC}(\Omega)} \frac{1}{K^{exp}(\Omega)} \quad K^{exp} = \frac{\varepsilon_{CC}(\Omega)}{\varepsilon_{AT}(\Omega)} K^{th}(\Omega)
\]

QM analytical factor:

\[
K^{th}(\Omega) = \frac{(2 \pi \alpha M_\pi)^3}{\pi} \sum \frac{1}{n^3} \int_\Omega A_C(Q) d^2Q
\]

- Acceptance factors \( \varepsilon_i \) determined by our Monte Carlo method.

- Standard choice for \( \Omega = (0, Q^C_T) \times (0, Q^C_L) \) is \( Q_{lc}=2 \text{ MeV/c} \) and \( Q_{Tc}=5 \text{ MeV/c} \).
Accidental pairs, different proton interactions in the target.

Coulomb pairs. From short lived sources. $r < 3$ fm, $< R(A2\pi)$

Non Coulomb pairs. From long lived sources. $r \sim 1000$ fm.

Prompt events = Delta_T $< 0.5$ ns (13% accidentals contamination)
## Monte Carlo

<table>
<thead>
<tr>
<th>Sample</th>
<th>Coulomb</th>
<th>Non Coulomb</th>
<th>Atomic pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 94um</td>
<td>200,000,000</td>
<td>50,000,000</td>
<td>10,000,000</td>
</tr>
<tr>
<td>2001 98um</td>
<td>50,000,000</td>
<td>15,000,000</td>
<td>10,000,000</td>
</tr>
<tr>
<td>2002 20GeV/c</td>
<td>110,000,000</td>
<td>30,000,000</td>
<td>10,000,000</td>
</tr>
<tr>
<td>2002 24GeV/c</td>
<td>160,000,000</td>
<td>45,000,000</td>
<td>10,000,000</td>
</tr>
<tr>
<td>2003 20GeV/c</td>
<td>50,000,000</td>
<td>15,000,000</td>
<td>10,000,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>570,000,000</strong></td>
<td><strong>155,000,000</strong></td>
<td><strong>50,000,000</strong></td>
</tr>
</tbody>
</table>
Upstream multiple scattering

Necessary to increase upstream multiple scattering in a 15% !! (1.5% of precision)

Systematic error in Pbr $\rightarrow 0.04\%$

Real data

MC

(P<1.65 GeV/c)

(P<3.25 GeV/c)
KK contamination

KK/pipi at 2.9 GeV/c → 0.238 ± 0.035 %

Systematic error in Pbr → 0.24 %
Momentum resolution. Lambda analysis

Real data

Monte Carlo
No P smearing

Monte Carlo
P smearing 0.06%

Systematic error in Pbr $\rightarrow 0.6\%$
Method

\[
\chi^2 = \sum_k \left( \frac{N_p^k - \beta(\alpha_1[\epsilon \frac{N_p^k}{N_{KK}} + (1 - \epsilon) \frac{N_p^{kC}}{N_{CC}}] - \alpha_2 \frac{N_p^{kAC}}{N_{AC}} - \alpha_3 \frac{N_p^{kNC}}{N_{NC}} - \gamma \frac{N_p^{kAA}}{N_{AA}})}{N_p^k + \beta^2(\alpha_1^2[(1 - \epsilon)^2 \frac{N_p^{kC}}{N_{CC}} + \epsilon^2 \frac{N_p^{kKK}}{N_{KK}}] + \alpha_2^2 \frac{N_p^{kAC}}{N_{AC}} + \alpha_3^2 \frac{N_p^{kNC}}{N_{NC}} + \gamma^2 \frac{N_p^{kAA}}{N_{AA}})} \right)^2
\]
Figure 7.8: Lego plot showing the pionium break-up spectrum in Ni in the $(Q_T, Q_L = |Q_Z|)$ plane, after subtraction of the Coulomb background.
Figure 7.9: Lego plot showing the pionium break-up spectrum in Ni in the $(Q_{xy}, Q_L)$ plane, after subtraction of Coulomb background. The transverse component $Q_{xy} = Q_T \cos \phi$ is defined as the product of the measured $Q_T$ value times the cosine of a random azimuth.
Projections

QL for QT<2MeV/c

Prompt data

MC

QT for QL<2

Atomic pairs MC

QT for QL>2

MC

Prompt data (QL<2MeV/c)
Fit results: Breakup probability versus laboratory momentum

Pbr vs $P$ for a $\tau=2.99$ fs
Fit results: Laboratory momentum

Non Coulomb

Atomic pairs

Coulomb pairs

$P_{\pi\pi}(\text{GeV}/c)$
Stability of Pbr with QL and QT cut
## Systematic errors table

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) MS Ni (1%)</td>
<td>0.00767</td>
</tr>
<tr>
<td>MS Up (8%)</td>
<td>0.00017</td>
</tr>
<tr>
<td>Collapsed tracks</td>
<td>0.00144</td>
</tr>
<tr>
<td>Finite size</td>
<td>0.00108</td>
</tr>
<tr>
<td>Background</td>
<td>0.00014</td>
</tr>
<tr>
<td>Trigger simulation</td>
<td>0.00042</td>
</tr>
<tr>
<td>KK &amp; pp</td>
<td>0.00110</td>
</tr>
<tr>
<td>Lambda (0.00066)</td>
<td>0.00260</td>
</tr>
<tr>
<td>Target impurity</td>
<td>0.00131</td>
</tr>
<tr>
<td>A2pi-Ni cross section (0.5%)</td>
<td>0.00224</td>
</tr>
<tr>
<td>A2pi transport eq. (0.8%)</td>
<td>0.00358</td>
</tr>
<tr>
<td>Total (sqrt(es_i^2))</td>
<td>0.00939</td>
</tr>
</tbody>
</table>

(statistical error is 0.0093)
Summary for the Pbr measurements and results

<table>
<thead>
<tr>
<th>Data Sample</th>
<th>PBR</th>
<th>Chi2/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 94um</td>
<td>0.4195 +- 0.0165</td>
<td>267/280</td>
</tr>
<tr>
<td>2001 98um</td>
<td>0.4747 +- 0.0280</td>
<td>316/280</td>
</tr>
<tr>
<td>2002 20 GeV/c</td>
<td>0.4808 +- 0.0231</td>
<td>301/280</td>
</tr>
<tr>
<td>2002 24 GeV/c</td>
<td>0.4311 +- 0.0161</td>
<td>267/280</td>
</tr>
<tr>
<td>2003 20 GeV/c</td>
<td>0.4708 +- 0.0295</td>
<td>266/280</td>
</tr>
</tbody>
</table>

**DIRAC results**

\[
\tau_{\text{fs}} = 2.99 \pm 0.18 - 0.17 \, \text{(stat)} \pm 0.19 - 0.17 \, \text{(syst)}
\]

\[
\tau_{\text{fs}} = 2.99 \pm 0.26 - 0.24 \, \text{(8.7\%)}
\]

\[
|a_{0} - a_{2}| = 0.2606 \pm 0.011 \, \text{(4.2\%)}
\]

**ChPT calculations**

\[
\tau = 2.9 \pm 0.1 \, \text{(3.4\%)}
\]

\[
|a_{0} - a_{2}| = 0.265 \pm 0.004 \, \text{(1.5\%)}
\]
Conclusions:

- A new final state, the Pionium, has been copiously produced in the laboratory (22287 atomic pairs), and its ionization spectrum has been fully mapped in both the longitudinal and transverse projections.

- Making no assumptions on the physics of pNi collisions, we have determined the pionium lifetime (in 1S state), to be \( T_{1s} = 2.99^{+0.26}_{-0.24} \text{ fs} \), using the full DIRAC experiment data sample.

- Given the existence of a rigorous next-to-leading order calculation in QCD and QED, the pionium lifetime determination has been converted into a 4% measurement of the s-wave isospin pipi scattering length difference \(|a_0-a_2|\) in the process \( \pi^+\pi^- \rightarrow \pi^0\pi^0 \) at threshold, with the result \(|a_0-a_2|=0.261^{+0.011}_{-0.011} \text{ Mpi}^{-1} \).