Determination of the Spin Triplet $p\Lambda$ Scattering Length from the Reaction $\bar{p}p \rightarrow pK^+\Lambda$

May 16, 2016 | Florian Hauenstein for the COSY-TOF collaboration | Baryons 2016, Tallahassee, Florida
Physics of $\bar{p}p \rightarrow pK\Lambda$

- Investigation of production mechanism of associated strangeness close to threshold
  - Which kind of meson-exchange (no perturbative QCD)
  - Role of $N^*$ resonances ($N^*(1650), N^*(1710), N^*(1720)$)

- $p\Lambda - N\Sigma$ coupled channel (cusp) effect
- $p\Lambda$ final state interaction (FSI)
  - Connection to $p\Lambda$ interaction
  - Extraction of parameter $a$

Sibirtsev et al., arXiv:nucl-th/0004022

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Determination of $p\Lambda$ Scattering Length $a$

- Extraction from $p\Lambda \rightarrow p\Lambda$ scattering
  - total cross section for $k = p/\hbar \rightarrow 0$ is
  \[
  \lim_{k \rightarrow 0} \sigma_{\text{tot}} = 4\pi a^2
  \]
  - highly model dependent
  - scarce data

- Model independent extraction of scattering length from the shape of the $p\Lambda$-FSI
  - based on dispersion integral
  - known theoretical precision (0.3 fm)
Determination of $p\Lambda$ Scattering Length

- Model independent extraction from shape of the FSI
- Parametrization: \[ \frac{d\sigma}{dm_{p\Lambda}} = PS \cdot \exp \left[ C_0 + \frac{C_1}{m_{p\Lambda}^2 - C_2} \right] \]
- \[ a(C_1, C_2) = -\frac{1}{2} C_1 \sqrt{\left( \frac{m_0^2}{m_p m_\Lambda} \right) \cdot \frac{(m_{max}^2 - m_0^2)}{(m_{max}^2 - C_2)(m_0^2 - C_2)^3} \hbar c} \]
- Spin resolved measurement via suitable polarization observable

- COSY-TOF measurement at 2.95 GeV/$c$
  (42,000 events)
- Effective scattering length \[ a_{eff} = (-1.25 \pm 0.08_{\text{stat.}} \pm 0.3_{\text{theo.}}) \text{ fm} \]
- Large systematic error (1 fm) due to kinematical reflection of $N^*$ resonance
Effective $p\Lambda$ Scattering Length for $m_{K\Lambda}$ Regions


- $a_{\text{eff}} = (-1.25 \pm 0.08_{\text{stat.}} \pm 0.3_{\text{theo.}}) \text{ fm}$ (full data)
- $a_{\text{eff}} = (-2.06 \pm 0.16_{\text{stat.}} \pm 0.3_{\text{theo.}}) \text{ fm}$ (upper region)
- $a_{\text{eff}} = (-0.86 \pm 0.06_{\text{stat.}} \pm 0.3_{\text{theo.}}) \text{ fm}$ (lower region)

- Strong influence of $N^*$ resonances
- Error in the order of 1 fm
Dalitz Plot Dependence on Beam Momentum

- Contributions of $N^*$ change with beam momenta
- Expected smaller systematic effect for measurement at 2.7 GeV/c?

⇒ Comparison of results from the COSY-TOF measurements at 2.7 GeV/c and 2.95 GeV/c beam momentum

COSY-TOF Detector

Time Of Flight

Features:

- Full phase space coverage
- Clear signature for $pK\Lambda \rightarrow pK \{p\pi\}$ (2 primary and 2 secondary tracks)
- Primary and hyperon decay vertex ($c\tau(\Lambda) = 7.89\,\text{cm}$)

Measurements of $\bar{p}p \rightarrow pK\Lambda$:  

- 2.95 GeV/$c$ with $(61.0 \pm 1.7)\%$ polarization $\rightarrow$ 42,000 events
- 2.95 GeV/$c$ with $(87.5 \pm 2.0)\%$ polarization $\rightarrow$ 132,000 events
- 2.70 GeV/$c$ with $(77.9 \pm 1.2)\%$ polarization $\rightarrow$ 220,000 events
$\bar{p}p \rightarrow pK\Lambda$ Dalitz Plot

### 2.7 GeV/c

- Preliminary

### 2.95 GeV/c

- Preliminary

- Full phase space acceptance
- Reconstruction efficiency relatively flat
- Strong $p\Lambda$ final state interaction for both data sets
- More substructures for 2.95 GeV/c

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**Effective $p\Lambda$ Scattering Length**

- **Parametrization:**
  \[
  \frac{d\sigma}{dm_{p\Lambda}} = PS \cdot \left| \tilde{A}(FSI) \right|^2 = PS \cdot \exp \left[ C_0 + \frac{C_1}{m_{p\Lambda}^2 - C_2} \right]
  \]

- **$a_{\text{eff}} = (-1.38^{+0.04}_{-0.05}\text{stat.} \pm 0.22\text{syst.} \pm 0.3\text{theo.})\text{ fm (preliminary)}**

- **Compatible with the result at 2.95 GeV/c:**
  \[
  a_{\text{eff}} = (-1.25 \pm 0.08\text{stat.} \pm 0.3\text{theo.})\text{ fm}
  \]

- **Systematic error from influence of $N^*$ resonances weaker than for 2.95 GeV/c (1 fm)**

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Systematic Error from $N^*$ Resonances (1)

Dalitz plot slices

- Dalitz plot sliced by cuts on helicity angle ($\cos \theta^{R_{p\Lambda}}_{pK}$) → same $m_{p\Lambda}$ phase space but different $N^*$ fraction
- Determination of effective scattering length for each slice → access to systematic error from $N^*$s in the $K\Lambda$ channel

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Systematic Error from $N^*$ Resonances (2)

1

$\chi^2 / \text{ndf}$ 52.42 / 36

$p_0$ -0.1236 ± 0.0779

$p_1$ 1.188e+05 ± 1.864e+04

$p_2$ 4.16e+03 ± 8.48e+03

preliminary

2

$\chi^2 / \text{ndf}$ 36.5 / 36

$p_0$ -0.08675 ± 0.09093

$p_1$ 2.466e+04 ± 1.291e+05

$p_2$ 1.195e+04 ± 4.148e+06

preliminary

3

$\chi^2 / \text{ndf}$ 38.61 / 36

$p_0$ -0.02102 ± 0.02102

$p_1$ 1.213e+05 ± 2.184e+04

$p_2$ 4.16e+03 ± 8.48e+03

preliminary

4

$\chi^2 / \text{ndf}$ 58.25 / 36

$p_0$ -0.3731 ± 0.1007

$p_1$ 1.628e+05 ± 2.627e+04

$p_2$ 4.142e+06 ± 1.133e+04

preliminary
Systematic Error from $N^*$ Resonances (3)

<table>
<thead>
<tr>
<th>$\cos \theta^{R_{P \Lambda}}_{pK}$ range</th>
<th>$a_{\text{eff}}$ [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) $\cos \theta^{R_{P \Lambda}}_{pK} &gt; 0.5$</td>
<td>$-1.51^{+0.09}_{-0.10}$</td>
</tr>
<tr>
<td>2) $0 &lt; \cos \theta^{R_{P \Lambda}}_{pK} &lt; 0.5$</td>
<td>$-1.33^{+0.08}_{-0.08}$</td>
</tr>
<tr>
<td>3) $-0.5 &lt; \cos \theta^{R_{P \Lambda}}_{pK} &lt; 0$</td>
<td>$-1.43^{+0.08}_{-0.10}$</td>
</tr>
<tr>
<td>4) $\cos \theta^{R_{P \Lambda}}_{pK} &lt; -0.5$</td>
<td>$-1.33^{+0.06}_{-0.07}$</td>
</tr>
<tr>
<td>full range</td>
<td>$-1.38^{+0.04}_{-0.05}$</td>
</tr>
</tbody>
</table>

- Systematic error from $N^*$'s is about 0.1 fm
- Assume similar error for spin triplet scattering length
Spin Triplet $p\Lambda$ Scattering Length 


- $\{p\Lambda\}$ in S-wave and kaon in P-wave $\Rightarrow$ $\{p\Lambda\}$ in spin triplet configuration due to parity and angular momentum conservation
- Analyzing power $A^K_y$ sensitive to kaon P-wave contribution
- Expand in associated Legendre Polynomials $P^1_1(\cos \theta) = -\sin \theta$ and $P^1_2(\cos \theta) = -3 \cos \theta \sin \theta$

$$A^K_y(\cos \theta, m_{p\Lambda}) \approx \alpha(m_{p\Lambda})P^1_1(\cos \theta) + \beta(m_{p\Lambda})P^1_2(\cos \theta)$$

- Kaon P-wave contribution proportional to $A^K_y(\cos \theta = 0) = -\alpha$
  $\rightarrow$ $\alpha$ gives relative contribution of spin triplet scattering
  $\rightarrow$ Measurement of $\alpha$ dependence on $m_{p\Lambda}$ to determine spin triplet scattering length using the formula

$$|A(FSI)_t(m_{p\Lambda})|^2 = -\alpha(m_{p\Lambda}) \cdot |\tilde{A}(FSI)_{\text{eff}}(m_{p\Lambda})|^2$$
Analyzing Power
Determination Principle

Angular distribution for particles with polarization $P_Y$:

$$(\frac{d\sigma}{d\Omega})_{\text{pol.}} = (\frac{d\sigma}{d\Omega})_0 \cdot (1 + A_N P_N) = (\frac{d\sigma}{d\Omega})_0 \cdot (1 + A_N P_Y \cos \phi)$$

- Azimuthal left-right asymmetry
  $$\epsilon_{LR}(\cos \theta^{\text{CMS}}, \phi) = \frac{L(\theta_p^{\text{CMS}},\phi) - R(\theta_p^{\text{CMS}},\phi)}{L(\theta_p^{\text{CMS}},\phi) + R(\theta_p^{\text{CMS}},\phi)}$$

- Count rates
  $$L(\theta_p^{\text{CMS}},\phi) = \sqrt{N^+(\phi) \cdot N^-(\phi + \pi)}$$ and $$R(\theta_p^{\text{CMS}},\phi) = \sqrt{N^+(\phi + \pi) \cdot N^-(\phi)}$$

- Beam polarization $p_B$
Analyzing Power at 2.7 GeV/c

Fit with associated Legendre polynomials and dependence on $m_{p\Lambda}$

- Reasonable fit of analyzing power by $A^K_y = \alpha P^1_1 + \beta P^1_2$
- $\beta$ decreases for higher $m_{p\Lambda}$ masses (expected due to lower kaon momentum)
- $\alpha$ non zero for low $m_{p\Lambda}$ mass $\rightarrow$ extraction of spin triplet scattering length possible
Spin Triplet Scattering Length $a_t$

- Fit limit as for effective scattering length
- $a_t = (-1.81^{+0.5}_{-0.8}\text{stat.} \pm 0.51\text{syst.} \pm 0.3\text{theo.})$ fm (preliminary)
- First direct model independent determination of $a_t$
- Comparison:
  - $a_t = (-1.6^{+1.1}_{-0.8})$ fm ($\Lambda p$ elastic scattering)
  - $a_t = -1.54$ fm (theoretical calculation [NPA 915, 24-58 (2013)])
  - $a_t = (-1.56^{+0.19}_{-0.22}\text{stat.} \pm 0.4\text{theo.})$ fm ($pp \rightarrow KX$ [PLB 687, 31 (2010)])
Overview of Considered Systematic Errors

<table>
<thead>
<tr>
<th>Error</th>
<th>$a_{\text{eff}}$</th>
<th>$a_{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit limit</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>Wrong beam polarization</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>Improper acceptance correction</td>
<td>0.2 fm</td>
<td>0.2 fm</td>
</tr>
<tr>
<td>Influence of $N^*s$</td>
<td>0.1 fm</td>
<td>0.1 fm</td>
</tr>
<tr>
<td>Binning of $m_{p\Lambda}$</td>
<td>0.02 fm</td>
<td>0.46 fm (prel.)</td>
</tr>
<tr>
<td>Total</td>
<td>0.22 fm</td>
<td>0.51 fm (prel.)</td>
</tr>
</tbody>
</table>
Summary

- High resolution measurement with full phase space acceptance of the $\bar{p}p \rightarrow pKL$ reaction at 2.7 GeV/c
- $\approx 200,000$ reconstructed events
- Results:
  - Dalitz plot: Strong $p\Lambda$ final state interaction seen
  - Effective $p\Lambda$ scattering length
    - $a_{\text{eff}} = (-1.38^{+0.04}_{-0.05}\text{stat.} \pm 0.22\text{syst.} \pm 0.3\text{theo.})$ fm (preliminary)
    - Compatible with previous TOF result at 2.95 GeV/c:
      - $a_{\text{eff}} = (-1.25 \pm 0.08\text{stat.} \pm 0.3\text{theo.})$ fm
  - Systematic error from influence of $N^*$ resonances factor ten weaker
  - Kaon analyzing power: $P_1^1$ not vanishing for low $m_{p\Lambda}$ masses
  - First direct measurement of spin triplet $p\Lambda$ scattering length
    - $a_t = (-1.81^{+0.5}_{-0.8}\text{stat.} \pm 0.51\text{syst.} \pm 0.3\text{theo.})$ fm (preliminary)
Outlook

- Publication of the result for the scattering length soon
- Further results for the data sets
  - $\Lambda$ polarization and spin transfer coefficient
  - Partial wave analysis for the determination of the $N^*$ resonance contributions
Backup Slides
Parametrisation Dependence on $a$ for Fixed $C_2$

$|A_{\text{FSI}}|^2$ Gasparyan Parametrization [a.U.]

- $a = -1.00$ fm
- $a = -1.40$ fm
- $a = -1.50$ fm
- $a = -2.00$ fm
- $m_p + m_\Lambda$

$M_{p\Lambda}$ [MeV/c$^2$]

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Dalitz Plot for $pp \rightarrow pK\Lambda$


- Clear enhancement at low $m_{p\Lambda}$ masses from final state interaction
- Full phase space coverage
- $p\Lambda - N\Sigma$ coupled channel enhancement (cusp effect)
Measurement of $\alpha$ at 2.95 GeV/c

- Unexpected: $\alpha$ is $< 11\% \ (3\sigma)$ for low invariant mass
  $\rightarrow$ no sufficient precision for extraction of spin triplet $p\Lambda$
  scattering length
- $\beta$ behavior reasonable (high $p\Lambda$ mass $\rightarrow$ low momentum
  kaons)
  $\rightarrow$ Additional measurement at 2.95 GeV/c to reduce statistical
  error
Dalitz Plot for Measurements at 2.95 GeV/c

- Enhancement at $p\Lambda$-FSI and $N\Sigma$ threshold (cusp effect)
**pp Elastics Event Selection and Beam Polarization Determination**

- Selection of elastics with circular cut on missing energy and coplanarity ($\cos \alpha$)
- Determination of polarization in bins of $\theta_p^{CMS}$ using analyzing power from SAID
Analyzing Power of Final State Particles

- Proton and kaon analyzing power: Similar behavior for different momenta
- $\Lambda$ analyzing power: for $\cos(\theta_\Lambda^{CMS} > 0)$ different behavior
Event Selection at 2.7 GeV/c

Selection criteria

- $\chi^2_{\text{kin.fit}} < 5$
- $\Lambda$ decay length $> 3$ cm
- $\angle(\Lambda, \text{decay proton}) > 2^\circ$
- Similar for 2.95 GeV/c

Monte Carlo simulations

- Low background from other reactions ($pp \rightarrow pK\Sigma^0 < 1\%$)
- Reconstruction efficiency $\sim 15\%$ (20\% for 2.95 GeV/c)
Straw-Tube-Tracker (STT)

- 2704 straw tubes \((l = 1\, \text{m}, \, d = 1\, \text{cm})\) arranged in 13 double layers
- \(\text{Ar} : \text{CO}_2\) gas mixture with ratio 8 : 2 at 1.2 bar overpressure
- Drift time information used for track to wire distance
- Obtained averaged spatial resolution \(\sigma = (137 \pm 9) \, \mu\text{m}\)