Toward polarized antiprotons: 
*Machine development for spin-filtering experiments at COSY*

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Motivation

- The PAX collaboration proposed to investigate Drell Yan processes in scattering of polarized proton - antiproton beams at the HESR (FAIR).

- Annihilation of valence quark with an antivalence quark allows direct access to: transversity, ....

\[
A_{TT} = \frac{d\sigma^\uparrow\downarrow - d\sigma^\uparrow\downarrow}{d\sigma^\uparrow\downarrow + d\sigma^\uparrow\downarrow} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_q^q(x_1, M^2) h_1^q(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)}
\]

- Requirements:
  - Polarized proton beam
  - Polarized antiproton beam

Perspectives for Polarized Antiprotons
How to Polarize Antiprotons?

- Spin-1/2 particles: 2 states
  - Selective removal reduces beam intensity - Selective flip does not affect intensity
  - but at COSY we demonstrated that
  - $e^+\overline{p}$ spin-flip cross-section is too low to use selective flip


$\sigma_\parallel < 8.0 \times 10^6 \text{ b}$
$\sigma_\perp < 5.5 \times 10^6 \text{ b}$
Spin-filtering

Polarization build-up of a circulating particle beam by interaction with a polarized gas target
Spin-filtering

\[ \sigma_{tot} = \sigma_0 + \sigma_1 (\vec{P} \cdot \vec{Q}) + \sigma_2 (\vec{P} \cdot \hat{k}) (\vec{Q} \cdot \hat{k}) \]

- \( \sigma_0 \) is the background signal.
- \( \sigma_1 \) and \( \sigma_2 \) are the polarization coefficients.
- \( \vec{P} \) is the polarization vector of the beam.
- \( \vec{Q} \) is the polarization vector of the target.
- \( \hat{k} \) is the beam direction vector.

\[ P(t) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \tanh \left( \frac{t}{\tau_1} \right) \approx t \cdot \tilde{\sigma}_1 \cdot Q \cdot d_t \cdot f \]

- \( P(t) \) is the polarization of the beam.
- \( N_\uparrow \) and \( N_\downarrow \) are the number of particles in the up and down states.
- \( \tau_1 \) is the decay time.
- \( d_t \) is the target thickness.
- \( f \) is the factor accounting for the decay.

\( P \ldots \) beam particle spin orientation
(beam direction)

\( Q \ldots \) target particle spin orientation

Perspectives for Polarized Antiprotons
Spin-filtering

\[ \sigma_{tot} = \sigma_0 + \sigma_1 (\vec{P} \cdot \vec{Q}) + \sigma_2 (\vec{P} \cdot \hat{k})(\vec{Q} \cdot \hat{k}) \]

- \( P \) ... beam particle spin orientation
- \( Q \) ... target particle spin orientation
- \( k \parallel \) beam direction

\[ P(t) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \tanh \left( \frac{t}{\tau_1} \right) \approx t \cdot \tilde{\sigma}_1 \cdot Q \cdot d_t \cdot f \]
1992: Filter Test at TSR with protons

Spin filtering works for protons

PAX submitted new proposal to find out how well does spin filtering work for antiprotons

Measurement of the Spin-Dependence of the pp Interaction at the AD Ring

(CERN-SPSC-2009-012 / SPSC-P-337)
Spin-dependence of the pbar-p interaction


Oct. 2009 SPS Committee:
... Taking into account the timeline and constraints of the various projects concerned, the SPSC encourages the PAX Collaboration to first perform their spin filtering measurements at COSY...
Spin Filtering at COSY

Spin filtering with protons to confirm understanding of the process and to commission the experimental setup

- Length: 183.4 m
- Injection energy: 45 MeV
- Electron cooling for long lifetimes up to 600 MeV/c (p)
Spin-filtering cycle

- Spin-flipper
- Cluster target + STT (beam polarimetry)
- p
- COSY ring
- Polarized target

Graphs showing deuteron asymmetry vs $\Theta_p$ and polarization buildup with filter time.
Spin-filtering: result

- **Milestone for the field**
  - Confirms understanding of spin-filtering as a viable method to polarize a stored beam.
  - Confirms complete control of the systematics of the experiment.

Mar. 2012 SPS Committee:
... many positive developments have occurred at the AD, leading to an updated program for the coming years .... *We consider that PAX is now incompatible with this program.*
1. Maximum polarizing cross section
   - small kinetic energy, where
   - the analyzing power is known

FILTEX
F. Rathmann. et al., PRL 71, 1379 (1993)
Comments: II

1. **Maximum polarizing cross section**
   - small kinetic energy

2. **Maximum revolution frequency**
   - large kinetic energy (compromise between 1. & 2. needed)
   - short accelerator

\[
P(t) = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} = \tanh \left( \frac{t}{\tau_1} \right) \approx \tilde{\sigma}_1 \cdot f \cdot Q \cdot d_1 \cdot t
\]
Comments: III

1. **Maximum polarizing cross section**
   - small kinetic energy

2. **Maximum revolution frequency**
   - large kinetic energy
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3. **Maximum target polarization and density**
   - high dense polarized gas target (*Atomic Beam Source*)
   - storage cell

\[
P(t) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \tanh \left( \frac{t}{\tau_1} \right) \approx \bar{\sigma}_1 \cdot f \cdot Q \cdot d_t \cdot t
\]
Comments: IV

\[ P(t) = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} = \tanh \left( \frac{t}{\tau_1} \right) \approx \tilde{\sigma}_1 \cdot f \cdot Q \cdot d_i \cdot t \]

1. Maximum polarizing cross section
   - small kinetic energy
2. Maximum revolution frequency
   - large kinetic energy
   - short accelerator
3. Maximum target polarization and density
   - high dense polarized gas target (Atomic Beam Source)
   - storage cell
4. Maximum filtering time
   - long beam lifetime (UHV, good beam preparation, etc.)
Experimental setup and commissioning

- ABS
- Low-β Quadrupoles
- BRP
- Target Chamber

Spin-filtering studies at COSY
Atomic Beam Source

Perspectives for Polarized Antiprotons
Low-β section

\[
\mu_{\text{acc}}^2 \mu \frac{1}{2}
\]

- Significant reduction of the machine acceptance due to storage cell (d = 9.6 mm, l = 400 mm)
- Solution: low-β section

Low-β section OFF

Spin-filtering studies at COSY
Low-β section

\[ \mu \frac{2}{\mu_{acc}} \mu \frac{1}{2} \]

- Significant reduction of the machine acceptance due to storage cell (d = 9.6 mm, l = 400 mm)
- Solution: low-β section
Vacuum system: I

PAX vacuum section

IG pumps 100 l/s

NEG coated beam pipes (each 5000 l/s)

3×10^{16} \frac{atoms}{s}

<10^{-11} mbar

<10^{-9} mbar

<2×10^{-10} mbar

<2×10^{-7} mbar

target switched off

target switched on

IG pumps 100 l/s

<10^{-10} mbar

<2×10^{-9} mbar

<10^{-9} mbar

<2×10^{-7} mbar

Spin-filtering studies at COSY
Fast shutters (<15 ms)

Flow limiters
(d = 19 mm, l = 80 mm)

SAES getter pump (each 1900 l/s)

HiPace 1800 turbo (1200 l/s)

Beam losses due to $\tau(s)$

<table>
<thead>
<tr>
<th></th>
<th>$\tau(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>single-scattering in storage cell</td>
<td>48500</td>
</tr>
<tr>
<td>gas load elsewhere in the low-$\beta$ section</td>
<td>47500</td>
</tr>
<tr>
<td>machine vacuum alone</td>
<td>12000</td>
</tr>
</tbody>
</table>

24000s
Identification of optimal working point

- Search for optimal betatron tune by varying currents in quads ± 3%
- Beam lifetime increase as by decreasing tune spin: $\Delta Q_{\text{split}} = |Q_x - Q_y|$
- Difference resonance not reachable due to coupling of betatrons motion
- Improvement by sextupole or orbit corrections

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1. $\Delta Q_{\text{split}} = 0.014$
2. $\Delta Q_{\text{split}} = 0.006$ (sextupoles)
3. $\Delta Q_{\text{split}} = 0.008$ (orbit correction)
Space charge effects

- Measure beam lifetime as function of space charge
- Variation of beam emittance for constant intensity
- Tilt of e-beam with respect to p-beam changes cooling performance
- Beam lifetime increases with decreasing space charge
- Betatron amplitude-dependent detuning ("tune spread")

Maximal incoherent tune shift given by:

\[ Q_{x,y}^{\text{inc}} = \frac{r_0 \cdot N}{2 \cdot L^2} \cdot \frac{F_{x,y} G}{B_f} \cdot \frac{1}{x,y + \sqrt{x \cdot y}} \]

Future plans

Waiting for CERN ... (or construction of FAIR facility)
Longitudinal spin-filtering test at COSY

Superconducting 2.1 Tm at ANKE place
Longitudinal polarization at PAX place

Longitudinal beam polarimeter in preparation

(⇒ G. Ciullo 24.10)
Summary

Status:
• Successfull spin filtering measurement at COSY on transverse polarized target.
• Excellent agreement with theoretical predictions for protons
• Development of a protocol for spin-filtering tests
• Excellent performance for the COSY ring (precision machine)

Future plans at COSY
• Spin filtering with protons and a longitudinally polarized gas target at COSY at \( T_p = 130 \text{ MeV} \) \((\bar{p}p \text{ scattering})\)

Still pending:
• Spin-filtering experiments at AD (or FAIR) (transv. and long. polarization)

Thank you!
Additional Slides
Expected Polarizations for pbar

A. Transversal polarization

D. Longitudinal polarization

Spin-filtering studies at COSY
Spin Filtering with Longitudinal Polarization

- Buildup of longitudinal beam polarization due to repeated interaction with a longitudinally polarized hydrogen target
- $T_p$ 45 - 130 MeV kinetic proton energy
- **Detector**: Measurement of longitudinal beam polarization using elastic scattering
  - Measurement during filtering with hydrogen target possible
  - Spin correlation coefficient ($\sim 0.5$)
  - No background

\[
\frac{d}{d}\frac{d}{d^0} (1 + C_{zz}P_zQ_z)
\]

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Spin-filtering studies at COSY
Low-\(\beta\) section: II

Measurement of \(\beta\)-function

\[
x, y = \frac{4}{l} \left| \frac{Q_{x,y}}{k} \right|
\]

- Measure tune change as function of quadrupole strength
- PAX magnets are powered pairwise
Low-β section: II

Measurement of β-function

\[ x, y = \frac{4}{l} \left| \frac{Q_{x,y}}{k} \right| \]

- Measure tune change as function of quadrupole strength
- PAX magnets are powered pairwise

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Model calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PAX 1</td>
</tr>
<tr>
<td>( \beta_x ) (m)</td>
<td>2.31±0.13</td>
</tr>
<tr>
<td>( \beta_y ) (m)</td>
<td>12.41±1.01</td>
</tr>
</tbody>
</table>

Spin-filtering studies at COSY
Orbit Correction

- Corrections of deviations from ideal orbit
- Closed orbit correction scheme based on orbit response matrix (ORM)

\[ u(s) = R_{s,i}^u \times u(s) \quad \text{with} \quad R_{s,i}^u = \sqrt{u_i \cdot u_s \cos \left( \frac{Q_u}{u,s \rightarrow i} \right)} \]

\[ \frac{\cos \left( \frac{Q_u}{u,s \rightarrow i} \right)}{2\sin \left( \frac{Q_u}{u,s \rightarrow i} \right)} \]

- \( \chi^2 \) minimization to determine correction angle kicks \( \theta_u \)