How to produce polarized antiprotons and what to do with them at FAIR

Polarized Antiproton EXperiments

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STORI 08, Lanzhou 16.09.08
Introduction

A Method to Polarize Stored Antiprotons to a High Degree

~ 3 years ago, we proposed a method to polarize antiprotons by „spin-filtering“
The FAIR facility at Darmstadt

New initiative, driven by the FAIR-project at GSI
The FAIR facility at Darmstadt

High Energy Storage Ring (HESR) for a beam of antiprotons
Polarized Antiprotons: a long story

- 1985 - Bodega Bay:
  “International Workshop on Polarized Antiprotons Beam”
- 2007 - Daresbury:
  “Polarized Antiprotons: How”
- 2008 – Bad Honnef:
  Heraeus Seminar: “Polarized Antiprotons”

**Intense beam of polarized antiprotons never produced:**

- Conventional methods (ABS) not applicable
- Polarized antiprotons from antilambda decay
  - \( I < 1.5 \times 10^5 \text{ s}^{-1} (P \approx 0.35) \)
- Antiproton scattering off liquid H\(_2\) target
  - \( I < 2 \times 10^3 \text{ s}^{-1} (P \approx 0.2) \)
- Little polarization from pbarC scattering exp’ts at LEAR

**Methods not applicable to storage rings**
Polarized Antiproton in Storage Rings

- Two possible methods:

  Spin-filtering  Spin-flip

selective loss
discard (one) substate
(more than the other)
Spin-flip: a recent proposal

- Antiproton beam polarization by interaction with a polarized positron beam

A surprising method for polarizing antiprotons

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Abstract. We propose a method for polarizing antiprotons in a storage ring by means of a beam moving parallel to the antiprotons. If the relative velocity is adjusted to \( v/c \) for spin-flip is as large as about 0.2 barn as shown by new QED calculations.

2x10\(^{13}\) barn!

\[ \text{\rightarrow need for} \text{ experimental test} \]
Depolarization studies at COSY: idea

• Use proton beam and co-moving electrons
• Turn experiment around: $p_e \rightarrow p_e \rightarrow p_e \rightarrow p$
  i.e. depolarization of a polarized proton beam
Depolarization studies at COSY: principle

- Use (transversely polarized) proton beam in COSY
- Switch on (detuned) electron cooler to depolarize proton beam
- Analyze proton polarization with internal D$_2$-cluster target at ANKE
Depolarization studies at COSY: cycle

$\Delta V \sim$ few 100 V

Nominal Cooler Voltage
$T_{\text{nominal}} = 250$ s

Detuned Cooler Voltage
$T_{\text{detuned}} = 250$ s

$D_2$ target off
Ecooler on/detuned

$D_2$ target on
Ecooler on
Depolarization studies at COSY: cycle

Detuned Cooler
Voltage $T_{\text{detuned}} = 50 \text{ s}$

$\Delta V \sim \text{few 100 V}$

Nominal Cooler
Voltage $T_{\text{nominal}} = 100 \text{ s}$

$f_{\text{shift}}(10\text{ s}) = 80 \text{ Hz} \rightarrow v_{\text{shift}} = 0.07 \times 10^{-3}c$

$\Delta f_{\text{broad}}(10\text{ s}) = 25 \text{ Hz} \rightarrow \Delta v_{\text{broad}} = 0.02 \times 10^{-3}c$

Negligible with respect to:

$\Delta V = 245 \text{ V} \rightarrow v_{\text{rel}} = 1.46 \times 10^{-3}c$
Depolarization studies at COSY: cycle

Detuned Cooler Voltage
$T_{\text{detuned}} = 250 \, \text{s}$

$\Delta V \sim \text{few} \, 100 \, \text{V}$

Nominal Cooler Voltage
$T_{\text{nominal}} = 250 \, \text{s}$

$D_2$ target off
Ecooler on/detuned

$D_2$ target on
Ecooler on

Number of Beam Particles

Time (s)
Depolarization studies at COSY: Polarimetry

-p-d elastic scattering detection in silicon tracking telescopes
Depolarization studies at COSY: Results (Feb. 08)

-> No effect observed: cross section must be many orders of magnitude lower than $10^{13}$ b!!
Polarized Antiproton in Storage Rings

- Two possible methods:

Spin-filtering

Spin-flip

selective loss

discard (one) substrate (more than the other)

selective flip

reverse (one) substrate (more than the other)
Spin-filtering

Polarization build-up of an originally unpolarized particle beam by repeated interaction with polarized hydrogen target:

Spin-filtering is known to work (FILTEX); not clear how
Spin-filtering at TSR: “FILTEX”

TSR … Test Storage Ring at MPI Heidelberg
FILTEX … Filter Experiment (1992)
Spin-filtering at TSR: “FILTEX” proof of principle

PhD of F. Rathmann
Spin-filtering at COSY: understand and optimize “FILTEX”

Spin-filtering at CERN/AD: pbar-p and pbar-d scattering

• First ever measurement of pbar-p, pbar-d spin correlations
Spin-filtering at COSY: understand and optimize “FILTEX”

Spin-filtering at CERN/AD: $\bar{p}$-$p$ and $\bar{p}$-$d$ scattering

Theoretical estimate of Antiproton Beam Polarization (Hadronic Interaction: Longitudinal Spin Filtering)


Experimental setup for spin-filtering tests

PAX Overview

- Superconducting quadrupole pair with cryo-pump inside
- Polarized atomic beam source
- Superconducting quadrupole pair with cryo-pump inside
- Breit-Rabi-Polarimeter
S.C. quads for low-\(\beta\) section:

(COSY ring)

**PAX Overview**

- Superconducting quadruple pair with cryo-pump inside
- Polarized atomic beam source
- Brent-Rabi-Polarimeter

**NbTi RACETRACK COILS**
- integrated gradient  24.4 T
- coil length   450 mm
- Je    220 A/mm²
- total current 606 kA
- max. magnetic field 7.1 T
- stored energy 227 kJ
- inductivity 5 H
- max. voltage 6 kV
- max. temperature 250 K
Openable storage cell for operation at AD
Polarized Atomic Beam Source + Breit-Rabi polarimeter (from HERMES-DESY)
Silicon detector for beam polarimetry

- Pbar-Beam polarization by using the (measured) analysing power of pbar-p elastic

- Modular structure
- 10 cm x 10 cm silicon wafers
- 300 μm thick
- Open cell without moving det.
- Re-use of HERMES recoil

<table>
<thead>
<tr>
<th>beam energy:</th>
<th>43 MeV</th>
<th>120 MeV</th>
<th>220 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>total number of primary events:</td>
<td>1 M</td>
<td>1 M</td>
<td>1 M</td>
</tr>
<tr>
<td>Primary antiproton-proton elastic:</td>
<td>0.33 M</td>
<td>0.33 M</td>
<td>0.33 M</td>
</tr>
<tr>
<td>accepted: elastic</td>
<td>48 k</td>
<td>57 k</td>
<td>40 k</td>
</tr>
<tr>
<td>total 'run' time:</td>
<td>4000 sec</td>
<td>5700 sec</td>
<td>6898 sec</td>
</tr>
<tr>
<td>good (reconstructed) event rate:</td>
<td>12 evt/sec</td>
<td>10 evt/sec</td>
<td>5.8 evt/sec</td>
</tr>
</tbody>
</table>

(after spin-filtering)
Silicon detector for beam polarimetry

HERMES recoil
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Polarized Antiproton Experiments

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Study of the proton spin

Quark structure of the nucleon

\[ \Phi_{\text{Corr}}^{T_w^2}(x) = \frac{1}{2} \left\{ q(x) + S_L \Delta q(x) \gamma_5 + \delta q(x) \gamma_5 \gamma^1 S_T \right\} n^+ \]

\( q = \)

\( \Delta q = \)

\( h_1 = \)

unpolarised quarks and nucleons

longitudinally polarised quarks and nucleons

transversely polarised quarks and nucleons

Well known

Known

Only glimpse
Transversity

\[ h_1^q = \begin{cases} \uparrow & \text{transversely polarised quarks and nucleons} \\ \downarrow & \end{cases} \]

- Probes relativistic nature of quarks
- No gluon analog for spin-1/2 nucleon
- Different \( Q^2 \) evolution than \( \Delta q \)
- Sensitive to valence quark polarization

\( h_1 \) is chirally odd -> it needs a chirally odd partner
\[ h_1 \text{ from Drell-Yan} \]

\[ q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^- \]

Drell-Yan

\[ \frac{d^2 \sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9M^2s} \frac{1}{x_1 + x_2} \sum_q e_q^2 [q(x_1) \bar{q}(x_2) + \bar{q}(x_1) q(x_2)] \]

\[ x_F = x_1 - x_2 \quad x_1x_2 = M^2 / s \equiv \tau \quad x_F = 2Q_L / \sqrt{s} \]

\[ A_{TT} = \frac{d\sigma_{\uparrow\uparrow} - d\sigma_{\uparrow\downarrow}}{d\sigma_{\uparrow\uparrow} + d\sigma_{\uparrow\downarrow}} = \hat{a}_{TT} \sum_q e_q^2 [h_{1q}(x_1)h_{1\bar{q}}(x_2) + h_{1\bar{q}}(x_1)h_{1q}(x_2)] / \sum_q e_q^2 [q(x_1)q(x_2) + \bar{q}(x_1)\bar{q}(x_2)] \]

\[ q = u, \bar{u}, d, \bar{d}, ... \]

\[ M \text{ invariant Mass of lepton pair} \]
EXPERIMENT:
Asymmetric collider:
- polarized protons in HESR ($p=15$ GeV/c)
- polarized antiprotons in CSR ($p=3.5$ GeV/c)

**PAX phase-II: Asymmetric collider**

s=200 GeV$^2$
$h_1$ from $\bar{p}$-$p$ Drell-Yan at PAX

$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} + \hat{a}_{TT} \sum_q e_q^2 \left[ h_{1q}(x_1)h_{1q}(x_2) + h_{1\bar{q}}(x_1)h_{1\bar{q}}(x_2) \right]$$

1 year run: 10% precision on the $h_{1u}(x)$ in the valence region

- $u$-dominance
- $|h_{1u}| > |h_{1d}|$

$A_{TT} \approx \hat{a}_{TT} \frac{h_{1u}(x_1)h_{1u}(x_2)}{u(x_1)u(x_2)}$

PAX: $M^2/s = x_1x_2 \sim 0.02 - 0.3$

valence quarks

($A_{TT}$ large $\sim 0.2 - 0.3$)
Study of the Proton Electromagnetic Form-Factors

Space-Like FFs: proton data

Time-Like FFs: proton data

JLab results dramatically changed picture of the Nucleon:
- $G_E^p/G_M^p$ decreases with $Q^2$
- data suggest $G_E^p$ crosses 0 at $Q^2 \approx 8$ GeV$^2$

Expected $Q^2$ behaviour reached quite early, however ...
... there is still a factor of 2 between timelike and spacelike.

Additional direct measurement needed
PAX-Phase I: fixed target experiments

EXPERIMENT:
Fixed target experiment:
- polarized antiprotons protons in CSR (p>200 MeV/c)
- fixed polarized protons target
Double polarized pbar–p annihilation

\[ A_{xx} = \sin^2 \theta \left( |G_M|^2 + \frac{1}{\tau} |G_E|^2 \right) \mathcal{N}, \]
\[ A_{yy} = -\sin^2 \theta \left( |G_M|^2 - \frac{1}{\tau} |G_E|^2 \right) \mathcal{N}, \]
\[ A_{zz} = \left[ (1 + \cos^2 \theta) |G_M|^2 - \frac{1}{\tau} \sin^2 \theta |G_E|^2 \right] \mathcal{N}, \]
\[ A_{xz} = \left( \frac{d\sigma}{d\Omega} \right)_0 A_{zz} = \frac{1}{\sqrt{\tau}} \sin 2\theta \text{Re} G_E G_M^* \mathcal{N}. \]

- Most contain moduli $G_E, G_M$
- Independent $G_E$-$G_M$ separation
- Test of Rosenbluth separation in the time-like region
- Access to $G_E$-$G_M$ phase
- Very sensitive to different models (next transparencies)

E. Tomasi, F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419(2005)
Hard p-p polarized scattering

“The greatest asymmetries in hadron physics ever seen by a human being” (Brodsky)

“One of the unsolved mysteries of hadron physics” (Brodsky, 2005)

It would be very interesting to perform these measurements with polarized antiprotons.
Summary

• Outstanding physics case for polarized antiprotons
• PAX Collaboration took over the challenge of polarizing antiprotons

-2008-09 beam lifetime
-2009-10 SC quadrupoles
  + int.region
-2010-11 spin-filtering
-2012-13 spin-filtering
-2013 APR design
Theoretical models

Spacelike

Timelike

Electric

Magnetic

Electric

Magnetic

QCD inspired

Extended VDM

VDM: IJL
F. Iachello, PLB 43, 191 (1973)

Hohler
*NPB* 114, 505 (1976)

Polarization and Models in T.L. Region

\[ A_y \]
\[ A_{xx} \]
\[ A_{yy} \]
\[ R \]
\[ A_{zz} \]
\[ A_{xz} \]

VDM : IJL
Ext. VDM
'QCD inspired'

E. Tomasi, F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419(2005)
Depolarization studies at COSY: cycle