http://www.fz-juelich.de/ikp/pax

Polarized Antiproton EXperiments

Spokespersons
Paolo Lenisa    Ferrara University    lenisa@mail.desy.de
Frank Rathmann  FZ-Jülich             f.rathmann@fz-juelich.de

Mikhail Nekipelov  
Institut für Kernphysik    
Forschungszentrum Jülich

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Overview

- Goal: effective method to polarise antiprotons
- Polarisation build-up
- Spin filtering at COSY (do electrons play a role?)
- Spin filtering at AD (CERN)
- Antiproton polariser ring
- Physics with PAX
- Detector concept
**Polarised Antiprotons**

Intense beam of polarised antiprotons was never produced:

- Conventional methods (ABS) not applicable
- Polarised antiprotons from antilambda decay
  - \( I < 1.5 \cdot 10^5 \text{ s}^{-1} \) (\( P \approx 0.35 \))
- Antiproton scattering off liquid H\(_2\) target
  - \( I < 2 \cdot 10^3 \text{ s}^{-1} \) (\( P \approx 0.2 \))
- Stern-Gerlach spin separation in a beam (never tested)
- Polarised electrons/positrons (never tested)

- **Spin filtering** is the only successfully tested (with protons) technique
Polarisation Build-up
of the stored beam in 2 substates: up/down (+/-)

\[ \sigma_{\text{tot}} = \sigma_0 + \sigma_\perp \cdot \vec{P} \cdot \vec{Q} + \sigma_\parallel \cdot (\vec{P} \cdot \vec{k})(\vec{Q} \cdot \vec{k}) \]

P beam polarisation
Q target polarisation
k || beam direction

\[ P(t) = \frac{I_+ - I_-}{I_+ + I_-} = -\tanh \left( \frac{t}{\tau_{\text{pol}}} \right) \]
\[ I(t) = I_+ + I_- = I_0 \cdot e^{-\frac{t}{\tau_{\text{beam}}}} \cdot \cosh \left( \frac{t}{\tau_{\text{pol}}} \right) \]

\[ \tau_{\text{pol}} = \frac{1}{\sigma_{\text{pol}} \cdot Q \cdot d_i \cdot f_{\text{rev}}} \]

selective loss
discard (one) substate
(more than the other)

selective flip
reverse (one) substate
(more than the other)
Polarisation Evolution

\[
\frac{d}{dt} \left( \begin{array}{c} N^+ \\ N^- \end{array} \right) = -d_t \left( \begin{array}{cc} \sigma_{loss}^+ + \sigma_+ & -\sigma_- \\ -\sigma_+ & \sigma_{loss}^- + \sigma_+ \end{array} \right) \left( \begin{array}{c} N^+ \\ N^- \end{array} \right)
\]

Intensity

\[
N^- + N^+ \quad (N^- - N^+)/ (N^- + N^+) \quad P^2 \cdot I
\]

Polarisation

- No flip, \( \frac{\sigma_{loss}^-}{\sigma_{loss}^+} = 5 \)
- No loss, \( \frac{\sigma_+}{\sigma_-} = 5 \)
- \( \frac{\sigma_{loss}^-}{\sigma_{loss}^+} = 5, \frac{\sigma_+}{\sigma_-} = 5 \)
- \( \frac{\sigma_{loss}^-}{\sigma_{loss}^+} = 5, \frac{\sigma_+}{\sigma_-} = 0.2 \)
1992 Filter Test at TSR with protons

Experimental Setup

Results

F. Rathmann. et al., PRL 71, 1379 (1993)
Two interpretations of FILTEX result

Observed polarisation build-up: \( \frac{dP}{dt} = \pm (1.24 \pm 0.06) \times 10^{-2} \text{ h}^{-1} \)
\( \sigma_{\text{pol}} = 72.5 \pm 5.8 \text{ mb} \)

Spin filtering works! But how?

1994 Meyer and Horowitz: three distinct effects
1. Selective removal through scattering beyond \( \theta_{\text{acc}} = 4.4 \text{ mrad} \) \( (\sigma_{R\perp} = 83 \text{ mb}) \)
2. Small angle scattering off target prot. into ring acceptance \( (\sigma_{S\perp} = 52 \text{ mb}) \)
3. Spin-transfer from pol. el. of target atoms to stored prot. \( (\sigma_{E\perp} = -70 \text{ mb}) \)
\[ \sigma_1 = \sigma_{R\perp} + \sigma_{S\perp} + \sigma_{E\perp} = 65 \text{ mb} \]

2005 Milstein & Strakhovenko + Nikolaev & Pavlov: only one effect
Only pp elastic scattering contributes
No contribution from other two effects \( \sigma_1 = 85.6 \text{ mb} \)
Spin Filtering: Present Status

Present understanding: spin filtering is expected to be an effective way to polarise antiprotons

1. Controversial interpretations of FILTEX experiment
   • Further experimental tests necessary
     • How does spin filtering work?
     • Which role do electrons play?
       → Tests with protons at COSY

2. No data to predict polarisation from filtering with antiprotons
   → Measurements with antiprotons at AD/CERN
Spin Filtering Studies at COSY

Goal:
• Understanding the spin filtering mechanism
• Disentangle electromagnetic and hadronic contributions to the polarising cross section

... only hadronic (Budker-Jülich)
- electromagnetic + hadronic (Meyer-Horowitz)

A measurement of $\sigma_{\text{eff}}$ to 10% precision requires polarisation measurement with $\Delta P/P = 10\%$
Expectations based on Budker-Jülich:
• \( T = 40 \text{ MeV} \)
• \( N_{\text{inj}} = 1.5 \times 10^{10} \) protons

### ANKE vs. new IP: Polarisation

<table>
<thead>
<tr>
<th>PIT</th>
<th>Filter. time</th>
<th>Polar.</th>
<th>Total rate</th>
<th>Meas. Time ((\Delta P/P=10%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANKE</td>
<td>( 2\tau = 16 \text{ h} )</td>
<td>1.2 %</td>
<td>( 7.5 \times 10^2 \text{ s}^{-1} )</td>
<td>44 min</td>
</tr>
<tr>
<td></td>
<td>( 5\tau = 42 \text{ h} )</td>
<td>3.5 %</td>
<td>( 5 \times 10^3 \text{ s}^{-1} )</td>
<td>26 min</td>
</tr>
<tr>
<td>New IP</td>
<td>( 2\tau = 5 \text{ h} )</td>
<td>16 %</td>
<td>( 2.2 \times 10^4 \text{ s}^{-1} )</td>
<td>1 s</td>
</tr>
<tr>
<td></td>
<td>( 5\tau = 13 \text{ h} )</td>
<td>42 %</td>
<td>( 1.5 \times 10^3 \text{ s}^{-1} )</td>
<td>&lt; 1 s</td>
</tr>
</tbody>
</table>
Common Experimental Setup for COSY and AD

Atomic Beam Source

Detector System surrounding Storage Cell Target

SC Quadrupoles

Mikhail Nekipelov
Detector Concept

- Will measure beam polarisation by using the polarisation observables:
  - $p$-$p$ elastic (COSY)
  - $p$-$\bar{p}$ elastic (AD)
- Good azimuthal resolution (up/down asymmetries)
- Low energy recoil (<8 MeV)
  - Silicon telescopes
  - Thin 5μm Teflon cell needed
- Angular resolution for the forward particle for $p$-$p$-$\bar{p}$ at AD
- AD experiment will require an openable cell
Two Silicon Tracking Telescopes
How to disentangle hadronic and electromagnetic contributions to $\sigma_{\text{eff}}$?

Injection of different combinations of hyperfine states to provide:

- Pure electron polarized target ($P_z = 0$)
- Pure nuclear polarized target ($P_e=0$)

<table>
<thead>
<tr>
<th>Inj. states</th>
<th>$P_e$</th>
<th>$P_z$</th>
<th>Interaction</th>
<th>Holding field</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>1\rangle$</td>
<td>+1</td>
<td>+1</td>
<td>Elm. + had.</td>
</tr>
<tr>
<td>$</td>
<td>1\rangle +</td>
<td>4\rangle$</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>$</td>
<td>1\rangle +</td>
<td>2\rangle$</td>
<td>+1</td>
<td>0</td>
</tr>
</tbody>
</table>

Strong fields can be applied only longitudinally (minimal beam interference)
- Snake necessary
How to polarise Antiprotons?

A surprising method for polarising antiprotons

Th. Walcher$^{1,2,a}$, H. Arenhövel$^1$, K. Aulenbacher$^1$, R. Barday$^1$, and A. Jankowiak$^1$

$^1$ Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
$^2$ Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati (Rome), Italy

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Abstract. We propose a method for polarising antiprotons in a storage ring by means of a polarised positron beam moving parallel to the antiprotons. If the relative velocity is adjusted to $v/c \approx 0.002$ the cross-section for spin-flip is as large as about $2 \cdot 10^{13}$ barn as shown by new QED calculations of the triple spin cross-sections. Two possibilities for providing a positron source with sufficient flux density are presented. A polarised positron beam with a polarisation of 0.70 and a flux density of approximately $1.5 \cdot 10^{10}/(\text{mm}^2\cdot\text{s})$ appears to be feasible by means of a radioactive $^{11}\text{C}$ de-source. A beam of polarised positrons by pair production with circularly polarised laser light and requires the injection into a small storage ring. Such polarised positron beams as well as at high (1 GeV) energy storage rings providing a time of flight of about $10^{10}$ antiprotons to a polarisation of about 0.18. A compact design in the figure of merit by a factor of about ten.

Depolarisation Studies using Unpolarised Electrons

Use electrons in e-cooler as target electrons to observe depolarisation

Typical parameters of COSY Cooler
- Electron Current 240 mA
- Cross section 5 cm$^2$
- Length 2 m
- Nominal Voltage 24.5 kV
- Electron target thickness seen by the p $\sim 10^8$ cm$^{-2}$
Energy Resolution of Protons in Electron Rest System

\[
\frac{\Delta p}{p} \cdot \gamma + 1 \cdot T = \Delta T
\]

to electron rest system

Tp = 65, 45, 30 MeV
Preliminary Results of the Depolarisation Studies

\[ \sigma = -\ln\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right) \]

\[ \Delta t \cdot d_t \cdot f_{\text{rev}} \]

Ratio of polarizations

Proton kinetic energy in electron rest frame / keV

Preliminary
AD Ring at CERN

Study of spin filtering in pbar-p (pbar-d) scattering

- Measurement of effective polarisation cross section
  - Both transverse and longitudinal
- First measurement for spin correlations in pbar-p (and pbar-d)

Target
Snake
E-cooler

T=5-2800 MeV
N_p=3 \cdot 10^7
Beam Polarisation
(Hadronic Interaction: Longitudinal Case)

Measurements at AD lead to final design of APR at FAIR

Model A (phenom. optical pot.):
T. Hippchen et al.,

Model D (hybrid model):
V. Mull, K. Holinde,
World-First: Antiproton Polarizer Ring (APR)

Small Beam Waist at Target
High Flux ABS
→ Dense Target

\[ \beta = 0.2 \text{ m} \]

\[ q = 1.5 \cdot 10^{17} \text{ s}^{-1} \]

\[ T = 100 \text{ K}, \text{ longitudinal } Q \text{ (300 mT)} \]
PAX Accelerator Setup

Antiproton Polarizer Ring (APR) +
Cooler Storage Ring (CSR, COSY-like): 3.5 GeV/c +
HESR: 15 GeV/c → Asymmetric Double-Polarized Antiproton-Proton Collider
Luminosities for Asymmetric Collider

**Evaluation by QCD-PAC (March 2005):**
Explore all options to increase the luminosity to the value of $10^{31} \text{ cm}^{-2}\text{s}^{-1}$

**STI Working Group on FAIR (August 2005):**
STI requests R&D work to be continued on the proposed asymmetric collider experiment with both polarised anti-protons and protons,
- to demonstrate that the required luminosity for decisive measurements can be reached.

### Luminosity Evaluation (3.5 GeV pbars on 15 GeV protons):

<table>
<thead>
<tr>
<th></th>
<th>Bunched</th>
<th></th>
<th>Coasting</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p</td>
<td>pbar</td>
<td>p</td>
<td>pbar</td>
</tr>
<tr>
<td><strong>Smirnov (6/2006)</strong></td>
<td>$2.4 \cdot 10^{12}$</td>
<td>$5 \cdot 10^{11}$</td>
<td>$1 \cdot 10^{13}$</td>
<td>$5 \cdot 10^{11}$</td>
</tr>
<tr>
<td>Luminosity [$10^{31} \text{ cm}^{-2}\text{s}^{-1}$]</td>
<td>0.5</td>
<td></td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td><strong>Shatunov (12/2006)</strong></td>
<td>$7 \cdot 10^{12}$</td>
<td>$1 \cdot 10^{12}$</td>
<td>$7 \cdot 10^{12}$</td>
<td>$1 \cdot 10^{11}$</td>
</tr>
<tr>
<td>Luminosity [$10^{31} \text{ cm}^{-2}\text{s}^{-1}$]</td>
<td>3</td>
<td></td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
PAX Physics

- Transversity
- Electromagnetic Form Factors
- Hard Scattering Effects
- SSA in DY, origin of Sivers function
- Soft Scattering
  - Low-t Physics
  - Total Cross Section
- pp interaction
Transversity distribution of the nucleon:

last leading-twist piece of the QCD description of the partonic structure of the nucleon

\[ q(x) \text{ spin averaged well known} \]

\[ f_1 = \]

\[ \Delta q(x) \text{ helicity known} \]

\[ g_{1L} = \]

\[ \delta q(x) \text{ transversity unknown} \]

\[ h_1 = \]

directly accessible uniquely via the double transverse spin asymmetry \( A_{TT} \) in the Drell-Yan production of lepton pairs

\[
A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\downarrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\downarrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_q^1(x_1, M^2) h_q^\bar{q}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)} \quad q = u, \bar{u}, d, \bar{d}, \ldots
\]

\[
\hat{a}_{TT} = \frac{\sin^2 \phi}{1 + \cos^2 \phi} \times \cos 2\varphi
\]

Spin asymmetry of the QED elementary process

definitive observation of \( h_1^q(x, Q^2) \) of the proton for the valence quarks (\( A_{TT} \) in Drell-Yan >0.2)
Transversity

Properties:
- Probes relativistic nature of quarks
- Does not mix with gluon polarisation
- Different $Q^2$ evolution than $\Delta q$
- Sensitive to valence quark polarization
- Chiral-odd: can’t occur alone, requires another chiral-odd partner

Indirect Measurement: Convolution of with unknown fragment. fct.
Anselmino et al., PLB 594, 97 (2004)

$s \approx 200 \text{GeV}^2$, $\tau = x_1 x_2 = M^2 / s \approx 0.05$

→ Exploration of valence quarks $h_1^q(x, Q^2)$ large

$A_{TT} / a_{TT} > 0.2$

Models predict $|h_1^u| >> |h_1^d|$
Extension of the “safe” region

Determination of $h_1^q(x, Q^2)$ not confined to the “safe” region ($M > 4$ GeV)

$\bar{q}q$ → $J/\Psi$

unknown vector coupling,
but same Lorentz and spinor structure as other two processes

Unknown quantities cancel in the ratios for $A_{TT}$, but helicity structure remains!

Cross section increases by two orders from $M=4$ to $M=3$ GeV

→ Drell-Yan continuum enhances sensitivity of PAX to $A_{TT}$

Anselmino et al. PLB 594, 97 (2004)  
Mikhail Nekipelov

Proton Electromagnetic Form Factors

suggests different charge and magnetization distributions inside nucleon

• factor of 2 between time like and space like FFs
• no direct measurement of $G_E$ existing
Proton Electromagnetic Form Factors

- Measurement of relative phases of magnetic and electric FF in the time-like region
  - Possible only via SSA in the annihilation $\bar{p}p \rightarrow e^+e^-$

- Double-spin asymmetry (most contain moduli of FF)
  - independent $G_E - G_m$ separation

Phase I: PAX at CSR

Physics: Electromagnetic Form Factors
pp elastic scattering

Experiment: polarized/unpolarized p on polarized target

Independent of HESR experiments
Phase II: PAX at CSR

Physics: Transversity

EXPERIMENT: Asymmetric Collider:
- Polarized Antiprotons in HESR (15 GeV/c)
- Polarized Protons in CSR (3.5 GeV/c)

Second IP with minor interference with PANDA
PAX Detector Concept

**Physics:**
- $h_1$ distribution: $\sin^2 \theta$
- EMFF: $\sin 2\theta$
- pp-p elastic: high $|t|$  

**Azimuthal Symmetry:**
- LARGE ANGLES

**Detector:**
- Extremely rare DY signal ($10^{-7}$ p-pbar)
- Maximum Bjorken-x coverage ($M$ interval)
- Excellent PID (hadron/e rejection $\sim 10^4$)
- High mass resolution ($\leq 2\%$)
- Moderate lepton energies (0.5-5 GeV)

**Magnet:**
- no precession of beam polarization
- Compatible with Cerenkov
- Compatible with polarized target

**Azimuthal Symmetry:**
- LARGE ANGLES

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Double Polarisation Experiments → Azimuthal Symmetry

- 800 x 600 mm coils
- 3 x 50 mm section (1450 A/mm²)
- average integrated field: 0.6 Tm
- free acceptance > 80%

Superconducting target field coils do not affect azimuthal acceptance.
PAX Conceptional Detector Design

- Large angular acceptance
- Sensibility to electron pairs
- Toroid magnet

Designed for Collider but compatible with fixed target
Phase 0: 2005-2012
Physics: buildup measurements @ COSY and CERN
APR design and construction.

Phase I: 2013-2017
APR+CSR @ GSI
Physics: EMFF, p–pbar elastic with fixed target

Phase II: 2018 - ...
HESR+CSR asymmetric collider
Physics: $h_1$
Conclusions

Challenging opportunities accessible with polarised pbar’s

- Unique access to a wealth of new fundamental physics observables
- Central physics issue: $h_1^q(x,Q^2)$ of the proton in DY processes
- Other issues:
  - Electromagnetic Form Factors
  - Polarisation effects in Hard and Soft Scattering processes
  - differential cross sections, analysing powers, spin correlation parameters

Staged approach

- Filter Tests Experiments with protons (COSY), and, once hadronic buildup mechanism is verified, antiprotons (CERN) to optimise APR design

Projections for double polarisation experiments:

- $P_{\text{beam}} > 0.20$
- Collider: $L > 1.2 \cdot 10^{31} \text{ cm}^{-2} \text{s}^{-1}$
- Fixed Target: $L \approx 2.7 \cdot 10^{31} \text{ cm}^{-2} \text{s}^{-1}$

Detector concept:

- Large acceptance detector with a toroidal magnet