COSY Summer Student Program 2004

Polarisation Experiments in Storage Rings

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Introduction

Hadronic Probes:
- IUCF-PINTEX:
  - Proton-Proton Elastic
  - NN → NNπ
  - Proton-Deuteron Elastic
- COSY
  - EDDA:
    - Proton-Proton Elastic
    - Time-Reversal Invariance
  - ANKE:
    - Proton-Deuteron Breakup
    - Proton-Neutron Elastic
- WASA:
  - Parity of θ+
- RHIC-SPIN

Electromagnetic Probes:
- Bates-BLAST
- Novosibirsk-VEPP-3
- HERA-HERMES

Past ~15 years, tremendous progress in spin-physics experiments with polarized beams on internal targets

Near future exploitation at COSY

Experimental and theoretical developments pave the way to Future Hadron Physics programs at FAIR
Outline

- Basics
- Medieval Warfare
  - Storage Rings and Internal Targets
- Polarimetry
  - Selected Experimental Results
- Production of Polarized Antiprotons
- Medical Application of Polarized Targets
Basics: Polarization

Spin $s$: $2s+1$ possible orientations along quantization axis $z$
- Spin $\frac{1}{2}$ → 2 orientations
- Spin 1 → 3 orientations

Magnetic quantum number $m=s_z$ (z-component in units of $\hbar$)

Two numbers $N_-$ and $N_+$ fully characterize the beam. Usually linear combinations are used:

**Intensity**
$$I = N_- + N_+$$

**Polarization**
$$P_z = (N_+ - N_-)/(N_+ + N_-)$$
$$-1 \leq P_z \leq +1$$
Three numbers $N_-$, $N_0$ and $N_+$, or linear combinations:

**Intensity**

$$I = N_- + N_0 + N_+$$

**Vector Polarization**

$$P_z = \frac{(N_+ - N_-)}{(N_+ + N_0 + N_-)}$$

$$-1 \leq P_z \leq +1$$

**Tensor Polarization**

$$P_{zz} = \frac{(N_+ - 2 \cdot N_0 + N_-)}{(N_+ + N_0 + N_-)}$$

$$-2 \leq P_{zz} \leq +1$$

**Q:** What is $P_z$ if $P_{zz}=0$?

**A:**

$$-2/3 \leq P_z \leq +2/3$$
Basics: continued

\[
P_{zz} = 0 \rightarrow N_+ - 2 \cdot N_0 = 0
\]
\[
\rightarrow N_+ = 2 \cdot N_0
\]
\[
\rightarrow P_z = \frac{(N_+ - N_-)}{(N_+ + N_0 + N_-)}
\]
\[
= \frac{2 \cdot N_0}{2N_0 + N_0}
\]
\[
= +\frac{2}{3}
\]

(other case analog)
**Basics: A Polarization Experiment**

Example: \( \frac{1}{2}^+ + 0 \rightarrow \frac{1}{2}^+ + 0 \)

Target \( ^4\text{He}, ^{12}\text{C} \)

Experiment measures "asymmetry"

\[ \varepsilon = P_y \cdot A_y = \frac{N_L - N_R}{N_L + N_R} \]

Analyzing Power \( A_y(\theta, E) \)

Beam Polarization

Approximation \( N_L \sim N_R \sim N \)

\[ \Delta A_y = \frac{1}{P \cdot \sqrt{2 \cdot N}} \sim \frac{1}{P \cdot \sqrt{I}} \]

<table>
<thead>
<tr>
<th>( \Delta A_y = 0.1 )</th>
<th>( N(\sim t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P = 1 )</td>
<td>50</td>
</tr>
<tr>
<td>( P = \frac{1}{2} )</td>
<td>200</td>
</tr>
</tbody>
</table>

\[ \rightarrow \text{FOM} = P^2 \cdot I \]
Basics: **Spin-dependence of NN interaction**

Description of Interaction between Nucleons requires spin-orbit term in the NN potential

\[ V_{LS}(r)(\vec{L} \cdot \vec{S}) \]

\[ \vec{L} = \vec{r} \times \vec{p} \]

→ Left-Right Asymmetry \( \perp \) to scattering plane
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Carcassonne

South of France, between Toulouse and the Mediterranean
Carcassonne

Philippe III (the Strong) built the fortress (1270-1285).
Medieval Warfare

Multiple use of a projectile oscillating in a potential well.

Figure from Willy Haeberli Workshop on Polarized Sources and Targets Erlangen, Germany (1999)
Internal Target in a Storage Ring

H, D, etc.
$\tilde{H}, \tilde{D}, ^3\tilde{He}$

Target Beam

orbiting beam of projectiles

Storage Ring: Re-usable Projectiles
Carcassonne application (type 1)
New approach (~15 years) to scattering experiments

\[ L = I_{\text{beam}} \cdot d_t \]

\[ L = N_{\text{stored}} \cdot f_{\text{rev}} \cdot d_t \]
Example: Parity of $\Theta^+$ Pentaquark

Double polarization experiment fixes parity of $\Theta^+$ free of any model!

Spin-correlation coefficient $A_{xx}$ in $\bar{p}p \to \Theta^+\Sigma^+$

**TOF-COSY** with a NH$_3$ polarized target

$\rho_t = 0.93 \text{g/cm}^3 \cdot 0.8 \text{cm}$

= $0.74 \text{g/cm}^2$

= $3.7 \cdot 10^{23} \text{nucl./cm}^2$

$I = 5 \cdot 10^6 \text{s}^{-1}$

$FOM = (3/17 \cdot 0.6)^2 \cdot \rho_t \cdot I$

= $2.1 \cdot 10^{28} \text{cm}^{-2}\text{s}^{-1}$

**WASA-COSY** with a polarized gas target

$\rho_t,\text{Jet} = 10^{12} \text{nucl./cm}^2$

$\rho_t,\text{Cell} = 5 \cdot 10^{13} \text{nucl./cm}^2$

$I = 5 \cdot 10^{10} \cdot 1.6 \cdot 10^6 \text{s}^{-1}$

$FOM_{\text{Jet}} = (0.8)^2 \cdot \rho_t,\text{Jet} \cdot I$

= $5 \cdot 10^{28} \text{cm}^{-2}\text{s}^{-1}$

$FOM_{\text{Cell}} = 2.5 \cdot 10^{30} \text{cm}^{-2}\text{s}^{-1}$

3-120 x shorter measurement time
Polarized Storage Cell Target

After wall collisions, atoms can intercept beam again.

Cell Target: Re-usable target atoms
Carcassonne application (type 2)
Principle of a polarized internal target

Interaction Region

<table>
<thead>
<tr>
<th>Type</th>
<th>Distance</th>
<th>State</th>
<th>Density</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>point-like</td>
<td>5-10 mm</td>
<td>free jet</td>
<td>low density</td>
<td>$10^{12}$ cm$^{-2}$</td>
</tr>
<tr>
<td>extended</td>
<td>200-500 mm</td>
<td>storage cell</td>
<td>high density</td>
<td>$10^{14}$ cm$^{-2}$</td>
</tr>
</tbody>
</table>
**Principle of a polarized internal target**

Distinct advantages over solid or high pressure targets:

- **rapid reversal** of target spin ($x,y,z$): In H/D up to 100 Hz achieved
- **isotopically pure**, no contamination by unpolarized components in the target
- **low background** due to absence of container walls
- **no radiation damage**, target gas replenished every few ms
  \[\Rightarrow \text{Ideally suited for high precision experiments}\]
Four main types of sources for PITs

1. Atomic beam source

Atoms with $m_j = +\frac{1}{2}$ focused in sextupole magnets. RF transitions select HFS.

2. Ultra-cold source

$W_{\text{thermal}} \ll W_{\text{magnetic}}$

One electron spin state $m_j = \frac{1}{2}$ extracted from strong solenoid field and focused.
Main types of sources (cont’d)

3 Spin-Exchange source

\[ \overset{\uparrow}{K} + D \xrightarrow{\text{spin-exchange}} \overset{\uparrow}{K} + D \]

Deuterium or Hydrogen atoms polarized by spin-exchange with optically pumped potassium vapor

4 $^3$He source

\[ \overset{\uparrow}{^3\text{He}(2^3S_1)} \xrightarrow{\text{metastable exchange collisions}} \overset{\uparrow}{^3\text{He}(\text{g.s.})} \]

Small fraction of metastable $^3$He ($2^3S_1$) atoms pumped with laser optical pumping. Ground state atoms polarized via exchange collisions
Stern-Gerlach Experiment (1922)

- Beam of Silver atoms
- Aperture
- Electromagnet
- Glass plate
- Magnetic field with gradient \( \frac{dB}{dz} \neq 0 \)

Intensity
- Magnet on
- Magnet off
Spin-Selection

Deflection through interaction between magnetic field and magnetic dipole moment of silver atoms.

potential Energy

\[ U = -\vec{\mu} \cdot \vec{B} = -\mu_z B \]

Force

\[ F_z = -\frac{dU}{dz} = u_z \frac{dB}{dz} \]

classically: Smearing of atoms over area

Silver atoms possess same dipole moment, as single electron, \( \Rightarrow \) one component \( m_s=+\frac{1}{2} (\uparrow) \)

other one \( m_s=-\frac{1}{2} (\downarrow) \).
Erlangen (Birthplace of polarized Sources)

Selection of H-Atoms, in the gradient field of a Quadrupol

Fig. 2. Technische Ausführung des magnetischen Vierpolfeldes. 
N, S Polschübe; W Wicklungen; Sr Segmente zur vakuumdichten Begrenzung des Strahlraumes; d = 4 mm; E Eisenjoche

$B \propto r \Rightarrow F = \text{const.}$
Hyperfine Transitions (1-3) or (2-4) enable to make beams of ONE state only.

\[ \Delta W = h \cdot 1420.4 \text{ MHz} \ (5.9 \cdot 10^{-6} \text{ eV}) \]

\[ B_c = 50.7 \text{ mT} \]

"Target holding field"
Modern Sources

Use of Permanent-Sextupoles (VAC):
\[ B \sim r^2 \Rightarrow F \sim r \]

One quadrant

\[ I = 7.5 \times 10^{16} \text{ H/s} \]
Exact calculations

Progress since 1956
~ $10^6$ more Flux of atoms
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Polarimetry of PIT’s

Three different approaches are distinguished:

I. Calibration by a known reaction
   • FILTEX test (αp scattering)
   • pp elastic scattering (PINTEX at IUCF)

II. Ion extraction
    • NIKHEF Ion extraction polarimeter

III. Neutral gas extraction
     • Breit-Rabi Polarimeter for HERMES
     • Lamb-shift Polarimeter for ANKE

Method I does not distinguish atoms from molecules or any other material in the target ⇒ 1st choice where applicable

Methods II and III measure the polarization of atoms in the target, with additional instrumentation also the degree of dissociation in the target
   but: Molecules dilute the polarization!
   and: What is the polarization of the molecules? (ISTC Project)
Ex. 1: $\alpha p$ scattering at 27 MeV
**FILTEX Results**

- **Sept. 2, 1992**
  - $P = 0.80 \pm 0.02$
  - $d_t = (5.4 \pm 0.3) \times 10^{13}$ 1/cm$^2$
  - No radiation damage of the wall coating

- **Oct. 1, 1992**
  - $P = 0.79 \pm 0.02$
  - $d_t = (5.4 \pm 0.3) \times 10^{13}$ 1/cm$^2$

$T_{\text{opt}} = 125$ K
Ex. 2: PINTEX pp elastic scattering (IUCF)

Beam Intensity: $2 \text{ HFS } 6.7 \cdot 10^{16} \text{ H/s}$
Polarization: $P_{\text{max}} = 0.87$
Conservation of Polarization in a Storage Ring

T = 200-450 MeV

Indiana Cooler

H.O. Meyer et al., PRE 56, 3578 (1997)
Frank Rathmann  

**Target Polarization vs time and vs z**

\[ Q = \frac{1}{2} (Q_x + Q_y) \]

⇒ no radiation damage!

no change of Q along cell  
⇒ Prob\(_{\text{depol/bounce}}\) = 1/5000

with \( I_{\text{beam}} = 100 - 400 \ \mu A \)  
⇒ \( L = 5 \cdot 10^{28} \ \text{cm}^{-2}\text{s}^{-1} \)
Relativ statistical error
of the normalization

$\delta k/k$ (%)

0.31
1.08
0.89
1.17
1.01
1.03
0.86
1.00
Ex. 3: NIKHEF Ion-extraction polarimeter

Principle based on Price & Haeberli

Measurement of Tensorpolarization via \(^3\text{H}(d,n)^4\text{He}\)

Frank Rathmann
Polarisation Experiments in Storage Rings
**Ex. 3: NIKHEF Ion-extraction polarimeter**

Ionization in AmPS via stored $e^-$: $\sigma(1 \text{ keV})/\sigma(565 \text{ keV}) \sim 1/50$


PolarizedIon Measurement with a prototype

$-0.89^{+0.03}_{-0.05} \text{ stat.} < P_{zz} < 0.49^{+0.01}_{-0.03} \text{ syst.}$
Ex. 4: HERMES Breit-Rabi Polarimeter

Determination of Hyperfine state population numbers by
• RF transitions
• sextupole magnet system
Polarized Internal Target for ANKE

Atomic Beam Source

Lamb-Shift Polarimeter

3 magnets form a schikane
• Spectrometer magnet D2 moves transversly
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Polarization Buildup: General Features I

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

**P beam polarization**

**Q target polarization**

**k \parallel beam direction**

For initially equally populated spin states: \( \uparrow (m=+\frac{1}{2}) \) and \( \downarrow (m=-\frac{1}{2}) \)

**transverse case:**

\[ \sigma_{\text{tot} \pm} = \sigma_0 \pm \sigma_\perp \cdot Q \]

**longitudinal case:**

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

\[ \tau_{\text{beam}} = \frac{1}{(\sigma_0 + \Delta \sigma_c) \cdot d_t \cdot f_{\text{rev}}} \]

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

\[ I_+ (t) = \frac{I_0}{2} \cdot e^{- \frac{t}{\tau_{\text{beam}}}} \cdot e^{- \frac{t}{\tau_{\text{pol}}}} \]

\[ I_- (t) = \frac{I_0}{2} \cdot e^{- \frac{t}{\tau_{\text{beam}}}} \cdot e^{\frac{t}{\tau_{\text{pol}}}} \]

**Time dependence of P, I, and FOM**

\[ P(t) = \frac{I_+ - I_-}{I_+ + I_-} = -\tanh \left( \frac{t}{\tau_{\text{pol}}} \right) \]

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

\[ \text{FOM}(t) = P(t)^2 \cdot I(t) \]
Polarization Buildup: General Features II

Statistical error of a double polarization observable ($A_{TT}$)

$$\delta_{A_{TT}} = \frac{1}{P \cdot Q \cdot \sqrt{N}}$$

Measuring time $t$ to achieve a certain error $\delta_{A_{TT}}$

$$t \sim \text{FO}M = P^2 \cdot I$$

Optimum time for Polarization Buildup given by maximum of FOM($t$)

$$t_{\text{filter}} = 2 \cdot T_{\text{beam}}$$
**1992 Filter Test at TSR with protons**

**Experimental Setup**

- **Beams**: Up, Down, Left, Right
- **Components**: Dissociator, Beam Formation, Sextupole, HF-Transition
- **Target Area**: $p, \alpha$
- **Beam Path**: Circulating Beam, Storage Cell

**Results**

- **Excitation**: T=23 MeV
- **Graph** showing polarization vs. asymmetry for filter time [min]

**Low energy pp scattering**

$\sigma_1 < 0 \Rightarrow \sigma_{tot+} < \sigma_{tot-}$

**Expectation Table**

<table>
<thead>
<tr>
<th>Target</th>
<th>Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>↓</td>
<td>↓</td>
</tr>
</tbody>
</table>

Experimental Setup at TSR (1992)
Beam Polarization in a dedicated Antiproton Polarizer

Polarisation buildup through spin transfer

\[
\bar{p} + e^- \rightarrow \bar{p} + e^+
\]

Horowitz & Meyer, PRL 72, 3981 (1994)

\begin{center}
\textbf{PAX} will exploit spin-transfer to polarize antiprotons and to do Spin-Physics at the HESR
\end{center}
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Polarized $^3$He for NMR's of the human lung (Werner Heil)

Spin-Off of Polarized Gas Target Technology

Human Lung with 0.7 bar\times liter of polarized $^3$He

$P_H \sim \mu \cdot B / kT$

$\sim 5 \cdot 10^{-6}$

$P_{He} \sim 1$

$\rho_H / \rho_{He} \sim 2500$

signal $P \cdot \mu \cdot \rho$

$S / S_H > 10$

amount of gas:

1 bar \cdot liter

Proton - MRI (1 H)  Helium - MRI ($^3$He)

DKFZ, HD Nov. 1995; Lancet 1996
Transport time:
Mainz-Sheffield: 10 h
Mainz-Copenhagen: < 7 h
Mainz-Orsay (Paris): 8 h
T₁ ~ 160 h
Funktionelle NMR mit $^3$He
Final Remark

In 1981 Rudolf Fleischmann (1903-2002)
• Professor of Physics in Erlangen
• “originator” of the first polarized atomic beam source (1956)
asked himself at a conference, why progress in physics sometimes was so slow and took so many roundabouts.

“It seems to me that the main reason is that too much confidence is put in theoretical, and therefore quite hypothetical concepts and models, which are popular during the corresponding period and that it is very difficult to free oneself from them.”

from D. Fick, Talk held on 5.5 2003 in the Physics Colloquium at University of Erlangen