Review of Polarized Targets

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1. Introduction
2. Polarized Solid Targets
3. Polarized Gas Targets
4. Examples (COMPASS, HERMES, PAX)
5. Outlook
1. INTRODUCTION

Two-body reaction: \( a + b \rightarrow c + d \)

- **Aim**: Study of the Spin dependence of Scattering Processes
- **Method**: Measure scattering rates for different spin populations in the entrance and/or exit channel. Many combinations possible, e.g. beam polarized, target unpolarized, no polarization measurement in the exit channel (Observable: Analyzing Power \( A_y \) or \( T_{10} \), for \( s = 1 \) also \( A_{yy} \) or \( T_{20} \), etc. Formalism: see famous article by Léhar and Winternitz, ....)
- **Target is at rest** (alternative: colliding beams). Beams could be
  - **extracted** from a Cyclotron, Synchrotron, Linac, or
  - **circulating** in a Storage Ring!
- **Two practical cases**: -- **extracted beam** of relatively low intensity, combined with a polarized **solid target** (@ about 1 K), or
  -- **stored beam** of high intensity with a polarized **gas target**.
1. Introduction

- Beam vertically polarized with $P_y = (N_+ - N_-)/(N_+ + N_-)$, target unpolarized, no polarization measurement in exit channel
  
  Left-Right asymmetry

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

- Same, but $P_y = \pm P$ (polarization switchable!)
  
  Count-rate asymmetry

  \[ \varepsilon_L = \frac{N_L + N_R - N_L}{N_L + + N_L} = P \cdot A_y \]

  \[ \varepsilon_R = \frac{N_R + N_R - N_R}{N_R + + N_R} = -P \cdot A_y \]

Scattering normal $\mathbf{n}$

\[ \mathbf{n} = \frac{\mathbf{k}_i \times \mathbf{k}_f}{|\mathbf{k}_i \times \mathbf{k}_f|} \]

Observable: vector analyzing power

Need to know polarization!
1. Introduction

This was the simplest case (Single Spin measurement). Similar: target polarized, or detection of polarization of the ‘ejectile’.

More elaborate: Two Spin measurements, e.g. beam and target polarized.

Availability of polarized beams and/or targets depends on the required effort; examples:

- **Beams** from polarized source have to be accelerated to the final energy. Low energy accelerators (e.g. electrostatic machines, small linacs) are polarization-transparent; acceleration no problem! But high-energy (circular) machines suffer from resonant depolarization – needs to be suppressed by means of very elaborate methods!

- **Dense solid targets** are polarized at high B (few Tesla) and low T (1 K or below). Require a big effort, e.g. LHe, superconducting magnets, sometimes a dilution refrigerator!

The first polarization data in High Energy physics were taken with polarized (DNP) proton target and unpolarized proton beam.
2. Polarized Solid Targets

Most targets are based on Dynamical Nuclear Polarization (DNP), - Jeffries, Abragam, Borghini 1963/64.

Consider system of unpaired electrons (‘paramagnetic centers’) in a solid, strongly coupled to the lattice of temperature T, in a magnetic field B.

The electron polarization is defined as

\[ P_e = \frac{n_+ - n_-}{n_+ + n_-} \]

with \( N^\pm \) the population of states parallel and anti-parallel to B.

Note that \( \mu_e \) and \( s_e \) are anti-parallel for a negatively charged particle.

\[ n_\pm = n_0 \cdot \exp(\mp \mu_B B / kT) \quad \text{(Boltzmann statistics)} \]

\[ P_e = \frac{n_+ - n_-}{n_+ + n_-} = \frac{\exp(-x) - \exp x}{\exp x + \exp(-x)} = \tanh(-x) = \tanh(-\mu_B B / kT) \]

\( P_e \leq 0 \) in thermal equilibrium!
2. Polarized Solid Targets

• Brute Force Polarization calculated

\[ |P_e| = \tanh(\mu_B B / kT) \quad \text{with} \quad \mu_B = 5.8 \times 10^{-5} \text{ eV/T} \quad \text{and} \quad k = 8.6 \times 10^{-5} \text{ eV/K} \]

Assume \( B = 2.5 \text{ T} \) and \( T = 1 \text{ K} \)

\[ \rightarrow P_e = 0.93 \text{ in thermal equilibrium!} \]

Compare with protons by inserting \( \mu_p / \mu_e = 1.52 \times 10^{-3} \)

\[ \rightarrow P_p = 0.026 \quad \frown \quad \text{not the right way to polarize protons!} \]

• Consider coupled system

Electrons \quad \text{and} \quad \text{Protons}

paramagn. centers \quad \text{isolated spin system}

strongly coupled to lattice \quad \text{weakly coupled}

• allowed ESR resonances \( W_1 \) and \( W_4 \)

at \( v_e \approx 2 \mu_B B / h \)

• forbidden double-flip transitions \( W_2 \) and \( W_3 \) \text{ at slightly different } \mu W \text{ frequency.}
2. Polarized Solid Targets

• We had: Forbidden double-flip transitions $W_2$ and $W_3$ at slightly different $\mu W$ frequency which are weaker by factor $\sigma$

$$\sigma = \left[\text{dipole-dipole energy/nucl. Zeeman energy}\right]^2 \approx 3/10 \cdot \left(g_e \mu_B / B\right)^2 \cdot r^6$$

with $r =$ average distance protons to paramagnetic centers

• In thermal equilibrium (2.5 T, 1 K) levels 3 and 4 are strongly populated. Assume that $W_3$ is saturated, i.e. levels 2 and 3 equally populated!

→ Strong spin-lattice relaxation drives electron spin flips, by ep coupling simultaneous proton spin flips are induced and build-up of proton polarization!

• Protons are polarized close to pm centers, and their polarization is distributed within the crystal via spin diffusion. Led to the picture of ‘King Salomo and his 700 princesses’, invented by A. Abragam.
2. Polarized Solid Targets

A. Abragam*, in Proceed. Int. Conf. on Polarized Targets and Ion Sources, Saclay 1966

*) Author of ‘The Principles of Nuclear Magnetism’, Lorentz medal 1982
2. Polarized Solid Targets

Target material, e.g. frozen NH$_3$ beads, immersed in LHe and surrounded by NMR coil and µW cavity.

![ESR System diagram]

**Typical parameters**

Detection of polarization (p: 106 MHz)

$\nu_e \pm \nu_p \approx 70$ GHz

$T \leq 0.5$ K

<table>
<thead>
<tr>
<th>Material</th>
<th>Polarizable fraction</th>
<th>Doping agent</th>
<th>$P_{\text{max}}$</th>
<th>$P_{\text{ave}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_4$H$_9$OH</td>
<td>13.5%</td>
<td>POR</td>
<td>0.80</td>
<td>0.11</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>17.6%</td>
<td>Irradiation</td>
<td>0.92</td>
<td>0.16</td>
</tr>
<tr>
<td>$^6$LiD</td>
<td>$\leq 50%$</td>
<td>“”</td>
<td>0.70?</td>
<td>0.35?</td>
</tr>
</tbody>
</table>
2. Polarized Solid Targets

• Dynamically polarized Solid Targets are workhorses in Spin Physics. They provide high target densities (typ. $10^{22}$/cm$^2$) and high proton or deuteron polarization. Less favorable are dilution by unpolarized nuclei, like N in NH$_3$, and by the coolant, the limited heat input by the beam, and the strong target holding field (→ frozen spin targets).

• New developments are
  - brute-force polarized HD target (‘pure’)
  - polarizable plastic scintillator material at room temperature

• The most elaborate polarized solid target to date: EMC/NMC/COMPASS target in a polarized muon beam at CERN – two target volumes (one split), 60 cm long each, with opposite (longitudinal) polarization! see COMPASS target
3. Polarized Gas Targets

Advantages of pol. gas targets:

• can be used with high beam current typical for Storage Rings
• high average polarization, low dilution
• rapid spin reversal for low systematic error

But: limited areal density (up to $\approx 10^{14}/\text{cm}^2\text{s}$, for $^3\text{He}$ $10^{15}$)

Several methods:

• polarized atomic beam by Stern-Gerlach separation (H, D)
• direct optical pumping ($^3\text{He}$)
• spin-exchange optical pumping
3. Polarized Gas Targets

Polarized atomic beam by Stern-Gerlach separation (H, D)

Slides by W. Haeberli

The Hydrogen atom

\[ J = \frac{1}{2}, \quad I = \frac{1}{2} \]

\[ \rightarrow F = 0, 1 \]

Critical field \( B_c \) for hydrogen is about 50 mT

- \( B \ll B_c \): weak field
  - \( J, I \) coupled to \( F \)
- \( B \gg B_c \): strong field
  - \( J, I \) decoupled

\[ \varepsilon \text{ (V/\text{cm})} = 42 \text{ (h} \text{/nA) JM} \]

\[ P = +1 \text{ in strong B-field} \]

\[ P = -1 \text{ in weak B-field} \]
Polarized atomic beam by Stern-Gerlach separation (H, D)

AtOMIC Beam Source (ABS)

Great increase in intensity by use of multipole field, suggested by Wolfgang Paul, Bonn 1951-(Nobel 1989).

Spin-up is focussed, spin-down defocussed

Development of atomic-beam sources in Europe starting in Erlangen (1958).
Atomic-beam improvements
From 1 to $10 \times 10^{16}$ atoms/s in 40 years

- cool beam
- sextupoles: rare-earth permanent magnets
- reduced gas scattering
- achromatic beam transport
- multidimensional search for optimum

Magnet for RHIC polaried H-jet target (T. Wise et al.) $\Rightarrow 12 \times 10^{16}$ atoms/s.
Polarized atomic beam by Stern-Gerlach separation (H, D)

Atomic-beam improvements
From 1 to $10 \times 10^{16}$ atoms/s in 40 years

- cool beam
- sextupoles: rare-earth permanent magnets
- reduced gas scattering
- achromatic beam transport
- multidimensional search for optimum

permanent magnet
sextupole - 1.7 T
gradient 5.7 T/cm
3. Polarized Gas Targets

**Target Densities:** relevant for the experiment is the Areal Density $t \ [\text{atoms/cm}^2]$

For a Luminosity of $1 \cdot 10^{31}/\text{cm}^2\text{s}$ and a beam current of $10 \ \text{mA} \ (6 \cdot 10^{16} / \text{s})$, a density of $t = 1.6 \cdot 10^{14} / \text{cm}^2$ is required!

Not sufficient $\rightarrow$ Recycle, don’t waste!

Idea (W. Haeberli 1965): to use a storage cell/bulb with coated walls in order to accumulate polarized atoms! Similar to Teflon-coated storage bulb of hydrogen maser (N. Ramsey et al.)
3. Polarized Gas Targets

"Storage Cell"

Beam tube

10 cm
feed tube

3 x 10^{16} \text{ H}^\uparrow/s

target thickness $10^{13}$ \text{ H}^\uparrow/cm^2
(100-times better than jet!)
3. Polarized Gas Targets

Storage Cell

expected target thickness $10^{13}$ H$\uparrow$/cm$^2$
(100-times better than jet!)
First test of the storage cell at a storage ring (TSR Heidelberg 1991/92)

Target test setup for 33 MeV $\alpha$ beam (MP-Tandem)

Participants of the Target Workshop - Heidelberg 1991
FILTEX target at the TSR

Target installed at TSR (1992)
FILTEX target at the TSR

Asymmetry with stored $\alpha$ beam

Target polarization $P = 0.8$ (single substate) at 100 K
FILTEX target at the TSR

Diagram:

- Dissociator
- Slit
- Sextupole magnet (polarizer)
- Holding field
- B
- Coasting beam
- Storage cell (thin-walled)
- Detector

Graphs:

- Target Density [10^19 H/cm^2]
- Cell Temperature [K]
- Polarization
- Cell Temperature [K]
3. Polarized Gas Targets

• Method with ABS and (cooled) Storage Cell are very successful for H (proton) and D (deuteron). Such targets were operational at TSR (Heidelberg) – test set-up only, at the IUCF Cooler (Bloomington) and at HERA (DESY, Hamburg), and still operational in the ANKE experiment at COSY (FZ Jülich). Future projects are PAX (FZJ) at FAIR (Darmstadt) with tests on Spin Filtering at COSY and AD (CERN, Geneva).

• Spin exchange between Alkali vapor, polarized by OP, and $^3$He has been successfully developed for high-pressure $^3$He target cells for electron scattering experiments at SLAC (e.g. E142). Attempts to polarize $^1$H or $^2$D in this way were unsuccessful.

• Direct OP of hydrogen requires intense UV laser light – not existing. But for $^3$He direct OP of atoms in exited (metastable) states is possible, followed by metastability-exchange collisions. – Polarized $^3$He can even be compressed mechanically to 1 bar and more. Polarized $^3$He is applied as Neutron Spin Filter (for thermal neutrons), and for MR tomography of the lung.
4. Examples

COMPASS (CERN)

- Internal structure of the Nucleon measured in muon scattering
- Muon beam 160 GeV/c momentum, from decay in-flight of pions, 80% longitudinal polarization
- Polarized NH$_3$ or $^6$LiD target (DNP, Frozen Spin)

- 60 m long, two-stage magnetic spectrometer for muons and leading hadrons
4. Examples

COMPASS (CERN)

• New COMPASS target with improved acceptance for the detector
• Target material arranged in three sections 1 – 3 (1/4 , 1/2 , 1/4 in length) with spin alternating parallel or anti-parallel to the momentum →
• Target material irradiated at liquid-nitrogen temperature by 20 MeV electrons in order to generate free radicals as paramagnetic centers
Frozen Spin Mode:
- Polarizing at $B = 2.5$ T with 70 GHz $\mu$W radiation at 100 – 300 mK (90% proton polarization in 36 h)
- Powerful Dilution Refrigerator required (400 mW at 300 mK)
- Measuring with muons at reduced B-field. At $T \leq 0.1$ K and in 1 Tesla field, proton spin relaxation is very low: less than 1% polarization loss per day!
4. Examples: HERMES

- Superconducting 920 GeV proton ring (> 100 mA)
- 30 GeV longitudinally polarized electrons or positrons (ca. 45 mA max.)
- Pre-accelerator chain DESY-II/III and Petra
4. Examples: HERMES

Polarized lepton scattering as a tool to measure quark polarization

• Assume electrons with longitudinal polarization or helicity $h = +1/2$
• Electrons emit virtual photons $\gamma^*$ with $h = +1$ and flip to $h' = -1/2$
• Virtual photons $\gamma^*$ can only be absorbed by quarks with $h = -1/2$, which have to flip to $h' = +1/2$
• In total: electrons with helicity $+', scatter from quarks with helicity $', only!
• The scattering rate $N_+$ with electron helicity $+', is proportional to the number of quarks with $', helicity, and vice versa.
• The ratio $\frac{N_+ - N_-}{N_+ + N_-}$ is proportional to the quark polarization!

Nucleon target polarized $\rightarrow$ Quark polarization w.r. to Nucleon spin!
Open Questions for HERMES Target
...after tests at the TSR storage ring in 1992...

1988 – 93 Study of target-related problems

- Target polarimetry
- Wake-Field heating of cell
- Buch-Field depolarization
- Effect of Synchrotron Radiation
- Optimum coating for target cell in HE electron storage ring –
  (with ANL, Madison, Novosibirsk)
The H & D Polarized Target

• Polarized atomic H or D beam injected from Atomic Beam Source (ABS)
• Storage cell with Drifilm coating in longitudinal guide field of ca. 330mT at about 100K
• Sample beam extracted by tube
• Analyzed by TGA w.r.t. atomic fraction $\alpha$
• Analyzed by BRP (~ inverted ABS) w.r.t. nuclear and electron polarization
4. Examples: HERMES

1996: H&D Target Installed
The Secret Trick: Water light/heavy

Deuterium
Top: atomic fraction $\alpha$
Bottom: electron polarization $P_e$
Both as function of cell temperature
Very sensitive indicator for quality of the wall!

- Excellent initial performance
- Improved with aging thanks to D$_2$O coverage
- High-quality layer took couple of weeks: stable target operation mandatory!
Performance of the Deuterium Target in 2000

Vector polarization $P_z$

Tensor polarization $P_{zz}$
Spin-dependent loss: Spin-filtering

Polarization build-up of an initially unpolarized particle beam by repeated passage through a polarized hydrogen target in a storage ring:
4. Examples: **PAX (FAIR)**

**Experimental Setup**

- Target chamber: Detector system + storage cell
- Atomic Beam Source
- Six additional quadrupoles
- Breit-Rabi Polarimeter
Atomic Beam Source and Polarimeter

ABS

Target chamber

Electric power

Cooling water

COSY/AD beam axis

Breit-Rabi polarimeter

E. Steffens

PAX Experiment
4. Examples: **PAX (FAIR)**

Atomic Beam Source and Polarimeter
4. Examples: PAX (FAIR)

Target chamber, cell and detector system

- Atomic beam
- Guide field coils (x, y, z)
- Movable flow limiter
- Stored beam
- Silicon strip detectors
- Storage cell: jet density $\times 100$
AD beam envelope at injection requires openable storage cell

Openable

PAX (FAIR)

P. Belochitsky - CERN

4. Examples: PAX Experiment

opened

closed
5. Outlook

Polarized targets have greatly contributed to our knowledge in Nuclear and Particle physics. Progress is always connected to new challenges from novel experimental questions. Here are some ideas on how these challenges might look like:

• Protons in solid material (= frozen liquid) polarized by DNP. The substance is instantaneously warmed up, dissolved and injected into living bodies for MRI studies: new diagnostic tool! (already working)

• Production of more intense atomic hydrogen beams for Stern-Gerlach separation in an ABS: one order of magnitude more? Note that progress on this key quantity was low (10x in 40 years). Brilliant ideas required!
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• How would a polarized H gas target for one of the LHC detectors look like? How would one feed a storage cell on the axis of the LHC? Same question for the PANDA detector (FAIR).

Thank you - I hope that you found some of the problems interesting!
5. Outlook
H&D Target: Test Set-up at JADE Hall (1995)

- First test of complete target set-up (ABS, BRP, diagnostic chamber)
- Preparations for installation