Introduction to Solid Polarized Targets
for Nuclear and Particle Physics

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JLab Target Group
Spin is an intrinsic property of all elementary particles

*(pay no attention to the higgs)*

### The basics

As well as many composite particles

*(baryons, mesons, nuclei, atoms...)*

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**Standard Model of Elementary Particles**

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
<th>Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>u, c, t</td>
<td>e, μ, τ</td>
<td>W, Z</td>
</tr>
<tr>
<td>d, s, b</td>
<td>νe, νμ, ντ</td>
<td>Higgs</td>
</tr>
</tbody>
</table>

**Gauge Bosons**

- W
- Z

**Scalar Bosons**

- Higgs

**Spin**

- 0: Scalar Bosons
- 1/2: Quarks and Leptons
- 1: Gluons
- 2: Photons

**Masses**

- u, c, t, d, s, b, e, μ, τ, νe, νμ, ντ
- W, Z
- Higgs

**Additional Note:**

- Other component particles, such as mesons and nuclei, also possess spin as an intrinsic property.
The basics

A polarized target is a collection of nuclei (solid or gas) used for a scattering experiment in which *most the nuclear spins point in the same direction*
**Uses for polarized targets**

- Spin structure of hadrons
- Sum rules
- Form Factors
- Baryon spectroscopy
- Transverse momentum distributions
- Generalized parton distributions
- Polarized PDFs

| Hall A | (E12-11-108) SIDIS with a transversely polarized proton target  
(E12-11-108A) Target single spin asymmetries using SoLID spectrometer |
| --- | --- |

| Hall B | (E12-06-109) Longitudinal spin structure of the nucleon  
(E12-06-119) DVCS with CLAS at 12 GeV  
(E12-07-107) Spin-orbit correlations with a longitudinally polarized target  
(E12-09-009) Spin-orbit correlations in kaon electroproduction in DIS  
(E12-14-001) EMC effect in spin structure functions ($^6$LiH & $^7$LiD)  
(E12-15-004) DVCS on the neutron with a longitudinally polarized target  
(C12-11-111) SIDIS on a transversely polarized target  
(C12-12-009) Dihadron production in SIDIS on a transversely polarized target  
(C12-12-010) DVCS on a transversely polarized target in CLAS12 |
| --- | --- |

| Hall C | (E12-14-006) Helicity correlations in wide-angle Compton scattering  
(C12-13-011) The deuteron tensor structure function $b_1$  
(C12-15-005) Meas. of quasi-elastic and elastic deuteron tensor asymm.  
(LOI-12-14-001) Search for exotic gluonic states in the nucleus |
| --- | --- |

<table>
<thead>
<tr>
<th>Hall D</th>
<th>(LOI-12-15-001) Physics opportunities with a secondary $K^0_L$ beam</th>
</tr>
</thead>
</table>
Polarization

The terms *polarization* and *orientation* are used to describe the distribution of a system of spins amongst their \((2I+1)\) magnetic substates.

Orientation parameters \(P_{ij}\) are defined in terms of expectation values of irreducible spin tensors \(I_{ij}\) which act as the basis set for the ensemble’s density matrix. The magnitude of the spin determines how many \(P_{ij}\) are required to describe the ensemble.

Vector polarization

\[
P_z \equiv \frac{\langle I_z \rangle}{I}
\]

Tensor polarization or *alignment*

\[
P_{zz} \equiv \frac{\langle 3I_{zz}^2 - I(I + 1) \rangle}{I^2}
\]
Today we're only going to talk about spin-1/2 systems...

**Spin-\(1/2\)**

\[
P_z = \frac{N_+ - N_-}{N_+ + N_-}
\]

\[
P_{zz} = 0
\]

**Spin-1**

\[
P_z = \frac{N_+ - N_-}{N_+ + N_0 + N_-}
\]

\[
P_{zz} = 1 - \frac{3N_0}{N_+ + N_0 + N_-}
\]
Brute force polarization

The simplest method to polarize the spins is to use the Zeeman Effect and leverage the interaction between the magnetic field and the nuclei’s magnetic moment, $\vec{\mu} \cdot \vec{B}$.

The Zeeman interaction tends to orient (polarize) the magnet moments. Oscillating EM fields produced by atomic vibrations (phonons) tends to randomize (de-polarize) the magnetic moments. Characterized by lattice thermal energy $kT$.

Eventually an equilibrium state is reached – thermal equilibrium (TE) polarization.
Brute force polarization

At equilibrium the populations of the Zeeman levels will obey a Boltzmann distribution.

\[ \frac{N(\uparrow)}{N(\downarrow)} = \exp \left[ \frac{-2 \mu B}{kT} \right] \]

\[ P_{te} = \frac{[N(\uparrow) - N(\downarrow)]}{[N(\uparrow) + N(\downarrow)]} = \tanh \left( \frac{\mu B}{kT} \right) \]

\( T = \text{temperature} \)

Thermal equilibrium polarization, spin \( \frac{1}{2} \)

The polarization will approach thermal equilibrium with a \( 1/e \) time constant called \( t_1 \), the spin-lattice relaxation time.

\[ P(t) = P_{te} \left[ 1 - e^{-t/t_1} \right] \]

\( t_1 \) depends on the temperature and the magnetic field. Nuclear \( t_1 \) can be VERY LONG. It’s usually determined by paramagnetic impurities.
Brute force polarization

\[ P = \tanh \left( \frac{\vec{\mu} \cdot \vec{B}}{kT} \right) \rightarrow \text{maximize } B \]
\[ \quad \text{minimize } T \]

Advantages:
- Works for almost any material
- Easy to explain

Disadvantages:
- Requires very large magnet
- Low temperatures mean low luminosity
- Polarization can take a very long time

Notice that it’s much easier to polarize electrons!! \( \mu_e \approx 1000 \mu_p \)
Dynamic nuclear polarization

For best results, DNP is performed at $B/T$ conditions where the electron $t_1$ is short (ms) and the nuclear $t_1$ is long (minutes or hours).

At 2.5 tesla and 1 kelvin, $t_{1p}$ is almost $10^5$ times longer than $t_{1e}$!!
Dynamic nuclear polarization

- Implant target material with paramagnetic impurities \( \sim 10^{19} \) e\textsuperscript{-} spins/cc
- Polarize the electrons in the radicals via brute force
- Use microwaves to “transfer” this polarization to nuclei

The dipole-dipole interaction between the electrons and nearby nuclear spins permits transitions in which both spins flip.

\[
\mathcal{H}_{SI} = \hbar^2 \left( \frac{\mu_0}{4\pi} \right) \gamma_S \gamma_I \left[ \frac{\hat{S} \cdot \hat{I}}{r^3} - \frac{3(\hat{S} \cdot \hat{r})(\hat{I} \cdot \hat{r})}{r^5} \right] \\
= \hbar^2 \left( \frac{\mu_0}{4\pi} \right) \gamma_S \gamma_I \frac{1}{r^3} (A + B + C + D + E + F)
\]

\[
A = (1 - 3 \cos^2 \theta) S_z I_z \\
B = -\frac{1}{4} (1 - 3 \cos^2 \theta) (S_+ I_- + S_- I_+) \\
C = -\frac{3}{2} \sin \theta \cos \theta e^{i\phi} (S_+ I_z + S_z I_+ ) \\
D = -\frac{3}{2} \sin \theta \cos \theta e^{i\phi} (S_- I_z + S_z I_- ) \\
E = -\frac{3}{4} \sin^2 \theta e^{-2i\phi} S_+ I_+ \\
F = -\frac{3}{4} \sin^2 \theta e^{2i\phi} S_- I_- 
\]
DNP: the solid effect

**Electron Spin Resonance of a polarized solid target**
- a solid dielectric with $\sim 10^{19}$ cm$^{-3}$ unpaired electrons
- low temperature
- high field

Electrons are polarized, so lower Zeeman level is filled.
Upper Zeeman level is unpopulated.
DNP: the solid effect

Electron Spin Resonance of a polarized solid target

- a solid dielectric with $\sim10^{19}$ cm$^{-3}$ unpaired electrons
- low temperature
- high field

Microwaves at the electron Larmor frequency $\omega_e = \gamma_e B$ flip the electron into the upper level.

Microwave absorption

$\omega_e$

140 GHz at 5 tesla
DNP: the solid effect

Electron Spin Resonance of a polarized solid target

- a solid dielectric with $\sim 10^{19}$ cm$^{-3}$ unpaired electrons
- low temperature
- high field

The electron will relax back to the ground state in about 100 ms (short $t_1$).
DNP: the solid effect

**Electron Spin Resonance of a polarized solid target**
- a solid dielectric with \(\sim 10^{19}\) cm\(^{-3}\) unpaired electrons
- low temperature
- high field

Microwave absorption

- **e**\(^{-}\) spin flip

Magnetic field

Energy levels of an electron + protons. Electron is polarized. Protons are not.
**DNP: the solid effect**

*Electron Spin Resonance of a polarized solid target*

- a solid dielectric with $\sim 10^{19}$ cm$^{-3}$ unpaired electrons
- low temperature
- high field

Microwaves at $\omega_e - \omega_p$ flips both electron & proton spins.
DNP: the solid effect

**Electron Spin Resonance of a polarized solid target**
- A solid dielectric with \( \sim 10^{19} \text{ cm}^{-3} \) unpaired electrons
- Low temperature
- High field

---

**Diagram: Microwave Absorption**
- **Magnetic field**
- **Microwave frequency**
- **e\(^{-}\) spin flip**
- **Positive polarization**
- **e\(^{-}\) & p “flip-flip”**
- **e\(^{-}\) & p “flip-flop”**
- **\( \omega_e - \omega_p \)**
- **\( \omega_e \)**
- **\( \omega_e + \omega_p \)**

---

The electron flips back to its ground state, the proton stays flipped (long \( t_1 \)).
**DNP: the solid effect**

**Electron Spin Resonance of a polarized solid target**
- a solid dielectric with $\sim 10^{19}$ cm$^{-3}$ unpaired electrons
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- high field

**Diagram:**
- Microwave absorption
- Microwave frequency
- Magnetic field
- Positive polarization
- $e^-$ spin flip
- $e^-$ & $p$ “flip-flip”
- $e^-$ & $p$ “flip-flop”

Repeating this over and over…
DNP: the solid effect

Electron Spin Resonance of a polarized solid target

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Microwave absorption

- $e^-$ spin flip

Positive polarization

- $e^-$ & $p$ "flip-flip"
- $e^-$ & $p$ "flip-flop"

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DNP: the solid effect

Electron Spin Resonance of a polarized solid target

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- Low temperature
- High field

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Microwave absorption

\[ e^{-} \text{ spin flip} \]

Positive polarization

\[ e^{-} \& \ p \ “flip-flip” \]

\[ e^{-} \& \ p \ “flip-flop” \]

Magnetic field

Microwave frequency

Repeating this over and over…
Electron Spin Resonance of a polarized solid target

- a solid dielectric with $\sim 10^{19}$ cm$^{-3}$ unpaired electrons
- low temperature
- high field

... leads to positive proton polarization.
DNP: the solid effect

*Electron Spin Resonance of a polarized solid target*
- A solid dielectric with \(~10^{19}\) cm\(^{-3}\) unpaired electrons
- Low temperature
- High field

Microwaves at \(\omega_e + \omega_p\) produces an electron-proton “flip-flop”...
DNP: the solid effect

Electron Spin Resonance of a polarized solid target

- a solid dielectric with $\sim 10^{19}$ cm$^{-3}$ unpaired electrons
- low temperature
- high field

Microwave absorption

$\omega_e - \omega_p$

$\omega_e$

$\omega_e + \omega_p$

Magnetic field

$e^{-}$ spin flip

$e^{-}$ & $p$ “flip-flip”

$e^{-}$ & $p$ “flip-flop”

Microwave frequency

... and generates negative proton polarization.
DNP: the solid effect

Electron Spin Resonance of a polarized solid target

- a solid dielectric with $\sim 10^{19}$ cm$^{-3}$ unpaired electrons
- low temperature
- high field

$e^{-}$ spin flip

Microwave absorption

Positive polarization
$e^{-}$ & $p$ "flip-flip"

Negative polarization
$e^{-}$ & $p$ "flip-flop"

Microwave frequency

Nuclear Polarization

$2\omega_p$

Jefferson Lab
Target Group
DNP: the solid effect

In 1957 Anatole Abragam (Saclay) and Carson Jefferies (Berkeley) independently demonstrate the transfer of electron polarization to nuclei by driving forbidden transitions directly in dielectric solids containing paramagnetic impurities.

Abragam called this “l'effet solide”, The Solid Effect.

Within 5 years, both were enlisted to build polarized targets for scattering experiments!

Anatole Abragam, 1914-2011

Carson Jeffries, 1922-1995
Electron Spin Resonance of a polarized solid target \textit{Irradiated Ammonia (NH}_3)\textit{)}

- a solid dielectric with $\sim 10^{19} \text{ cm}^{-3}$ unpaired electrons
- low temperature
- high field

High proton polarizations have been observed even in samples with broad ESR line. This isn’t easily explained by the Solid Effect.
DNP: beyond the solid effect

Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.
Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one proton.
DNP: beyond the solid effect

Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.

The electron relaxes, flipping a 2nd electron on the opposite side of the line, along with a nearby nuclear spin.

Frequency matching: \( \omega_{2e} = \omega_{1e} + \omega_p \)
Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.

Microwaves on the other side of the ESR line drives negative nuclear polarization.
DNP: beyond the solid effect

Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.

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DNP: beyond the solid effect

Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.

Microwaves on the other side of the ESR line drives negative nuclear polarization.

Frequency matching:

$$\omega_{2e} = \omega_{1e} - \omega_p$$
Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.

**The Cross Effect and/or Thermal Mixing**

\[
\omega_{2e} = \omega_{1e} - \omega_p
\]
Instrumentation

Target sample

Superconducting magnet

Refrigerator ≤ 1K

Microwaves (140 GHz @ 5T)

NMR

Refrigerator pumps

Liquid helium
Polarized target material can be characterized by four quantities:

- **Maximum polarization**
  “Can you make it higher?”

- **Speed of polarization**
  “How much longer?”

- **Polarization resistance to ionizing radiation**
  “Why is the polarization going down!”

- **Ratio of polarized-to-total number of nuclei**
  “What’s all this other junk?”

The figure-of-merit is given by:

\[ \text{Figure-of-Merit} = t \cdot f^2 \cdot P^2 \]
### Target samples

<table>
<thead>
<tr>
<th>Material</th>
<th>Dil. Factor (%)</th>
<th>Polarization (%)</th>
<th>Doping method</th>
<th>Rad. resistance</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butanol, C₄H₉OH</td>
<td>13.5</td>
<td>&gt; 90%</td>
<td>Chemical</td>
<td>moderate</td>
<td>Easy to produce and handle</td>
</tr>
<tr>
<td>Ammonia, NH₃</td>
<td>17.7</td>
<td>&gt; 90%</td>
<td>Radiation</td>
<td>high</td>
<td>Works well at 5T and 1K</td>
</tr>
<tr>
<td>Lithium hydride, ⁷LiH</td>
<td>25.0</td>
<td>90%</td>
<td>Radiation</td>
<td>extremely high</td>
<td>Slow polarization, long relaxation</td>
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<tr>
<td>D-Butanol, C₄D₉OD</td>
<td>23.8</td>
<td>&gt; 80%</td>
<td>Chemical</td>
<td>moderate</td>
<td>Easy to produce and handle</td>
</tr>
<tr>
<td>D-Ammonia, ND₃</td>
<td>30.0</td>
<td>50%</td>
<td>Radiation</td>
<td>high</td>
<td>Works well at 5T and 1K</td>
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<td>55%</td>
<td>Radiation</td>
<td>extremely high</td>
<td>Slow polarization, long relaxation</td>
</tr>
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</table>
1 K $^4$He evaporation refrigerator
base temperature: $\leq 1.0$ K
Cooling power: 0.8 W @ 1.0 K

courtesy of James Brock, Jefferson Lab
\(^3\text{He}-^4\text{He} \) dilution refrigerator
base temperature: < 25mK
cooling power: 0.1 W @ 0.3 K
Superconducting magnets

For optimum DNP, the field should be uniform over the volume of the target sample at a level of about 100 ppm
Microwave sources

Microwave frequency: 28 GHz/Tesla

Power requirements:  
~4 mW/g @ 2.5 T  (70 GHz)  
~20 mW/g @ 5.0 T  (140 GHz)

IMPATT Diode, 0.3 W @ 70 GHz  
VA Diode, Inc

Extended Interaction Oscillator, 20 W @ 140 GHz  
CPI Canada
Polarization measurement

NMR frequencies (MHz):

<table>
<thead>
<tr>
<th>Field (tesla)</th>
<th>Proton (MHz)</th>
<th>Deuteron (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>212.9</td>
<td>32.7</td>
</tr>
<tr>
<td>2.5</td>
<td>106.4</td>
<td>16.3</td>
</tr>
</tbody>
</table>

CW-NMR using Q-meter is the standard detection scheme.
G. Court et al, NIM A324 (1993) 433

Typical polarization accuracy is $\Delta P/P \approx 3 - 4\%$

Updated Q-meter, Bochum University
Improved S/N and stability
G. Reichertz, SPIN2016

Signal Area is proportional to the polarization
Polarization measurement

A new project at Jlab: Can we polarize two samples at once, in opposite directions?

Microwaves are tuned halfway between the normal (+) and (-) polarization frequencies:

- high field sample will polarize (+)
- low field sample will polarize (-)
Polarization measurement

A new project at Jlab: Can we polarize two samples at once, in opposite directions?

- Samples are 5-minute epoxy doped with TEMPO radical
- Two samples
- One NMR coil

32 AWG (0.20 mm) copper wire
Outer windings: 4 x 32 @ 2 amps
Inner windings: 4 x 43 @ 5 amps

5 T solenoid used for FROST

Courtesy of J. Maxwell

Courtesy of V. Lagerquist
Polarization measurement

A new project at Jlab: Can we polarize two samples at once, in opposite directions?

Answer: YES!
Further reading

Books
A. Abragam, “Principles of Nuclear Magnetism”, Oxford University Press, 1982

Review Articles

Biannual Workshops & Symposia
Workshop on Polarized Sources, Targets, and Polarimetry (PSTP): (Knoxville, 2019)
International Spin Physics Symposium: (Japan, 2020)
Summary

Polarized targets are fun instruments to build & work with (usually)

- condensed matter physics
- low temperature physics
- cryogenics
- magnet technology
- vacuum technology

They’re useful for nuclear and particle physics too

- Structure functions
- Sum rule rules
- Baryon spectroscopy

Technology developed for Polarized Targets is expanding into other areas of research

- Chemistry
- Biology
- Neutron crystallography

DNP is a mature technology, but a lot of advances in recent decades, and plenty of room for more!