Review of solid polarized targets

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Outline

• Highlights of Solid Targets at PSTP2013
• Highlights of Tensor Workshop at JLab
• Future target activities, primarily in the US
Three sessions (~ one dozen speakers) dedicated to polarized solid targets
http://faculty.virginia.edu/PSTP2013/

Proceedings are published online
http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=182
Physics of Polarized Targets
Presented in PSTP2013, Charlottesville, USA
with tributes to the work of Michel Borghini and Franz Lehar

1. Introduction to spins in solids at low temperature
   • tributes to the work of Michel Borghini and Franz Lehar
   • quantum statistics and spin temperature
   • saturation and relaxation in magnetic resonance

2. Equal spin temperature model for DNP

3. Magnetic resonance and relaxation at low temperatures

4. Radiolytic paramagnetic impurities usable for DNP

5. Weak saturation during NMR polarization measurement

6. Refrigeration using quantum fluids
Neutron spin filter based on dynamically polarized protons using photo-excited triplet states
— Tim Eichhorn, PSI

The photo-excited triplet state as source of paramagnetism

Electronic singlet states (S = 0)

\[ |S_0^\rangle \]

Fluorescence

Light excitation

Intersystem crossing ISC (spin-orbit coupling)

Electronic triplet states (S = 1) (paramagnetic)

\[ |T_\alpha^\rangle \]

\[ |T_\beta^\rangle \]

Zero field splitting (ZFS), selective population

\[ |T_\gamma^\rangle \]

ISC via phosphorescence / dark decay

Photo-excited triplet states of pentacene replace paramagnetic radicals polarized at low temperature, high field.
Neutron spin filter based on dynamically polarized protons using photo-excited triplet states
— Tim Eichhorn, PSI

1st setup on neutron beamline BOA

- Caliper for sample positioning
- Neutron detector
- Target Crystal
  \( P \sim 50\% \)
- Fiber coupled laser light \( @ 600 \text{ nm} \)
- Pulse ESR / DNP system
  9 GHz
- Pulse NMR system
- Cryostat \( T \sim 100 \text{ K} \)
- Magnet, 0.3 T (max 0.6 T)
- Neutron beam
DNP at 200mK and 2.5T with 70GHz microwaves. Frozen spin target (25mKelvin, 0.6T). Secondary particles punch through holding coil. Longitudinal and transverse holding coils.

\[ P_{\text{proton}} \sim 85\% \]
\[ P_{\text{deuteron}} \sim 75\% \]
\[ \tau \sim 1000 \ldots 2000 \text{ hours} \]
Internal Magnet Development

Idea: reduce the magnetic volume of the large external pol. magnet to the size/dimensions of the internal holding coil

- field strength: ~ 2.5 T
- as thin as possible (minimized absorption) ~ 2 mm
- homogeneity dB/B ≤ 10^{-3}

\[ B = \mu_0 \cdot N \cdot \frac{I}{l} \]

NC: ampere-turn : N\cdot I \sim 300 \text{ kA} \rightarrow \text{superconducting wire necessary}
High current operation (~100 A) in a dilution refrigerator
Longitudinally Polarized Target for CLAS12 at JLab

We intend to use internal superconducting *shim* coils to ensure the 5 T polarizing magnet (i.e. the CLAS12 solenoid) has $\Delta B/B \leq 10^{-4}$

Conceptual design of superconducting shim coils for CLAS12 polarized target
We also hope to use internal superconducting shim coils to adjust the polarizing field for multiple target samples, allowing independent polarizations with one microwave source.
Recent research activities and results of the Bochum/Bonn Polarized Target Group — Gerhard Reicherz, Bochum

Polarization of FinlandD36-doped C₈D₈

Temperature = 400 mK and magnetic field = 5 T

Wang Li | NIMA 729 (2013) 36–40
Recent research activities and results of the Bochum/Bonn Polarized Target Group — Gerhard Reicherz, Bochum

Bochum NMR Box


PSTP2013
Charlottesville, VA
http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=182
Recent research activities and results of the Bochum/Bonn Polarized Target Group
— Gerhard Reicherz, Bochum

Bochum NMR Box

New NMR Systems also being developed at

- Los Alamos
- PSI

http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=182
Target Polarizations during G-14 Run

HDice targets used in frozen spin mode during E06-101 (G-14) photon run.

Relaxation times were longer than a year at B=0.9T and T<100mK.
Electrons on the HDice Target: Results and Analysis of Test Runs at JLab in 2012
– Mike Lowry, JLab

- Directed at during-irradiation effects
- Confirm NMR RF screening
- Polarization decay $T1 \sim 3-6$ hr
- Re-growth after B zero’ing shows mechanism still active after beam gone but freeze out after 6-12 hr

$P(H)$ during the Mar’12 eHD test, with 0.3 tesla holding field during exposures. Shaded vertical bands indicate beam-on periods.
HIGS Frozen Spin Target System (HIFROST)
— Pil-Neyo Seo, UVa/TUNL

Horizontal dilution refrigerator

new mixing chamber
Tensor Spin Observables
Jefferson Lab
March 10-12, 2014

A three day workshop with approximately 40 participants and two dozen speakers.
http://www.jlab.org/conferences/tensor2014/

One day devoted to tensor-polarized deuteron targets.

Proceedings will be published online.
The Deuteron Polarized Tensor Structure Function $b_1$
— Karl Slifer, UNH

All conventional models predict small or vanishing values of $b_1$ in contrast to the HERMES data

$\frac{q^0(x) - q^1(x)}{2}$

$q^0$: Probability to scatter from a quark (any flavor) carrying momentum fraction $x$ while the Deuteron is in state $m=0$

$q^1$: Probability to scatter from a quark (any flavor) carrying momentum fraction $x$ while the Deuteron is in state $|m| = 1$

Nice mix of nuclear and quark physics measured in DIS (so probing quarks), but depends solely on the deuteron spin state

Investigate nuclear effects at the level of partons!

All conventional models predict small or vanishing values of $b_1$ in contrast to the HERMES data
Unpolarized electron beam: 115 nA
Luminosity: $10^{35}$ s$^{-1}$cm$^{-2}$
Tensor polarized deuteron target: 30%

$\sigma_T$ : tensor pol. cross section
$\sigma_0$ : unpolarized cross section
$P_{ZZ}$ : tensor polarization
$f$ : dilution factor

Jefferson Lab E12-13-011 (conditionally approved)
E. Long, K. Slifer, P. Solvignon (U. New Hampshire)  J.P. Chen (JLab)
O. Rondon, D. Keller (U. Virginia)  N. Kalantarians (Hampton U.)

$b_1 = -\frac{3}{2} F_1^d A_{ZZ}$

$A_{ZZ} = \frac{2}{f P_{ZZ}} \frac{\sigma_T - \sigma_0}{\sigma_0} = \frac{2}{f P_{ZZ}} \left( \frac{N_T}{N_0} - 1 \right)$
Tensor Polarization of the Deuteron

The deuteron is a spin-1 nucleus with three magnetic substates, \( m = +1, 0, \text{ and } -1 \)

Three quantities are required to fully describe an ensemble of the spins:

- **Vector polarization** \( P_z = (N_{+1} - N_{-1}) \)
- **Tensor polarization** \( P_{zz} = (N_{+1} - N_0) - (N_0 - N_{-1}) = (1 - 3N_0) \)
- **Normalization** \( (N_{+1} + N_0 + N_{-1}) = 1 \)

Vast majority of experiments using solid, polarized deuteron targets focus on the vector polarization (exceptions at Bonn and TRIUMF, for example)
• Deuteron also has an electric quadrupole moment, $e_{Q_D} = 2.86 \, \text{e}\cdot\text{fm}^2$

• $e_{Q_D}$ interacts with electric field gradients within the lattice producing two, overlapping NMR lines (Pake doublet)

$$E_m = -h
\nu_D m + h
\nu_Q \left[ 3 \cos^2 \theta - 1 \right] \left[ 3m^2 - I(I + 1) \right]$$

$\nu_D = \text{deut. Larmor freq.}$

$\nu_Q = \text{ND}_3\text{ quadrupole freq.}$

$e_{Q} = \text{deuteron quadrupole moment}$

$\theta = \text{angle between elec. & mag. fields}$
Spin Temperature Hypothesis: Zeeman levels are populated according to the Boltzmann relation with a (positive or negative) spin temperature $T_s$.

\[
P_z = \frac{4 \tanh\left(\frac{\mu B}{2kT_s}\right)}{3 + \tanh^2\left(\frac{\mu B}{2kT_s}\right)}
\]

\[
P_{zz} = \frac{4 \tanh^2\left(\frac{\mu B}{2kT_s}\right)}{3 + \tanh^2\left(\frac{\mu B}{2kT_s}\right)}
\]

\[
P_{zz} = 2 - \sqrt{4 - 3P_z^2}
\]

- Mutually allowed values for the vector and tensor polarizations are generally restricted to be on or within the black triangle, but...

- Spin Temperature hypothesis restricts the polarizations to only those values on the red parabola. Note: no negative $P_{zz}$ values!
Spin Temperature Hypothesis: Zeeman levels are populated according to the Boltzmann relation with a (positive or negative) spin temperature $T_s$.

Some Spin Temperature Values

<table>
<thead>
<tr>
<th>$P_z$</th>
<th>$P_{zz}$</th>
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<tbody>
<tr>
<td>0%</td>
<td>0%</td>
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<tr>
<td>10%</td>
<td>1%</td>
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<td>20%</td>
<td>3%</td>
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<td>30%</td>
<td>7%</td>
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<td>40%</td>
<td>12%</td>
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<td>50%</td>
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<td>60%</td>
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<td>70%</td>
<td>41%</td>
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<td>80%</td>
<td>56%</td>
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<td>90%</td>
<td>75%</td>
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<tr>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
RF saturation (hole burning) can be used to decrease the $m=0$ population and increase the tensor polarization. The effect can be significant, but not tremendous.

**Example: Burning a pedestal**

- $P_Z = 50.0\%$
- $P'_{ZZ} = 48.6\%$
- $\Delta P_Z = -1.4\%$
- $\Delta P_{ZZ} = 4.2\%$

**Example: Burning a peak**

- $P_Z = 50.0\%$
- $P'_{ZZ} = 45.0\%$
- $\Delta P_Z = -5.0\%$
- $\Delta P_{ZZ} = 3.5\%$

*These estimates assume no dipolar broadening of the NMR line, and no spectral diffusion (cross relaxation) through the line.*
• Perform 1\textsuperscript{st} expt. ever using a tensor polarized target!

• \( \sigma(\text{pol}) / \sigma(\text{unpol}) = 1 + 1 / \sqrt{2} \ p \Downarrow zz \ T \Downarrow 20 \), with longitudinal \( B \)
  
  - We thought we were pioneering this back in 1984
    • Knew about some CERN tech notes on pol tgts
  
  - No double scattering/recoil polarimeter
  
  - Fewer systematic errors: msr xsec ratios
  
  - Develop a large \( d\Omega \) detection system with lots of \( \Theta \) multiplicity
  
  - \textbf{Crucial} to insure \( |\Theta \Downarrow B - \Theta \Downarrow \pi| < 1 \, \degree \) to suppress other \( T_{ij} \)
    • Used a split counter with field on/off to do this, lasers & mirrors
  
  - Be damn sure you can msr \( p_{zz} \)
Perform 1st expt. ever using a tensor polarized target!

\[ \frac{\sigma(\text{pol})}{\sigma(\text{unpol})} = 1 + \frac{1}{\sqrt{2}} \ p \downarrow zz \ T \downarrow 20 \] , with longitudinal \( B \)

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- Be damn sure you can msr \( p_{zz} \)
Conditions:

- Dilution fridge ~ 120 mK
  - s.b. 50 mK!
- Longitudinal 2.5 T sc split pair
  - $\Delta B/B \sim 10^{-4}$, persistent mode
- 1 mm $\varphi$ deuterate butanol beads
  - 95% deuterate n-butyl alcohol
  - 5% D$_2$O doped with EHBA (Cr$^V$)
  - Teflon cell 16x16x5 mm$^3$

$P_z = 0.333 \pm 0.015$  $P_{zz} = 0.085 \pm 0.008$

- 3 techniques used to msr $P_{zz}$
  1. Thermal equilibrium calibration
  2. $P_z = (1 - R^2)/(1+R+R^2)$
  3. DIRECT MSR of $P_{zz}$ from $T_{20}(90^\circ)$
Future Use of Polarized Solid Targets

- COMPASS (Polarized Drell-Yan)
- MAMI (Compton Scattering)
- FermiLab (Polarized Drell-Yan)
Polarized Solid Targets at 12 GeV JLab

HALL A

(E12-11-108) *SIDIS with a transversely polarized proton target*

(E12-11-108A) *Target single spin asymmetries using the 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*

(E12-12-001) *EMC effect in spin structure functions*

(C12-11-111) *SIDIS on a transversely polarized target*

(C12-12-009) *Di-hadron 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 b1*

(LOI-12-14-001) *Search for exotic gluonic states in the nucleus*

(LOI-12-14-002) *Tensor asymmetry Azz in the x<1 region*
• No *earth-shattering* breakthroughs in recent years, but there has been steady progress and continuing R&D efforts are in progress

• Demand for polarized targets are at an all time high, especially at JLab

• We need more people (especially *young* people) to meet this demand