Freezing the Spin of the Proton
The Next Generation Polarized Target for CLAS

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Outline of the Talk

How to polarize spin
  1. The Basics of Polarization
  2. Polarization and Thermal Equilibrium
  3. Brute Force Polarization
  4. Dynamic Nuclear Polarization
  5. Materials for DNP

How to freeze the spin
The Basics of Polarization

Any ensemble of atoms or nuclei with a magnetic moment can be polarized via the Zeeman interaction: $\vec{\mu} \cdot \vec{B}$

Zeeman interaction tends to orient (polarize) the magnet moments.

Oscillating EM fields produced by atomic vibrations tends to randomize (de-polarize) the magnetic moments. Characterized by thermal energy $kT$. 

$B_{\text{ext}} = 0$
$P = 0$

$B_{\text{ext}} > 0$
$P > 0$
Polarization and Thermal Equilibrium

In general the populations of the Zeeman levels (once equilibrium has been reached) will obey a Boltzmann distribution.

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

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

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

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

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

Disadvantages:

1. Requires very large magnet
2. Low temperatures mean low luminosity
3. Polarization can take a very long time

We need a trick!
The Trick -- Dynamic Nuclear Polarization

Use brute force to polarize free electrons in the target material. Use microwaves to “transer” this polarization to nuclei. Mutual electron-nucleus spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other.

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

JLab: $B = 5$ Tesla
$T = 1$ Kelvin
The Resolved Solid Effect

Zeeman energy levels of a hydrogen-like atom

Positive polarization

Negative polarization
Materials for DNP Targets

- Choice of material dictated by 4 factors:
  1. Maximum polarization
  2. Resistance to ionizing radiation
  3. Presence of unpolarized nuclei
  4. Presence of unwanted, polarized nuclei

- Free electrons must be embedded into target material:
  1. Chemical doping with paramagnetic radicals
  2. Paramagnetic radicals created by ionizing radiation

- Typically 1 free electron can “service” ~ $10^3$ free protons

$$f \equiv \frac{\tilde{N}}{N_{total}}$$
## Materials for DNP Targets, examples

<table>
<thead>
<tr>
<th>Name</th>
<th>Dopant</th>
<th>f</th>
<th>Rad. Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene, C₂H₄</td>
<td>chemical</td>
<td>0.12</td>
<td>low</td>
</tr>
<tr>
<td>Polystyrene, C₈H₈</td>
<td>chemical</td>
<td>0.07</td>
<td>low</td>
</tr>
<tr>
<td>Propandiol, C₃H₆(OH)₂</td>
<td>chemical</td>
<td>0.11</td>
<td>moderate</td>
</tr>
<tr>
<td>Butanol, C₄H₉OH</td>
<td>chemical</td>
<td>0.13</td>
<td>moderate</td>
</tr>
<tr>
<td>Ammonia, ^15^NH₃</td>
<td>radiation</td>
<td>0.17</td>
<td>high</td>
</tr>
<tr>
<td>Lithium Hydride, ^7^LiH</td>
<td>radiation</td>
<td>0.12</td>
<td>very high</td>
</tr>
</tbody>
</table>
The Current Hall B Polarized Target

Protons (and deuterons) in $^{15}\text{NH}_3$ ($^{15}\text{ND}_3$) are continuously polarized by 140 GHz microwaves at 5 Tesla, 1 Kelvin

Used for several experiments (beam current $\sim$ 3 nA) over a 10 month period during 1999, and 2000-2001

Proton polarization: $\sim$75 - 85%
Deuteron polarization: $\sim$25 - 35%
The Current Hall B Polarized Target
The Current Hall B Polarized Target

Problem:
We have a “4π” detector. We need a “4π” target!
Physics Program with Polarized Target and Tagged Photons

Approved Experiments

E02-112: Missing Resonance Search in Hyperon Photoproduction
E01-104: Helicity Structure of Pion Photoproduction
E03-105: Pion Photoproduction from a Polarized Target

Letter of Intent

LOI-020104: Photoproduction Using Polarized Beam and Target
The Frozen Spin Target

1. Polarize target material via DNP at 5T and 0.5K

2. After optimum polarization is obtained, turn off microwaves, and magnet

3. Use a 2nd magnet (~0.5 T) and very low temperatures to “freeze” the polarization

4. Polarization will decay very slowly with a time constant (hopefully) of several days

5. After polarization decays to about 50% of its initial value, go back to Step 1
Outline of the Talk

How to polarize spin

How to freeze the polarization

1. The Basics of Frozen Spin
2. Specs. for the Hall B Target
3. Magnets
4. Refrigeration
Specifications for the Hall B Frozen Spin Target

Beam: Tagged photons
Target: $\varnothing 15 \text{ mm} \times 50 \text{ mm}$ butanol ($C_4H_9OH$)  \[ \mathcal{L} \sim 10^{30} - 10^{31}/s \text{ cm}^2 \]
Polarizing Magnet: 5 Tesla warm bore solenoid
Holding Magnet: 0.3 – 0.5 Tesla internal solenoid
Refrigerator Cooling Power:  \[ Q \sim 20 \text{ mW} @ 0.3 \text{ K} \]
\[ Q \sim 10 \mu\text{W} @ 0.05 \text{ K} \]
Polarizing Magnet

Max. Field: 5.1 T
ΔB/B: < 3×10^{-5}
Bore: Ø127 mm

Cryomagnetics, Inc.
Oak Ridge, TN, USA

A. Dzyubak, priv. comm..
Holding Magnet

Dimensions: $40 \times 250 \times 0.3$ mm
Max. Field: 0.32 Tesla
Homogeneity: $\Delta B/B \sim 3 \times 10^{-3}$
Refrigeration below 4.2 K – Evaporative Cooling

In order to evaporate 1 mole of $^4$He, heater must supply:
$L \sim 80 \text{ J/mol}$ \textit{(L is latent heat of vaporization)}

In absence of a heater, liquid will absorb heat from surroundings and temperature will drop.

Cooling power of a evaporation 'fridge is simply:

\[ \dot{Q} = \dot{n}L = \dot{V}PL \]

But since $P \propto \exp(-1/T)$

$\dot{Q} \propto \exp(-1/T)$
Evaporative Cooling

Insufficient for freezing the spin!
\( ^3\text{He}/^4\text{He} \) Dilution Refrigeration

- below 0.8 K, a \(^3\text{He}/^4\text{He}\) mixture will separate into two phases

- The specific heat of a \(^3\text{He}\) atom is higher in the lower, dilute phase than in the upper, concentrated phase.

\[
C_d = 107 \, T \, J/mol\, K \\
C_c = 25 \, T \, J/mol\, K
\]

- Therefore, \(^3\text{He}\) will absorb energy when it dissolves into the dilute phase.
**$^3$He in the Dilute Phase**

Even at absolute zero, $^3$He will dissolve into $^4$He until a concentration of 6.6% is reached.

Binding energy of a $^3$He atom in **conc** phase is $-L_3$, latent heat of $^3$He

Binding energy of a $^3$He atom in **dilute** phase is $-E_d(x)$

Total energy of a $^3$He atom in **dilute** phase is sum of binding energy and kinetic energies, $kT_f(x)$

At a concentration of $x=6.6\%$, the total energy of $^3$He in the dilute phase is same as the binding energy in the concentrated (pure) phase.
Thermodynamics of the Dilution Refrigeration

H. London, 1951:

If $^3$He is somehow preferentially removed from the lower part of the mixing chamber, $^3$He from the upper part will absorb heat from its surroundings in order to dissolve into the dilute phase and reestablish equilibrium.

Mixing occurs at a constant chemical potential: \[ H_d - T S_d = H_c - T S_c \]

Assuming a dilution rate of $\dot{n}$ mol/s, cooling power is $\dot{n} \Delta H$

\[
H_c = \int C_c \, dT = 12.5 T^2 \\
H_d = H_c + T (S_d - S_c) = 12.5 T^2 + T \int \left( \frac{C_d}{T} - \frac{C_c}{T} \right) dT = 12.5 T^2 + T (107 T - 25 T) = 94.5 T^2
\]

“Ideal” cooling power of the dilution process:

\[
\dot{Q} = \dot{n} [H_d - H_c] = 82 \dot{n} T^2 \quad \text{Watt/mol K}^2
\]
Practical Dilution Refrigeration

- $^3$He is “distilled” from the lower, dilute phase of the mixing chamber

- after distillation, the $^3$He is recondensed in a LHe bath at ~1.5K

- the cooling power and min. temperature depend strongly on heat exchange between the conc. (warm) and dil. (cold) fluid streams

\[
\dot{Q}(T_m) = \dot{n}[H_d(T_m^2) - H_c(T_c^2)] \\
= \dot{n}[94.5 T_m^2 - 12.5 T_c^2]
\]

Performance of HX determines $T_c^2$
Heat Exchange between $^3\text{He}_d$ and $^3\text{He}_c$

At low temperatures, the main impediment to heat transfer is the thermal boundary (Kapitza) resistance $R_k$ between the helium and the HX walls.

Only a small fraction of phonons from liquid will enter the HX walls:

\[
\frac{\rho_1 v_1^3}{\rho_2 v_2^3} \propto 10^{-5} \quad \Rightarrow \quad \dot{Q}_k = \frac{A}{2R_k} [T_2^4 - T_1^4]
\]

Or a more familiar form:

\[
\dot{Q}_k = \frac{\Delta T}{R} = \frac{A T^3}{R_k} \Delta T \quad \text{Heat transfer drops fast at low } T!
\]
Performance of an “Ideal” Heat Exchanger

(Giorgio Frossati, 1986)

dilute side: 
\[ s_d \frac{d}{dx} \left[ \kappa_d(T) \frac{dT_d}{dx} \right] + \eta_d \left( \frac{\dot{n}}{\rho_d} \right)^2 \frac{dZ_d}{dx} + \frac{dA}{dx} \frac{(T_c^4 - T_d^4)}{4R_{kT}} = \dot{n}C_d \frac{dT_d}{dx} \]

conc. side: 
\[ s_c \frac{d}{dx} \left[ \kappa_c(T) \frac{dT_c}{dx} \right] + \eta_c \left( \frac{\dot{n}}{\rho_c} \right)^2 \frac{dZ_c}{dx} + \frac{dA}{dx} \frac{(T_c^4 - T_d^4)}{4R_{kT}} = -\dot{n}C_c \frac{dT_d}{dx} \]

Axial conduction  Frictional heat  Kapitza conduction  Enthalpy change

s = sectional area  \eta = viscosity  A = HX area (1 side)
\kappa = thermal cond.  Z = flow impedance  R_{kT} = total Kap. resistivity
x = dir. of fluid flow  \rho = fluid density

Frossati: you can always design a HX so that 1st and 2nd terms are small compared to the 3rd
Performance of an “Ideal” Heat Exchanger

\[
\begin{align*}
\text{dilute side} & \quad s_d \frac{d}{dx} \left[ \kappa_d(T) \frac{dT_d}{dx} \right] + \eta_d V_d \frac{dZ_d}{dx} + \frac{dA}{dx} \frac{(T_c^4 - T_d^4)}{4 R_k T} = \dot{n} C_d \frac{dT_d}{dx} \\
\text{conc. side} & \quad s_c \frac{d}{dx} \left[ \kappa_c(T) \frac{dT_c}{dx} \right] + \eta_c V_c \frac{dZ_c}{dx} + \frac{dA}{dx} \frac{(T_c^4 - T_w^4)}{4 R_k T} = -\dot{n} C_c \frac{dT_d}{dx}
\end{align*}
\]

\[
\begin{align*}
\frac{(T_c^4 - T_d^4)}{4 R_k} = \dot{n} C_d \frac{dT_d}{dx} = 107 T \dot{n} \frac{dT_d}{dx} \\
\frac{(T_c^4 - T_w^4)}{4 R_k} = \dot{n} C_c \frac{dT_c}{dx} = -25 T \dot{n} \frac{dT_c}{dx}
\end{align*}
\]

\[
T_d^2(x) = \left( \frac{25}{107} \right)^2 T_c^2(x)
\]

\[
T_c^2 = \frac{2 \cdot 25}{(1 - (25/107)^2)} \frac{R_{kT}}{A} \dot{n} \approx 50 \frac{R_{kT}}{A} \dot{n}
\]

Temperature of \( ^3 \text{He}_c \) entering mixing chamber
Cooling Power with Ideal Heat Exchanger

(Giorgio Frossati, 1986)

Cooling power, assuming “ideal” heat exchange is determined by molar flow rate and $\frac{R_k}{A}$ of heat exchanger

\[ \dot{Q}(T_m) = \dot{n} \left[ 94.5 T_m^2 - 12.5 T_c^2 \right] \]

\[ = \dot{n} \left[ 94 T_m^2 - 625 \frac{R_k T}{A} \dot{n} \right] \]
Sintered Silver Heat Exchangers

- large surface areas are necessary to overcome Kapitza resistance problem
- use sinters of ultra-fine silver powder to provide several m² of area

**JLab:**
- 1 micron Ag powder
- Sinter at 250 °C ➔ 0.5 m²/g

**each segment:**
- Dil. = 15 g = 7.5 m²
- Conc. = 8.5 g = 4.2 m²

**5 segments:**
- Dil. = 37.5 m²
- Conc. = 21 m²
An example of a commercial, vertical dilution refrigerator

Very nice, but it won't fit inside CLAS...
Horizontal Dilution Refrigerator for Frozen Spin Target

T.O. Niinikoski, CERN 1971
Hall B Frozen Spin Target
Outer Vacuum Jacket

$^4\text{He}$ Precooling Stages

1.5K

4.2K
The Frozen Spin Waltz

Step 1: Polarizing
- Target is fully retracted, magnet is lifted to beam height
- Target is inserted into magnet, magnet energized, microwaves on

Step 2: Beam On
- Microwaves off, magnet off, holding coil on
- Target is fully retracted, magnet is lowered
- Target is fully insert into CLAS
Beam Direction

METERS
Summary

- A frozen spin polarized target for tagged photon experiments is under development at Jefferson Lab.

- 5 Tesla polarizing magnet is in house.

- Superconducting holding coils (~1mm thick), both longitudinal and transverse, are under development.

- Horizontal dilution refrigerator is under construction.

- Positioning system for Hall B is still in conceptual design stage.
Racetrack coils for transverse holding magnet (untested)