HDice, the Polarized Solid HD Target in the Frozen Spin Mode for Experiments with CLAS

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- and the CLAS Collaboration
Topics

• How the HDice target works
• Target Production
• Performance of HDice target
• $\gamma$+HDice results with CLAS
• $e$+HDice test results
• Conclusion
Topics

• **How the HDice target works**
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Polarizing HD: the rotational levels of the solid hydrogens

At liquid helium temperature and below, only $J=1$ and 0 states are occupied, for $H_2$ and $D_2$, and only $J=0$ is populated for HD.

The relative energy spacing of the low-lying nuclear spin, $I$, and molecular orbital angular momentum, $L$, levels in $H_2$, HD and $D_2$ system. The symmetries of the nuclear spin wavefunction, $\chi_s$, are indicated.
Polarizing HD: cross coupling between H and D, POLARIZING

At J=0 states, protons and deuterons are de-coupled from the lattice.
⇒ long relaxation time or non-polarizable
⇒ help from J=1 H₂ and D₂ through spin-wave is needed for polarizing HD

The relative energy spacing of the low-lying nuclear spin, I, and molecular orbital angular momentum, L, levels in H₂, HD and D₂ system. The symmetries of the nuclear spin wavefunction, χ_s, are indicated.
Polarizing HD: \( L=1 \) molecules decay to \( L=0 \), AGING

The life time for \( J=1 \) \( H_2 \) is 6.3 days whiles for \( J=1 \) \( D_2 \) is 18.6 days.  
⇒ polarization mechanism disappears after “aging”  
⇒ Highly polarized frozen spin target

The relative energy spacing of the low-lying nuclear spin, \( I \), and molecular orbital angular momentum, \( L \), levels in \( H_2 \), HD and \( D_2 \) system. The symmetries of the nuclear spin wavefunction, \( \chi_S \), are indicated.
Heat generation due to $L=1$ to $L=0$ Conversion

Heat generation ($J=1$ to $J=0$): 2.6mW/mole for $H_2$ and 0.46mW/mole for $D_2$.

$\Rightarrow$ For HDice at $c_1 \sim 0.001$, 0.94$\mu$W/target from $H_2$ and 0.17$\mu$W/target from $D_2$.

$\Rightarrow$ Heat has to be removed from HD in order to polarize HD target.

\[
\begin{align*}
\text{Ortho-}H_2 & \quad (\chi_S \text{ sym}) \\
I=1 & \quad L=1 \\
& \quad 172K \\
\tau=6.3 \text{ days} \\
\text{Heat:} & \quad 2.6\text{mW/mole} \\
\text{Para-}H_2 & \quad \text{H}_2 \\
I=0 & \quad L=0 \\
\text{heat} & \quad \text{HD} \\
I=1/2, 3/2 & \quad L=1, L=0 \\
& \quad 86K \\
\tau=18.6 \text{ days} \\
\text{Heat:} & \quad 0.46\text{mW/mole} \\
\text{Para-}D_2 & \quad (\chi_S \text{ anti-sym}) \\
I=1 & \quad L=1 \\
& \quad 128K \\
\text{HDice dilution refrigerator cooling power at 10mK : 10}\mu W
\end{align*}
\]

The relative energy spacing of the low-lying nuclear spin, $I$, and molecular orbital angular momentum, $L$, levels in $H_2$, HD and $D_2$ system. The symmetries of the nuclear spin wavefunction, $\chi_S$, are indicated.
Polarizing D with RF Transition

$D$ transitions between $m_D = +1$, $m_D = 0$, and $m_D = -1$.

$H$ transitions between $m_H = -1/2$ and $m_H = +1/2$. 

Transition paths are indicated by red and blue arrows.
Polarizing D with RF Transition

All 6 states are equally populated.

\[ \text{m}_D=+1 \quad \text{m}_D=0 \quad \text{m}_D=-1 \]

\[ \text{m}_H=-1/2 \quad \text{m}_H=+1/2 \]

\[ \text{PH}=0, \quad \text{PD}=0 \]
Polarizing H with brute force.

\( m_D = +1 \) \hspace{2cm} \( m_D = 0 \) \hspace{2cm} \( m_D = -1 \)

\[ P^H = 1, \quad P^D = 0 \]
Inducing RF transition to polarize D.

\[ m_D = +1 \quad m_D = 0 \quad m_D = -1 \]

\[ m_H = -1/2 \quad m_H = +1/2 \]

\[ P^H = -1/3, \quad P^D = +2/3 \]
Inducing RF transition to reverse $P^H$. 

$m_D=+1$  \hspace{2cm}  $m_D=0$  \hspace{2cm}  $m_D=-1$  \hspace{2cm}  $m_H=-1/2$  \hspace{2cm}  $m_H=+1/2$

$P^H=+1/3$,  \hspace{1cm}  $P^D=+2/3$
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**Instrumentation: Target Cell**

- **HDice target cells:**
  - 750 × 50μ Al wires
  - pCTFE cell

- **material in the beam path:**
  - 77% HD + 17% Al + 6% pCTFE (remove with vertex cuts)
Production Dewar (PD)

- sample space temperature
  2K-300K variable

- magnetic field
  2 Tesla

- target injection, transportation and NMR calibration
Transfer Cryostat (TC)

- temperature
  2K
- magnetic field
  0.1 Tesla
- target transfer between dewars
Dilution Fridge (DF)

- sample space temperature \( \geq 8\text{mK} \)
- magnetic field 15 Tesla
- polarization
**Instrumentation: Storage Dewar**

**Storage Dewar (SD)**

- sample space temperature
  1.6K-300K variable
- magnetic field
  7 Tesla
- storage and/or transportation
Instrumentation: In-Beam Cryostat

- T: 50mK
- $B_{\parallel}$: 1.0T
- $B_{\perp}$: 0.075T
- $B_{\text{auxiliary}}$: $>$0.1T
- $B_{\text{backup}}$: 0.01T

In-Beam Cryostat (IBC)
Operation: Target transfer

PD  DF  SD  TC
Operation: Target transfer

PD: (Injecting target, NMR-TE)
TC: (Moving target)
DF: (Polarizing target)
SD: (Storing/transporting target)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Magnetic Field</th>
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<tbody>
<tr>
<td>1.6K, 7T</td>
<td></td>
</tr>
<tr>
<td>0.01K, 15T</td>
<td></td>
</tr>
<tr>
<td>2K, 0.1T</td>
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<tr>
<td>2K, 2T</td>
<td></td>
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</tbody>
</table>
Operation: Target transfer

Target transfer between PD and DF
Operation: Target transfer

Target transfer between PD and DF
Operation: Target transfer

Target transfer between PD and DF
Operation: Target transfer

Target transfer between DF and SD
Operation: Target transfer

Target transfer between DF and SD
Operation: G-14 Run at Hall-B

Loading target into IBC and moving IBC inside CLAS
Operation: G-14 Run at Hall-B

Moving IBC into CLAS
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Target Polarization Calibration for G-14 Run

HD removed from DF after 3 months Aging at high field and low temp

- Frozen-spin NMR compared to thermal equilibrium (TE) calibration
  
B field sweep

- HD target 20b:

  \[ P(H) = 61.3 \pm 1.8\% \]

  \[ P(D) = 15.5 \pm 0.6\% \]

Number of sweeps: 1 for polarized signals and ~250 for TE signals
The HDice targets were in frozen spin mode during G-14 Run. Relaxation times was longer than one year at B=0.9T and T<100mK.
Polarization Manipulation during G-14 Run

Increasing $D$ polarization by spin transfer:

- **Brute force** (high $B$/low $T$) $\Rightarrow$ $P_D \sim 15\%$ $(\mu_D / \mu_H \sim 1/3)$

- $1^{st}$ forbidden adiabatic fast passage (**FAFP**) to invert state populations

Zeeman levels of $HD$

- polarize $H$
  - RF transfer $P(H) \rightarrow P(D)$

- requires high RF powers and very uniform fields

- alternative: **saturate the FAFP transition**
  $\rightarrow$ equalize $\{ m_H = +1/2; m_D = -1, 0 \} \leftrightarrow \{ m_H = -1/2; m_D = 0, +1 \}$
Polarization Manipulation with SFP during G-14 Run

\[ \text{P(H)}_{\text{init}} \sim 50\% \]

\[ \Rightarrow \text{SFP} \Rightarrow \]

\[ \text{P(H)}_{\text{final}} = 28 \pm 1\% \]

\[ \text{P(D)}_{\text{init}} \sim 16\% \]

\[ \Rightarrow \text{SFP} \Rightarrow \]

\[ \text{P(D)}_{\text{final}} = 27 \pm 1\% \]
In-Beam Cryostat Performance during G-14 Run
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• How the HDice target works
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Reconstructed Vertex for HDice Target during G-14 Run

Clean empty cell (21a) subtraction from $\gamma n \rightarrow \pi p$

- **Full target cell**
- **Empty cell**
- **HD from full-empty (flux weighted)**

<table>
<thead>
<tr>
<th>zvertex</th>
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<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
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</tbody>
</table>

Dao Ho (CMU)  
- preliminary
On-going Analysis for G-14 Run

identified analysis projects:

\[ \gamma n (p) \rightarrow \Lambda^0 (p) \]
\[ \gamma n (p) \rightarrow K^- (p) \]
\[ \gamma n (p) \rightarrow K^- \Sigma^+ (p) \]
\[ \gamma n (p) \rightarrow \pi^- p (p) \]
\[ \gamma n (p) \rightarrow \pi^+ \pi^- n (p) \Leftrightarrow \pi^+ \Delta^- (p), \ \pi^- \Delta^+ (p), \ \rho n (p) \]
\[ \gamma n (p) \rightarrow \pi^+ \pi^- \pi^0 n (p) \Leftrightarrow \eta n (p), \ \omega n (p) \]
\[ \gamma n (p) \rightarrow \pi^0 \pi^- p (p) \]

1st look at data

Beta vs. Momentum
1st look at neutron data from G-14/HDice (concluded on 05/18/2012)

- $\vec{\gamma} \vec{n} (p) \rightarrow \pi^- p (p)$

- E beam-target helicity asymmetry from a few % of the g14 data:

Preliminary - N. Walford, CUA

SAID extrapolations from proton data
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Electron Beam Tests, $e + HD$ to check radiation damage

- H is not harmed, $T_1(H) > 50 \text{ d}$. 

- Beam Heating is the main concern for H. 
  \( \Rightarrow \) redesign target cell 
  build faster beam raster 

- D is damaged by radiation, $T_1(D) = 0.2 \text{ d}$. 

- $T_1(D) = 0.2 \text{ d}$. 

- Beam Heating is the main concern for H.
Conclusion

• **HDice target has been successfully installed at CLAS.**

• **Performance of HDice target demonstrated a huge potential for photon experiments.**

• **Comparing with the conventional target, which polarizes 80% of the 20% usable material, the HDice has 20% polarization of 80% target material.**

  **BUT, WE TOOK THE DATA AT 10 TIMES FASTER RATE BECAUSE OF LOW BACKGROUND.**

• **Electron beam on HDice test shown the road of improvement.**