The HDice Target at JLab
Collaborators

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Overview

- Uses of HDice target
- Production of a target cell for experiment
- Polarization process/mechanisms
- Lessons learned: eHD during g14
- eHD test in the Upgraded Injector Test Facility
HDice

- A new type frozen spin target.
- Target material consists solely of polarizable protons and neutrons ⇒ no dilution factor coming from target material.
- Target material possesses a T1 on the order of years (no repolarization needed).
- Is a very complicated system requiring many steps in the production of a polarized target.
What is it good for?

- Has been used (with photons) in Hall B as part of the N* program \( \Rightarrow \text{g14 (Nov 2011-May 2012)} \)

- N* program seeks/sought to explore the excited states of the nucleon to better understand the internal dynamics of protons and neutrons
What is it good for?

- Next up: Transversely polarized frozen spin target for use with electrons.
- Three (A-rated) proposals from PAC 41 rated as having a high impact for Hall B:
  - SIDIS, C12-11-111, Marco Contalbrigo,… ⇒ [A;C1]
  - Dihadron production, PR-12-009, Harut Avakian,… ⇒ [A;C1]
  - DVCS, PR12-12-101, Latifa Elouadrhiri,… ⇒ [A;C1]
- C1 ⇒ requires successful demonstration to Lab management of viable performance in a subsequent eHD test run
Why eHD?

- Provides a way to study proton tomography through the measurement of Generalized Parton Distributions (GPDs)

2(xy) + 1(z) Dim Cat scan of the human brain

2(xy) + 1(p) Dim scan of the nucleon

Flavor dipole
Why eHD?

- Provides a way to study proton tomography through the measurement of Generalized Parton Distributions (GPDs):
  \[ E(x, \xi, t), \tilde{E}(x, \xi, t), H(x, \xi, t), \tilde{H}(x, \xi, t) \]
- GPDs themselves provide access to the underlying framework; observables are calculated via integration of GPDs
- Tomographic distributions:
  \[ q(x, b_{\text{perp}}) = \frac{1}{4\pi^2} \int e^{i\sqrt{ib_{\text{perp}}}} E(x, t) d^2 t \]

Transverse target polarization asymmetries are required for access to \( E \)
Why eHD?
(Why not a conventional target?)

Magnet (for transverse field)

UVA (Oxford) Transverse NH$_3$/ND$_3$ target with CLAS

$4^\circ$ chicane

Limits acceptance

H. Avakian & P. Bosted
Why eHD?
(Why not a conventional target?)

No large magnets to limit acceptance!
Life Cycle of HDice Target

Gas Handling
- HD purification (JMU/JLab)
- Gas analysis (Rome2)

Gas recovery

Gas Storage

Experiment
- eHD, γHD
- Spin Transferring
- Spin Flipping

Target Production
- Condensing
- Calibrating (NMR)
- Polarizing
- Aging
HDice polarized target production

- Made in the Production Dewar (PD)
  - gas to solid
  - initial NMR (TE calib)
- Transferred to Oxford Dilution Fridge (DF)
  - Polarized in a 15 T B field at 10 mK for at least 3 months
- Transferred to PD for NMR measurements
- Transferred to Storage Dewar (SD) for storage (or back to the DF)
- Transferred to the In-Beam Cryostat (IBC) for data taking
- All transfers facilitated by Transfer Cryostat (TC)
Target Transfers

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

Temperatures and fields:
- 2K, 2T
- 2K, 0.1T
- 0.01 K, 15 T
- 1.7 K, 4.5 T
Target transfer between PD and DF for polarization
Target transfer between PD and DF for polarization
Target Transfer: PD to DF

Target transfer between PD and DF for polarization
TC mounted on top of the DF
Polarization process

How does one make polarized, frozen-spin HD?

- Ortho-$H_2$ (sym)
  - $S=1$
  - $L=1$
  - 172 K

- Para-$H_2$ (anti-sym)
  - $S=0$
  - $L=0$

- $H_2$

- HD
  - $S=1/2, 3/2$
  - $L=1$
  - 128 K

- Para-$D_2$ (anti-sym)
  - $S=1$
  - $L=1$
  - 86 K

- Ortho-$D_2$ (sym)
  - $S=0, 2$
  - $L=0$
Polarization process

What polarization mechanisms can we use?
- For all molecules, we have 2 electrons paired in 1s orbital ⇒ no DNP
- For all molecules, we (initially) have $S \neq 0$ ⇒ couples to B field

Ortho-$H_2$
(sym)

Para-$H_2$
(anti-sym)

Para-$D_2$
(anti-sym)

Ortho-$D_2$
(sym)

$H_2$
HD
$D_2$

$S=1$, $L=1$

$S=0$, $L=0$

$S=1/2$, $3/2$, $L=1$

$S=0, 2$, $L=0$

$S=1$, $L=1$

$172$ K
$128$ K
$86$ K

$\uparrow$ = Spin
$\bullet$ = Hydrogen
$\bullet$ = Deuterium
Polarization process

External magnetic field rapidly aligns the Ortho-$H_2$ and Para-$D_2$ which spin-exchange with the H and D (respectively) in the HD crystal.

Ortho-$H_2$ (sym) → S=1, L=1

Para-$H_2$ (anti-sym) → S=0, L=0

H$_2$

HD

Ortho-$D_2$ (sym) → S=1, L=1

Para-$D_2$ (anti-sym) → S=0,2, L=0

B$_{L=1} \cdot S_H$
Polarization process

This process continues until there are only inactive, \( L=0 \) states remaining.

The nucleons are now in a frozen-spin state: a state in which the polarized nucleons are so cold, there are (essentially) no available depolarization mechanisms.
Polarization process
(in words)

- Solid HD target is loaded into Dilution Fridge.
- Spins are aligned using a 15 T magnet at temperatures of ~10 mK.
- The (L=1) H₂ and D₂ molecules are polarized (are considered impurities).
- Polarized (L=1) H₂ and D₂ nuclei spin exchange with HD, polarizing it.
- After ~3 months, the L=1 H₂ and D₂ molecules decay down to L=0 and are no longer polarizable.
- TE for these conditions lead to P(H) = 90% and P(D) = 30%
Polarizing the Target

- Why so long?
  - Reaches 50% of TE in ~7 days
  - Maximum polarization a few months

![Graph showing polarization changes over time](image-url)
Polarizing the Target

- After 3 months, target transferred from DF to PD for NMR
- Polarization can be determined and compared to before HD was aged in DF
Target Transfer: PD to SD

Target transfer to SD for storage/transport
Target Transfer: PD to SD

Target transfer to SD for storage/transport
Target Transfer: PD to SD

Target transfer to SD for storage/transport
Target Transfer: PD to SD

Target transfer to SD for storage/transport
• SD (with target) may be transported while magnet is on (persistent mode) and LHe space pumped to 1.7 K
For in-beam operations (data-taking), the In-Beam Cryostat (IBC) is used.
In-Beam Cryostat (IBC)

- IBC is a Dilution Refrigerator capable of operating both vertically (for docking with TC) and horizontally (for data-taking).
- $T = 50 \text{ mK}$
- $B = 1 \text{ T (solenoid); } 0.075 \text{ T (saddle)}$
In-Beam Cryostat (IBC)

- IBC is a Dilution Refrigerator capable of operating both vertically (for docking with TC) and horizontally (for data-taking).
- $T = 50 \text{ mK}$
- $B = 1 \text{ T (solenoid)}; 0.075 \text{ T (saddle)}$
...Is there anything we can do to improve the target polarization?

- $P(H) = 90\%$ and $P(D) = 30\%$ are **ideal** values.
- In reality, $P(H) = 60\pm 5\%$ and $P(D) = 15\pm 7\%$ is essentially the best we can hope for using aging alone.
- Can we give some of the H polarization to D?
Polarization Transfer

- Forbidden Adiabatic Fast Passage (FAFP):
  - Uses one large RF field sweep to transfer $P(H)$ to $P(D)$
  - Pros: potential 100% efficiency
  - Cons: only one chance (one large RF field sweep), everything must work perfectly, high RF power heats fridge, (RF) field jitter decreases efficiency

- Saturated Fast Passage-Multi FAFP:
  - Uses many small RF sweeps to transfer $P(H)$ to $P(D)$
  - Pros: guaranteed efficiency is 50%, lower RF power → less heating, (RF) field jitter helps
  - Cons: max efficiency is 50%
Polarization Transfer

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

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

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

\[ \text{P}(D) = 27 \pm 1\% \]
Analyses using g14 data

**Dao Ho (CMU):**
\[ \gamma_c D \rightarrow p \pi^- (p) \]
\[ \gamma_c D \rightarrow K^0 \Lambda (p) \]
\[ \gamma_c D \rightarrow D \pi^+ \pi^- \]
\[ \gamma_c D \rightarrow K^0 \Sigma^0 \]

**Peng Peng (UVA):**
\[ \gamma_c p(n) \rightarrow p \pi^+ \pi^- (n) \]
\[ \gamma_c n(p) \rightarrow n \pi^+ \pi^- (p) \]
\[ \gamma_c n(p) \rightarrow p \pi^- (p) \]

**Irene Zonta (Roma-II):**
\[ \gamma_c n(p) \rightarrow \rho n(p) \rightarrow n \pi^+ \pi^- (p) \]

**Tsuneo Kageya (JLab):**
\[ \gamma_c n(p) \rightarrow p \pi^- (p) \]

**Haiyun Lu (CMU, U. Iowa):**
\[ \gamma_L n(p) \rightarrow p \pi^- (p) \]

**Jamie Fleming (U. Edinburgh):**
\[ \gamma_L p \rightarrow p \pi^+ \pi^- \]
\[ \gamma_L n(p) \rightarrow n \pi^+ \pi^- (p) \]
\[ \gamma_c n(p) \rightarrow K^+ \Sigma^- (p) \]
Analyses using g14 data

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\[ \gamma_c D \to K^0 \Sigma^0 \]

Peng Peng (UVA):
\[ \gamma_c p(n) \to p \pi^+ \pi^- (n) \]
\[ \gamma_c n(p) \to n \pi^+ \pi^- (p) \]
\[ \gamma_c n(p) \to p \pi^- (p) \]

Tsuneo Kageya (JLab):
\[ \gamma_L n(p) \to p \pi^- (p) \]
\[ \gamma_L p \to p \pi^- \pi \]
\[ \gamma_L n(p) \to n \pi^+ \pi^- (p) \]
\[ \gamma_c n(p) \to K^+ \Sigma^- (p) \]

To be discussed at the Hadron Spectroscopy Working Group Meeting tomorrow
eHD

- During g14, eHD tests were conducted to study how the target (and IBC) fared with electrons.
eHD during g14

• Three depolarization mechanisms were found.

• Local beam heating:
  - The T1 of the target material is a function of B/T.
  - Temperature spikes reduce the T1 → no more frozen spin

• Unpairing of 1s electrons:
  - Beam heating unpairs the electrons in 1s shell
  - Residual electron is unpolarized (function of temp) → flips with a frequency that has Fourier components at D and H Larmor frequencies
  - Depolarizes nearby HD; depolarization spreads

• Ionization of HD:
  - HD molecule loses an electron (becomes ionized), is highly reactive
  - Chain of chemical reactions begin which culminate in a “recombination flash” → produces significant heat in target → loss of polarization
eHD during g14

Recombination Flash!

IBC target temp

some mixture out of IBC (note zero suppression)

Beam current

Charles Hanretty (JLab)

The HDice Target at JLab

17 June 2015
Three depolarization mechanisms were found.

- Local beam heating:
  - The T1 of the target material is a function of B/T.
  - Temperature spikes reduce the T1 and no more frozen spin.

- Unpairing of 1s electrons:
  - Beam heating unpairs the electrons in the 1s shell.
  - Residual electron is unpolarized (function of temperature).
  - Flips with a frequency that has Fourier components at D and H Larmor frequencies.
  - Depolarizes nearby HD; depolarization spreads.

- Ionization of HD:
  - HD molecule loses an electron (becomes ionized), is highly reactive.
  - Chain of chemical reactions begin which culminate in a “recombination flash” → produces significant heat in target → loss of polarization.

Solutions:
- Make target cell shorter and fatter.
- Make Aluminum wires shorter and fatter to remove heat faster.
- Faster Raster.
eHD: Target cell redesign

**g14 Cell:**

- 750 × 50μ Al wires
- pCTFE cell
- 15 mm Ø
- 50 mm
- Copper ring with RH/LH threads
eHD: Target cell redesign

- eHD target cell will be half the length and almost twice the diameter of the g14 cell
- Aluminum wires will be shorter and thicker
- Effect: Lower equilibrium temperature of HD
eHD: Target cell redesign

- eHD target cell will be half the length and almost twice the diameter of the g14 cell
- Aluminum wires will be shorter and thicker
- Effect: Lower equilibrium temperature of HD
The HDice Target at JLab

17 June 2015

New target cell design leads to equilibrium temp of 145 mK but local temps can still reach over 1000 mK

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eHD: Faster Raster

Equilibrium temp = 145 mK
Max local temp = 1.02 K

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Beam

What's a Raster?

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Upstream face of target

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What's a Raster?

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Charles Hanretty (JLab)
eHD: Faster Raster

- New target cell design leads to equilibrium temp of 145 mK but local temps can still reach over 1000 mK
eHD: Faster Raster

- New target cell design leads to equilibrium temp of 145 mK but local temps can still reach over 1000 mK
- By increasing the speed of the Raster (and altering the pattern), the temperature of the target material is greatly reduced

![Graph showing target temp using (new) Hall B Fast Raster](image)

- Equilibrium temp = 145 mK
- Max local temp = 286 mK / 331 mK
- Refresh rate = 900 Hz
- Max Freq = 24 kHz
eHD Tests in UITF
The Energy of the eHD tests is 5-10 MeV with a relative energy spread \( \sigma_E/E < 10^{-3} \). The current range is 100 pA to 5 nA in continuous wave (CW) mode, with a tune mode of 100 nA. The size of the beam is constrained by the condition \( 50 \mu m < \sigma_{x,y} < 150 \mu m \). Stability is maintained within \( \sigma_{x,y} \). The beam halo is less than \( 10^{-4} \). The polarization is greater than 70%, and the helicity flip frequency is 1-30 Hz.
eHD Tests in UITF

- **Energy**: 5-10 MeV; \( \sigma E/E < 10^{-3} \)
- **Current**: 100 pA-5 nA CW
  - 100 nA Tune-mode
- **Size**: \( 50 \mu m < \sigma_{x,y} < 150 \mu m \)
- **Stability**: within \( \sigma_{x,y} \)
- **Beam Halo**: \( < 10^{-4} \)
- **Polarization**: > 70%
- **Helicity flip**: 1-30 Hz

UITF at 10 MeV \( \simeq \) Hall B at 10 GeV

Ionization and energy deposition are approx independent of \( E_{\text{beam}} \)
Summary

- HDice is a new type frozen spin target designed for fixed target experiments at JLab.
- Is a complicated target system utilizing many steps and pieces of equipment in the production of a single target cell.
- Has been used with photons as part of the N* program in Hall B (g14).
- Has potential as a transversely polarized frozen spin target for use with electrons → no large magnets.
- eHD tests to be carried out in the UITF in Fall 2016
Cryostats

Helium Evaporation Fridge

LHe bath (4K)

VariTemp: 4K, 2K

VariTemp: 4K, 2K

LHe bath (4K)

Magnet

Magnet

LN: 77K

Insulating vacuum

LN: 77K

Insulating vacuum
Cryostats

(Horizontal) Dilution Fridge

LHe Bath: 4K

1K Pot

1K

Still: ~600 mK

Mixing Chamber: 50 mK (IBC)
10 mK (DF)

Target cell (IBC)

He3/He4 mixture

H₃ rich

LHe3

H₄ rich

LHe4

(to pump)
Great, so that means that $P(H)=90\%$ and $P(D)=30\%$, right?

If it were only that simple

$P(H)=90\%$ and $P(D)=30\%$ are TE values at 15 T and 10 mK

There are two effects that must strike a balance in this process:

As the (L=1) H2 and D2 states decay, the T1 of the target material grows
$\Rightarrow$ takes longer to reach the TE values
(deg of pol increases slower and slower)

L=1$\rightarrow$0 decays release heat which must be removed from the HD in order to reach the TE values
$\Rightarrow$ HD can't immediately reach low temperatures (10 mK)
(max pol is decreased)

The result is that $P(H)=60\pm5\%$ and $P(D)=15\pm7\%$
Target transfer & transport

T = 1.7 K
B = 4.5 T
Holds 3 targets

T = 4.2, 1.7 K
B = 3 T
Holds one target

Target transfer to SD for storage/transport
TC mounted on top of the DF
Target stacking in DF

8 ft
UITF Beamline

(A compressed view)

6 GeV Fast Raster
HDice_TN28: C. D. Bass,
Development of fast rasters for eHD test runs and experiments)

Being built by C. Cuevas
UITF Beamline

(A compressed view)

6 GeV Fast Raster
HDice_TN28: C. D. Bass,
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Being built by C. Cuevas
The following slides are pictures/cartoons made by [CMH]
$H_{2}$ = Hydrogen
$D_{2}$ = Deuterium
$s = 1/2, 3/2$
$L = 0$

Ortho-$H_{2}$ (sym)

Para-$D_{2}$ (anti-sym)

Para-$H_{2}$ (anti-sym)

Ortho-$D_{2}$ (sym)
$^2$H = Hydrogen
$^2$D = Deuterium
$S = \text{Spin}$
$\uparrow$ = Hydrogen
$\downarrow$ = Deuterium

Ortho-$H_2$ (sym)
Para-$H_2$ (anti-sym)
$H_2$

172 K

Para-$D_2$ (anti-sym)
Ortho-$D_2$ (sym)
$D_2$

128 K

86 K
$H_2$, $D_2$, $S=0, 1$, $L=0, 1$

Ortho-$H_2$ (sym) $\rightarrow$ Para-$H_2$ (anti-sym)

Para-$H_2$ (anti-sym) $\rightarrow$ $H_2$

Para-$D_2$ (anti-sym) $\rightarrow$ Ortho-$D_2$ (sym)

$B_{L=1} \cdot S_H$
Cryostats

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VariTemp: 4K, 2K

VariTemp: 4K, 2K

LHe bath (4K)

Magnet

Magnet

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LN: 77K

Insulating vacuum
Cryostats

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H₄ rich

LHe4