Potential for $\bar{e}+\bar{\text{HD}}$ experiments with Frozen-Spin HD

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experiments with polarized $^3$He

- $^3$He lifetimes with photon beams $\sim 2$ years:
  - PRL 102 (2009) 172002; PRL 118 (2017) 242002; ...
  - NIM A737 (2014) 107; NIM A815 (2016) 31; ...

- next goal – viable transverse frozen-spin target with electron beams

- PAC 39:

  ◊ SIDIS, C12-11-111, M. Contalbrigo,…
  ◊ dihadron production, PR12-12-009, H. Avakian,…
  ◊ DVCS, PR12-12-101, L. Elouadhrhiri,…
steps in polarizing solid HD – a brief overview

- HD gas distilled with impurity concentrations, $c = 10^{-3}$ to $10^{-4}$ of H$_2$ & D$_2$
- condensed to a solid, $\frac{3}{4}$ of H$_2$ & $\frac{1}{3}$ of D$_2$ are caught in their J=1 levels
- magnet field aligns 1$^{st}$ rotational states (J=1) of Ortho-H$_2$ & Para-D$_2$
- H$_2$ (& D$_2$) spin exchange with HD, polarizing target to $P(H) \sim 60$
- spin-exchange stops as J=1 states decay away $\Rightarrow$ HD with frozen spin

Ortho-H$_2$

\[
\begin{array}{c}
\uparrow \uparrow \\
I=1 \\
J=1 \\
172 \text{ K}
\end{array}
\]

Para-H$_2$

\[
\begin{array}{c}
\downarrow \\
I=0 \\
J=0 \\
H_2
\end{array}
\]

HD

\[
\begin{array}{c}
\downarrow \\
I=0, 2 \\
J=0 \\
D_2
\end{array}
\]

Para-D$_2$

\[
\begin{array}{c}
\uparrow \uparrow \\
I=1 \\
J=1 \\
86 \text{ K}
\end{array}
\]

Ortho-D$_2$

\[
\begin{array}{c}
\downarrow \\
I=0, 2 \\
J=0
\end{array}
\]
I. e\textsuperscript{-} beam ionization unpairs 1s molecular electrons of HD
- if residual 1s electron is unpolarized (depends on temperature)
  \rightarrow \text{flips with Fourier components at nuclear Larmor frequencies}
  \rightarrow \text{depolarizes the local HD}
  \rightarrow \text{depolarization diffuses out into the rest of the HD crystal}

\bullet \ T(\text{HD}) \sim 1.2\text{K in 2012 test runs}
  \rightarrow \text{P(e) \sim 20-50%}
  \rightarrow \text{depolarization is expected}
\Leftrightarrow \text{observed \sim 1 nA\text{-day in tests}
I. $e^-$ beam ionization unpairs $1s$ molecular electrons of HD
- if residual $1s$ electron is unpolarized (depends on temperature)
  - flips with Fourier components at nuclear Larmor frequencies
  - depolarizes the local HD
  - depolarization diffuses out into the rest of the HD crystal

Solution:
- colder running temps
  (new cell, new fast raster):
  - expected HDtemp $\sim 210 \pm 70$ mK
  - $B \sim 1 \frac{1}{4}$ tesla

$\Rightarrow$ will insure $P(e) \sim 100\%$
II. Hyperfine mixing of unpaired electrons with H spins

- $\mu(e)$ opposite in sign to that of H (or D)
- electrons polarized in the holding field have spins opposite to H
- total angular momentum projected along B is less than maximal
- Hyperfine mixing of $|F, m_F = m_H + m_e\rangle$ states with different $m_H$
  $\leftrightarrow \frac{1}{\sqrt{2}} \left\{ |\uparrow_H \downarrow_e\rangle + |\downarrow_H \uparrow_e\rangle \right\} \leftrightarrow$ dilutes H polarization
- depolarization can diffuse out into the rest of the HD crystal
  $\Rightarrow$ depolarization $\propto B^{-2}$ (& independent of temperature)
  (should also have contributed to depolarization in 2012 tests)

Solutions:
- use RF flip of H (or D) to align nuclear and electron spins $|\downarrow_H \downarrow_e\rangle$
- stretched state with maximal angular mom projection $\leftrightarrow$ unique
- prevents depolarization through hyperfine mixing
III. Radiation-induced Chemical changes
(following parallel literature on tritium chemistry after beta decay)

- ionized HD$^+$ will be highly reactive

- $\text{HD}^+ + \text{HD} \Leftrightarrow \text{H}_2\text{D}^+ + \text{D}$

  or $\Leftrightarrow \text{HD}_2^+ + \text{H}$

  $\uparrow$ no effect on polarization (paired e$^-$), but highly mobile

- $\text{H}_2\text{D}^+ + \text{e}^- \Leftrightarrow \text{H}_2 + \text{D} , ...$

  $\Rightarrow$ increased concentrations of (J=1) ortho-$\text{H}_2$ (para-$\text{D}_2$)

  $\uparrow$ polarization catalysts

  $\Rightarrow$ could H (& D) loose their frozen spin state?
Spin Transfer: eQQ and the role of J=1 pairs

- Molecular J=0 ground states are spherically symmetric.
- J=1 rotational excitations are NOT spatially degenerate.

Spatial degeneracy of an isolated J=1 H₂ or D₂ molecule

Very small energy splitting when a single J=1 is surrounded by other J=0 molecules

Degeneracy is lifted by large eQQ of a pair of J=1 molecule

I. Silvera, Rev Mod Phys 52 (1980) 393

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spin transfer mechanism - through J=1 pairs

- in some orientations, the electric Quadrupole-Quadrupole (eQQ) interaction is attractive
  - overwhelmed by collisions in the gas or liquid states
  - but this binding can be a significant effect in a solid

⇔ a J=1 molecule at the solid-liquid boundary (triple pt) has a slightly increased probability of capturing another J=1

- phonons in the solid lattice scatters from eQ moments of J=1 x J=1 molecular pairs, causing sudden transitions between their 3 x 3 substates
  - transitions ⇔ spatial reorientations
  - the magnetic dipole moments of the J=1 rotating molecules follow the reorientation

⇔ there is a sudden change in the magnetic field in the vicinity of nearby a HD, with Fourier components at H and D Larmor frequencies

degeneracy
Is lifted by large eQQ of a pair of J=1 molecule

I. Silvera, Rev Mod Phys 52 (1980) 393
Spin transfer mechanism

\[ \Rightarrow \text{these induces spin flips of H or D in nearby HD} \]

\[ \Rightarrow \text{depolarization resonantly hops outward through the HD (a Quantum crystal)} \]

- eQQ interaction energies are almost the same for all combinations of J=1 pairs:
  \[ (\text{oH}_2) \times (\text{oH}_2) \]
  \[ (\text{oH}_2) \times (\text{pD}_2) \]
  \[ (\text{pD}_2) \times (\text{pD}_2) \]

- number of J=1 x J=1 clusters is proportional to:
  \[ c(\text{oH}_2) \cdot c(\text{oH}_2) + 2 \cdot c(\text{oH}_2) \cdot c(\text{pD}_2) + c(\text{pD}_2) \cdot c(\text{pD}_2) \]
Reference gas (used for tune-up)

distilled NP grade gas

\[ c(H_2) = \frac{H_2}{HD} = 0.01874 \pm 0.00005 \]
\[ c(D_2) = \frac{D_2}{HD} = 0.01533 \pm 0.00012 \]

\[ c(H_2) = \frac{H_2}{HD} = 0.00067 \pm 0.00002 \]
\[ c(D_2) = \frac{D_2}{HD} = 0.00064 \pm 0.00004 \]
Correlations between $T_1$ (2K) and $c(H_2), c(D_2)$ from Raman

Measurements on a large number of distilled HD gas samples over the last decade:

- $T_1$ (2K) measurements, &
- Raman measurements of $c(H_2), c(D_2)$

- $T_1$ increases with time as $c(\text{ortho-H}_2)$ and $c(\text{para-D}_2)$ drop

- $c(\text{oH}_2) = \frac{3}{4} c(H_2) \exp(-t/6 \text{ days})$
- $c(\text{pD}_2) = \frac{1}{2} c(D_2) \exp(-t/27 \text{ days})$
Polarization decay ($T_1$) correlated with number of $J=1$ pairs

$T_1^H$ (sec)

$T_1$ at 2K

$c(\text{OH}_2)^2 + 2xc(\text{OH}_2)c(\text{pD}_2) + c(\text{pD}_2)c(\text{pD}_2)$
III. Radiation-induced Chemical changes

(following parallel literature on tritium chemistry after beta decay)

- Ionized HD\(^+\) will be highly reactive

- HD\(^+\) + HD $\Rightarrow$ H\(_2\)D\(^+\) + D   
  Or $\Rightarrow$ HD\(_2\)\(^+\) + H
  $\uparrow$ no effect on polarization (paired e\(^-\)), but highly mobile

- H\(_2\)D\(^+\) + e\(^-\) $\Rightarrow$ H\(_2\) + D , ...
  $\Rightarrow$ increased concentrations of (J=1) ortho-H\(_2\) (para-D\(_2\))
  $\uparrow$ polarization catalysts

  $\Rightarrow$ could H (& D) loose their frozen spin state?

Solution:

- Chemical processes will **NOT** produce J=1 species in pairs!
e− beam-induced depolarization mechanisms:

I. production of paramagnetic, unpaired electrons
   ⇔ should no be an issue at colder temperatures where they are fully polarized

II. polarization dilution through hyperfine splitting (HFS)
    ⇔ eliminate by operating with target and electron spins aligned

III. regeneration of J=1 rotational states through chain reactions
     ⇔ cannot generate the pairs of J=1 molecules that generate spin flips

Extrapolations from 2012 e+HD tests:

⇔ if the higher temperatures during the 2012 tests were the only source of loss, via the 1st mechanism, then we anticipate that our improvements would give
~ 400 nA-hr lifetimes, ... and possibly longer if HFS was an issue
Testing eHD at Jlab’s **Upgraded Injector Test Facility (UITF)**

- **Energy:** 7 – 10 MeV; $\sigma_E/E < 10^{-3}$
- **Current:** 100 pA – 5 nA CW
  - 100 nA Tune-mode
- **Size:** 50 µm $< \sigma_{x,y} < 150$ µm
- **Stability:** within $\sigma_{x,y}$
- **Beam Halo:** $< 10^{-4}$
- **Polarization:** $> 70\%$
- **Helicity flip:** 1-30 Hz
Electron energy loss in 5 cm of HD:

- loss dominated by bremsstrahlung

- deposition dominated by Møllers
  \( \sigma_{\text{Møller}} \sim (1 + 1/\gamma)^2 \)
  ~ independent of beam energy

- deposition: 2 Mev/e\(^-\) = 1 mW/ 1/2 nA
  ~ independent of beam energy
eg. pencil beam offset 14 mm at launch
- significant edge focusing from solenoids
- electrons make 2 ¼ rotations through In-Beam Cryostat (IBC)
electron transport studied with **G4BeamLine**

- UITF beam energy tuned to 7.86 MeV
- shifts focusing node to HD front face

eg. pencil beam into IBC with 14 mm offset

- offset focused to 10 mm at HD

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electron transport studied with G4BeamLine©

- UITF beam energy tuned to 7.86 MeV
- focusing node at HD front face

eg. uniform rastered beam on target

- 21 mm Ø HD target
**Heat load ➔ polarization of molecular electrons**

- beam will ionize HD, breaking paired 1s electrons
- unpaired electrons will be inert if they polarize in the 0.9 T IBC field
- polarization depends on temperature
- HD temp depends on deposited beam power & temp of Cu heat sink (↔ cooling pwr of IBC refrigerator)

<table>
<thead>
<tr>
<th>$P_e$</th>
<th>$I_e$</th>
<th>$Q_{HD}$</th>
<th>$T_{HD}^{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.99977</td>
<td>2 nA</td>
<td>1 mW</td>
<td>138 mK</td>
</tr>
<tr>
<td>0.99999</td>
<td>1 nA</td>
<td>½ mW</td>
<td>98 mK</td>
</tr>
</tbody>
</table>

↑ very promising!
eHD testing schedule

- beam up to ¼ CryoModule in cave-1 ✔
- 10 MeV OPS - waiting for the completion of safety reviews, expected ~ Dec/2018
- 1<sup>st</sup> beam into In-Beam Cryostat to study transport ~ Feb/2019
- beam on unpolarized HD ~ April/2019
- 1<sup>st</sup> beam on polarized HD ~ June/2019
Trapping a transverse field in an MgB$_2$ diamagnetic shell

- energize 1¼ T external Dipole magnet
- cool MgB$_2$ shell within the HDice IBC to 4K ($T_c = 39$ K)
- load polarized HD into the IBC, within the MgB$_2$ shell
- lower external Dipole field → 0
  ⇒ currents spontaneously flow in MgB$_2$ to maintain original internal field
  ⇒ talk by Marco Statera
• MgB$_2$ retains the “memory” of fields present when it was cooled below $T_c$ and became a diamagnetic SC

• as CLAS12 solenoid is energized, complex currents develop in the MgB$_2$ that are much more intricate than could be realized with an electromagnet

• rotate IBC horizontal and roll into CLAS12

• ramp up field in CLAS12 solenoid ⇒ additional currents begin to flow in MgB$_2$ to maintain original transverse field

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• chemical recombination is a function of concentration and mobility
• energy release raises local temp $\Rightarrow$ increases mobility
  $\Rightarrow$ can produce a chain reaction, a recombination flash

Recombination Flash!
15 min after beam-off

some mixture out of IBC (note zero suppression)

$^3\text{He}/^4\text{He}$ pressure in circulation line

e$^-$ beam current

IBC MIX temp

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• **g14 flash events**: about 1/week (from $\gamma \rightarrow e^\pm$ pair production)

Effect on polarization?
• **most** (as above example from Jan 24/12) had no effect on g14 targets
• **but events will be more frequent** with $e^-$ beams
Polarization decay ($T_1$) correlated with number of J=1 pairs

$T_1^H$ (sec)

$T_1^H$ (sec)

$T_1$ at 2K

$c(oH_2)$

$c(oH_2)^2 + 2xc(oH_2)c(pD_2) + c(pD_2)c(pD_2)$