Tensor Polarization on Solid Polarized Targets at UNH

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(she/her)

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2025-06-10

University of New Hampshire

Tensor Polarization

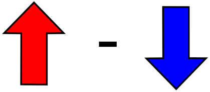
What Deuterons Do That Protons Don't

Proton

Spin-$\frac{1}{2}$ System

$m = +\frac{1}{2}$ $m = -\frac{1}{2}$

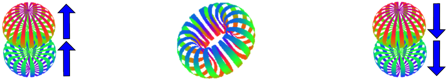
"Typical" Vector Polarization



$$P = p_+ - p_-$$

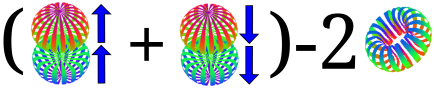
Deuteron

Spin-1 System



$m = +1$ $m = 0$ $m = -1$

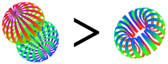
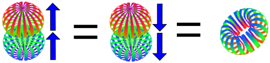
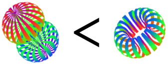
Vector **and** Tensor Polarization

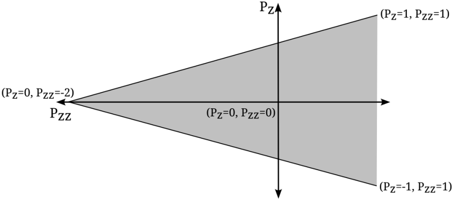


$$Q = (p_+ + p_-) - 2p_0$$

J Forest, et al, PRC **54** 646 (1996)

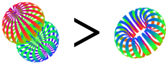
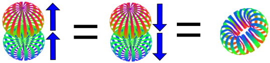
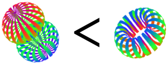
Tensor Polarization Properties

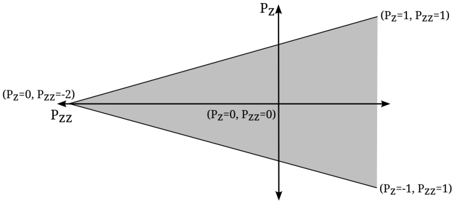
If. . .	**Then. . .**
	$0 < Q \leq 1$
	$Q = 0$
	$-2 \leq Q < 0$



- P ranges from -1 to +1
- Q ranges from -2 to +1
- In deuterons both P and Q can be nonzero simultaneously

Tensor Polarization Properties

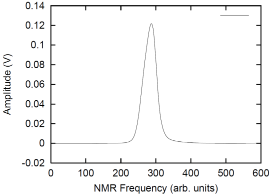
If...	Then...
	$0 < Q \leq 1$
	$Q = 0$
	$-2 \leq Q < 0$



A high-luminosity tensor-polarized target has promise as a novel probe of nuclear physics

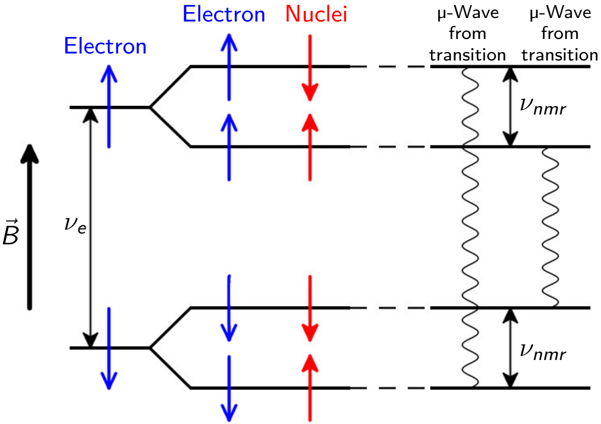
Dynamic Nuclear Polarization (DNP)

- Using μwaves, drive spin transitions of unpaired electrons
- Electrons transfer spin to nuclei
- Nuclear absorption spectrum gives polarimetry info



Above: Characteristic lineshape of the proton

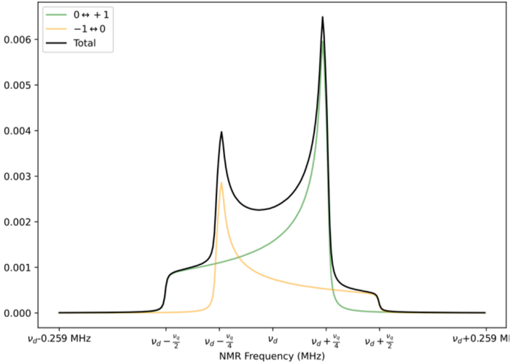
C.D. Keith *et al*, NIM A **501** (2003)



Above: Diagram of the energy level transitions in the DNP process. Adapted from *Annu. Rev. Nucl. Part. Sci. 1997. 47:67-109*

Deuteron Polarization

- NMR at nuclear spin transition frequency drives further spin transitions
- Proton lineshape from $-1/2 \leftrightarrow 1/2$ transition
- Deuteron lineshape has $-1 \leftrightarrow 0$ and $0 \leftrightarrow 1$ components
    - But NMR only gives the sum of the two
- Signal shape affected by material properties and magnetic field angle

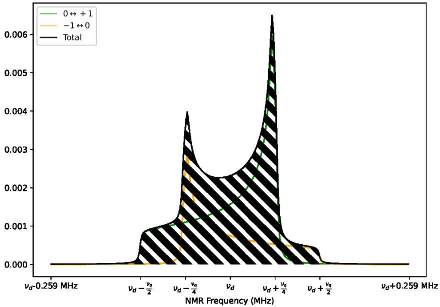


Above: Simulated deuteron lineshape showing the contributions from both the $-1 \rightarrow 0$ transition and the $0 \rightarrow 1$ transition.

Measuring Tensor Polarization

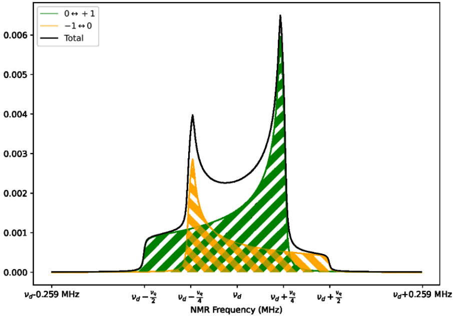
Vector Polarization Measurement

$$P = C(I_+ + I_-) \quad (1)$$



Tensor Polarization Measurement

$$Q = C(I_+ - I_-) \quad (2)$$



where C is a dimensionless calibration constant, $I_+ = n_+ - n_0$, and $I_- = n_0 - n_-$

Figures courtesy of E. Long

The Tensor Experiments

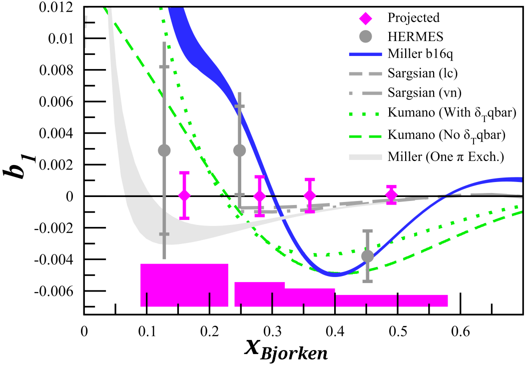
b_1 Experiment

- Intended to improve upon HERMES' 2005 data
- Verifications of zero-crossing
  - Implications for Close-Kumano sum rule
- Tensor physics at quark level
- Better understanding of b_1 allows discrimination of different deuteron components by spin (e.g., quarks vs gluons)

Approved by JLab with A-physics rating!

E12-13-011

The Deuteron Tensor Structure Function b_1



K. Slifer *et al*, JLab C12-13-011 **Spokespersons:** K. Slifer, O.R. Aramayo, J.P. Chen, N. Kalantrians, D. Keller, E. Long, P. Solvignon

A_{zz} Experiment

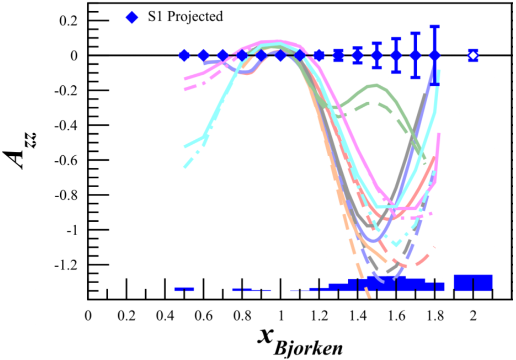
- First-of-its-kind quasielastic A_{zz} measurement
- Implications for SRC physics and deuteron wavefunction
- Widest range of x covered by a single measurement
- Measurement of T_{20} included!

Spokespersons: E. Long, K. Slifer, P. Solvignon, D. Day, D. Keller, D. Higinbotham

Approved by JLab with A-physics rating!

E12-15-005

Quasi-Elastic and Elastic Deuteron Tensor Asymmetries



E. Long *et al*, JLab C12-15-005

Tensor Target

b_1 Systematics Estimates

Source	Systematic
Polarimetry	8.0%
Dilution/Packing Fraction	4.0%
Others	2.1%
Total	9.2%

A_{zz} Systematics Estimates

Source	A_{zz} Systematic	T_{20} Systematic
Polarimetry	6.0%	6.0%
Dilution Factor	6.0%	2.5%
Packing Fraction	3.0%	3.0%
Others	2.5%	2.5%
Total	9.2%	7.4%

$$A_{zz} = \frac{2}{f\ Q}\left(\frac{\sigma_p}{\sigma_0} - 1\right)$$

Tensor Target

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Source	Systematic
Polarimetry	**8.0%**
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$$A_{zz} = \frac{2}{f\boxed{Q}}\left(\frac{\sigma_p}{\sigma_0} - 1\right)$$

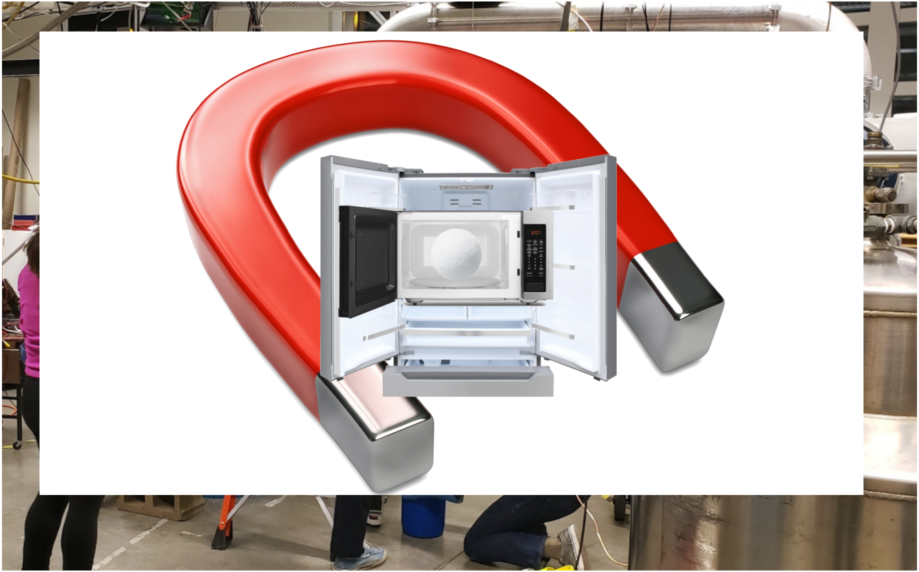
Both experiments require a highly (≥30%) tensor-polarized deuterium target with precise measurement of Q. How can we achieve that?

Target Polarization at UNH

UNH Polarized Target Lab

The UNH polarized target group is hard at work!

UNH Polarized Target Lab



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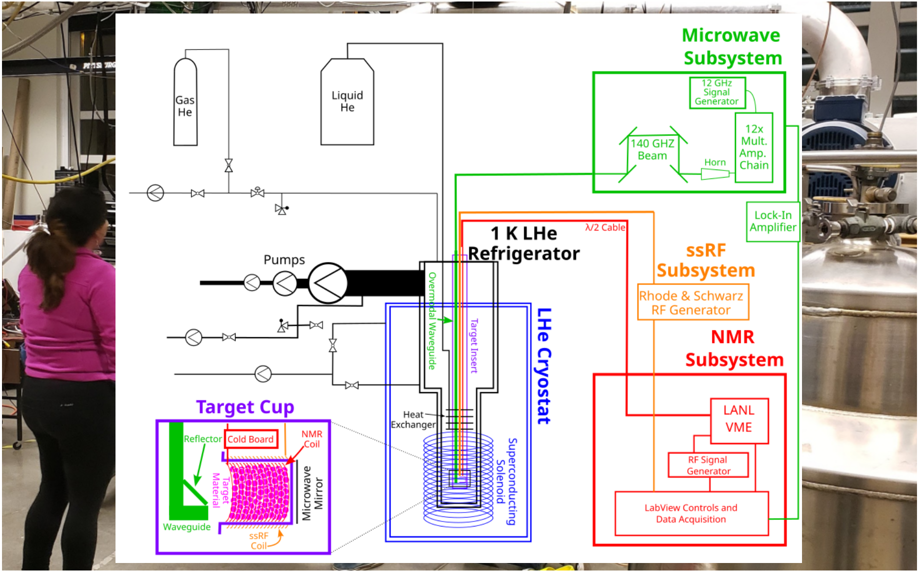
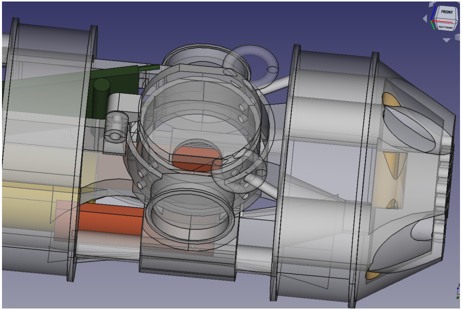


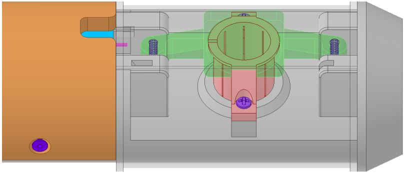
The UNH polarized target group is hard at work!

Target Cup Comparison

2022 Design



2024 Design

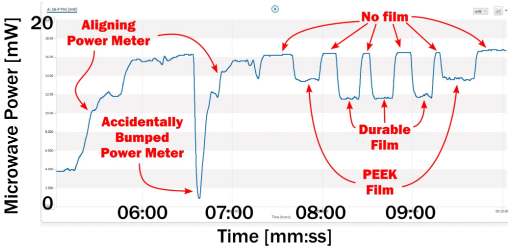


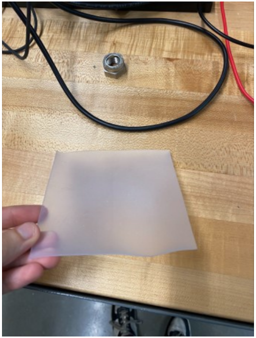
- ID: 20 mm, length: 10 mm
- Target cup fixed in ladder
- NMR coil outside cup
- Loose cup cap (material only in capsules)

- ID: 15 mm, length 16 mm
- Target cup removeable and replaceable
- NMR coil inside cup
- Tight cup cap (can have lose material)

Microwave Transmission: PEEK vs. Durable

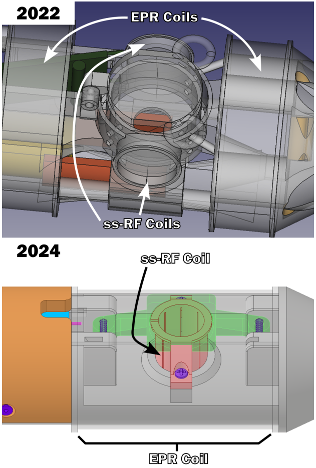
- PCTFE (Kel-F) is best plastic for target ladders, but difficult to acquire right now
- Durable resin or PEEK plastic, which transmited microwaves better?
- 0.5 mm-thick durable film: 35-40% loss at 140 GHz
- 0.5 mm-thick PEEK film: 20-25% loss at 140 GHz
- 2022 design used only durable resin, 2024 design will be first to use PEEK film





Top right: Microwave power test. **Bottom left:** PEEK film. **Bottom right:** Durable pseudo-film.

NMR Coil Winding



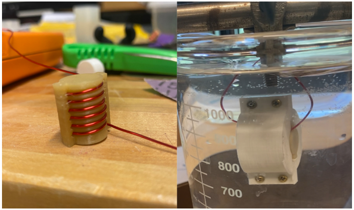
Above: 2022 and 2024 target ladder comparison with ss-RF and EPR coils labeled.

2022 Design:

- All RF coils (NMR, ss-RF, EPR) wound by hand
- NMR, ss-RF, EPR coils all on orthogonal axes
- Helmholtz ss-RF, EPR coils

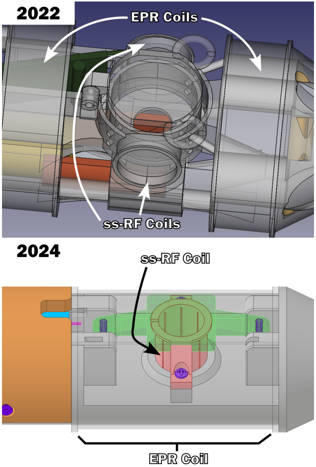
2024 Design:

- NMR coils wound on 3D-printed mold of PVA.
  - PVA is water-soluble, can dissolve to release uniform wound coil
- NMR and ss-RF coils coaxial, EPR solenoid along field direction
- Solenoidal ss-RF, EPR coils



Left: NMR coil wound around PVA mold. **Right:** Coil and mold submerged in water, to dissolve the mold away.

NMR Coil Winding



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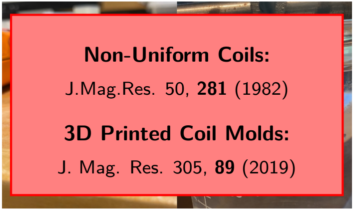
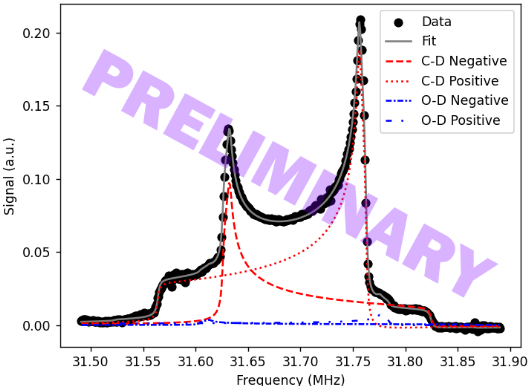


Left: NMR coil wound around PVA mold. **Right:** Coil and mold submerged in water, to dissolve the mold away.

Tensor Polarization Data

September 2024: Highest Polarization

- Polarized with Irrad. d-butanol
- Used the 2022 stick
- Fit with Dulya procedure closely matches data from recent UNH cooldown
  - C. Dulya et al, NIM A 398 (1997) 109-125
- Fit method works very well for UNH data!
- **Highest UNH deuteron vector polarization observed!**
- Q only from equilibrium, no tensor enchancement

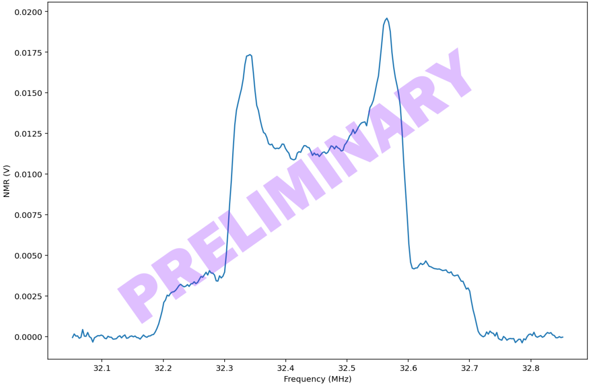


Above: Curve fit of NMR lineshape from recent target cooldown at UNH on irradiated d-butanol. courtesy of M. McClellan.

This Data (Preliminary)

P: 44.9%
Q: 15.8% (no ss-RF applied)

December 2024: First ND_3 Data

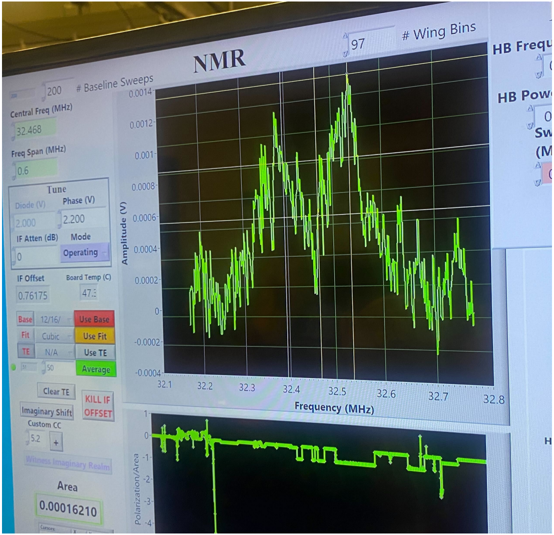


Above: ND_3 lineshape after microwave enhancement. Figure courtesy of E. Long

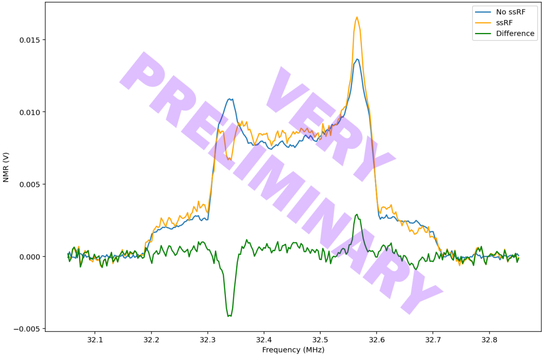
- Taken with warm-irradiated ND_3
  - Material irradiated at NIST by UNH group
- Using 2024 stick
- Lineshapes very noisy. . .
  - Fits unable to measure P or Q due to noise
  - P probably $< 10\%$
- First time ever using this batch of material
- Possible low microwave transmission?

December 2024: First ND_3 Data (TE)

- Low signal-to-noise on 2024 stick enables observation of thermal equilibrium (TE) polarization
- Observed on ND_3 on Dec. 18th
- 2024 stick has a 3x signal magnitude compared to 2022 stick
- Offline analysis made complicated by noise & NMR window size



December 2024: First ND_3 Data (ss-RF)



Above: Comparison between the lineshape before ss-RF (blue), directly following the application of ss-RF (orange), and the difference between the two at each frequency bin (green). Figure courtesy of E. Long

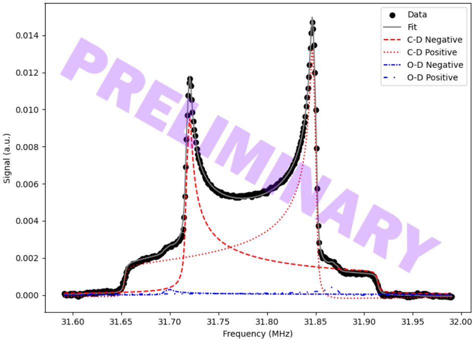
ss-RF (Hole Burning)

RF spin-manipulation at selected frequencies to enhance tensor polarization

- Applied via dedicated coil, coaxial to NMR coil
- On ND_3 burn lasted (by eye) ten minutes before lineshape recovered
- Analysis, being refined to estimated P and Q on ss-RF signal
- C. Lama developing numerical measure of lineshape recovery time

February 2025: More d-Butanol

- Polarized with Irrad. d-butanol
- Used the 2024 stick
  - Same material as Sept. 2024
- Polarization is lower on 2024 stick than on 2022 stick
- Microwave transmission down waveguide is normal. . .
- Operating theory: microwave optical effects induced by the smaller radius of the 2024 stick target cup (compared to 2022 cup)

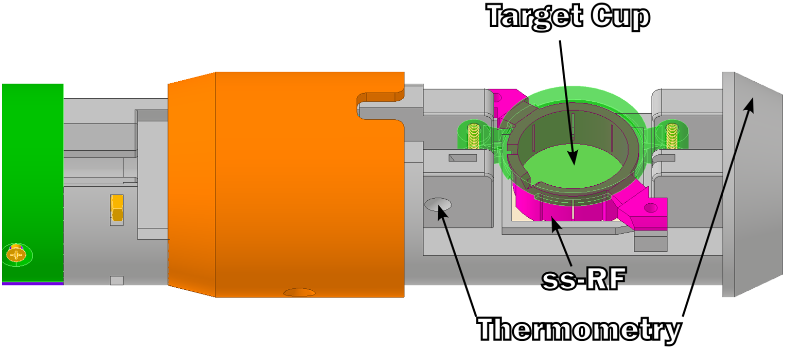


Above: Curve fit of NMR lineshape from Feb. 2025 cooldown at UNH on irradiated d-butanol. Courtesy of M. McClellan.

This Data (Preliminary)

P: 25.5%
Q: 4.9% (no ss-RF applied)

2025 Target Stick



Above: CAD design of the 2025 target ladder (codename: Diana)

- "Best of both worlds" design
- 2022 stick cup size
- 2024 stick ss-RF capability
- Will be deploying very soon!

Plus quality of life design improvements. . .

Summary

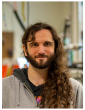
Professors


Karl Slifer

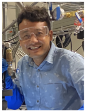

Elena Long


Nathaly Santiesteban

Graduate Students

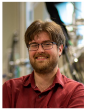

Michael McClellan


Anchit Arora


Chhetra Lama

Postdocs


Allison Zec


David Ruth

Undergraduate Student


Eli Phippard


Zoe Wolters


Muhammad Farooq


Olaiya Olokunboyo


Hector Chinchay

2024 UNH Polarized Target Group

Thank you to the UNH PolTarg Group and our collaborators at UVA!

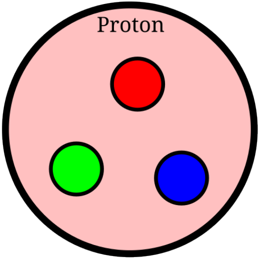
- Building up towards b_1/A_{zz} ERR
- September cooldown with 2022 stick: $> 40\%$ P
- December cooldown: first ND_3 data
- February cooldown: further data on d-butanol
- This summer: new target stick commissioning
- **Coming attractions:**
  - Lineshape fitting with ss-RF applied
  - ss-RF burn decay time analysis

Backup Slides

Protons & Deuterons

Proton

Spin-$\frac{1}{2}$ System



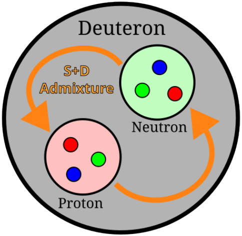
Three valence quarks + gluons and sea quarks

No nucleon-nucleon interactions

$m = \pm\frac{1}{2}$

Deuteron

Spin-1 System



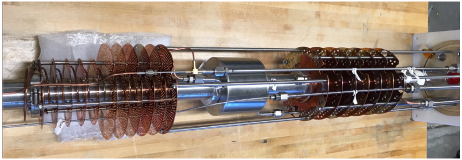
Proton-Neutron bound state

Simplest nuclear system: nucleon interaction effects

$m = \pm 1, 0$

S. Kumano, IOP Proc. Tens. Pol. Targ. (2014)

UNH Polarized Target Lab

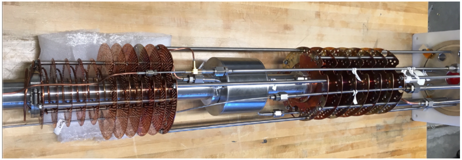


Above: UNH LHe refrigerator
D. M. Aliaga *et al.* NIM 976 (2020) 164277

Refrigerator and Magnet

1 K LHe evaporative fridge, with 2.4 W cooling power	5 T Nb-Sn superconducting solenoidal magnet

UNH Polarized Target Lab



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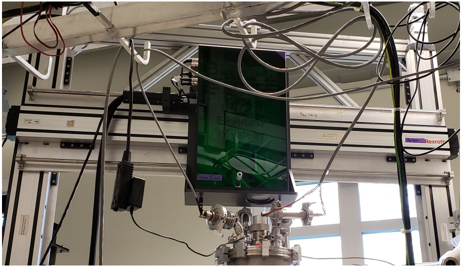
Microwaves

Solid-state microwaves producing >100 mW power between 136 and 144 GHz. Source is movable by remote motor control. System designed by Bridge12 inc.

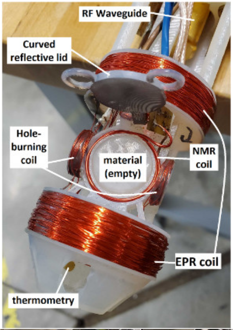
Below: Microwave source and mount.



Target Insert

Designed, printed and assembled in-house. Also houses overmodal microwave waveguide.

Right: 3D-printed target insert ladder with coils wound and no target material.



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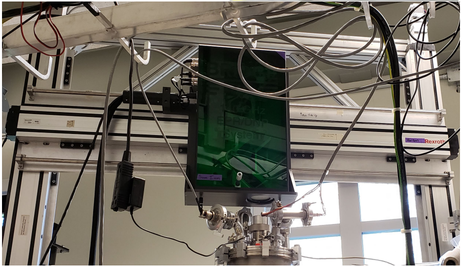

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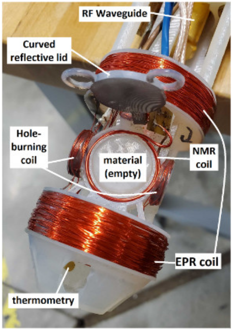
Target Insert

Designed, printed and assembled in-house. Also houses overmodal microwave waveguide.

Right: 3D-printed target insert ladder with coils wound and no target material.



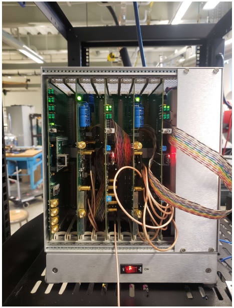
Below left: frozen unirradiated NH_3.
Below right: frozen doped butanol.

Target Material

Material, both ammonia and doped alcohols, frozen and stored on-site.

ALSO: now have irradiated deuterated ammonia!

UNH Polarized Target Lab



Left: VME crate for NMR control system and analyzer.

NMR System

NMR system with LANL design sweeps at deuteron transition frequency ($\simeq$30 MHz).

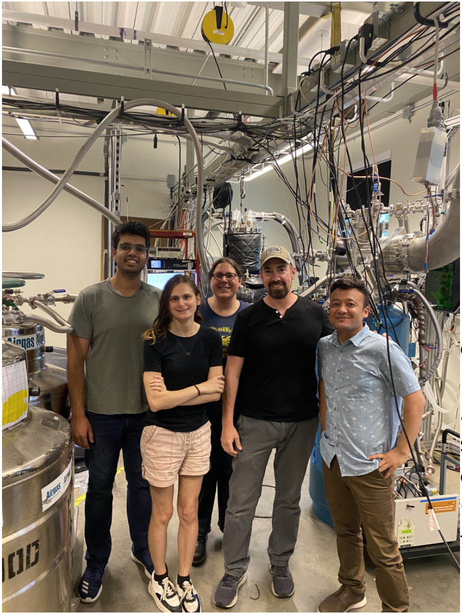
P. McGaughey, *et al*, NIM A **995** (2021) 165045

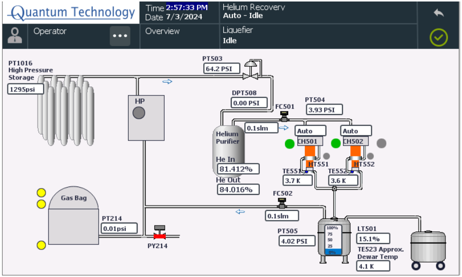
Below left: frozen unirradiated NH_3.
Below right: frozen doped butanol.

Target Material

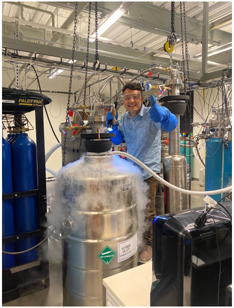
Material, both ammonia and doped alcohols, frozen and stored on-site.
ALSO: now have irradiated deuterated ammonia!

NEW Helium Reliquefaction System





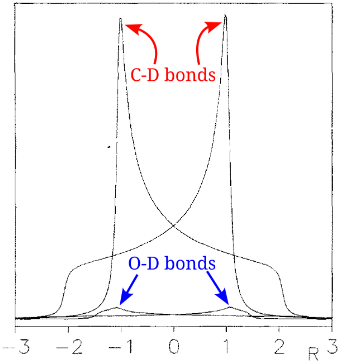
Left: group photo of the reliquefier installation team. **Above:** Reliquifier system software overview. **Right:** Chhetra adds LN2 to our helium purifier dewar.



BACKUP: Tensor Polarization Analysis

ND_3 and Other Target Materials

C. Dulya, *et al*, NIM A **398** (1997)



- Both b_1 and A_{zz} experiments call for solid ND_3 targets
- Polarization also done with frozen chemically-doped deuterated alcohols
- Lineshape affected by quadrupole splitting of molecule
  - Different for ND_3 vs butanol

Left: C-D, O-D bond contribution to the deuteron NMR lineshape in d-butanol

Material	Dopant & method	Polarizable nucleons % by weight
ND_3 d-ammonia	$\dot{N}D_2$ Irradiation	∼30%
C_4D_9OD d-butanol	TEMPO Chemical	23.7%

D. Crabb, W. Meyer, Annu. Rev. Nucl. Part. Sci **47** 67-109 (1997)

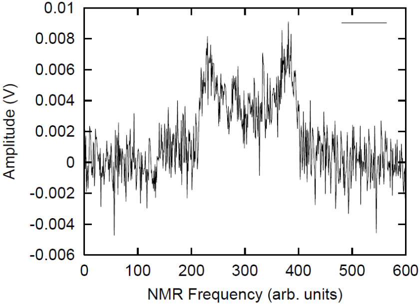
Thermal Equilibrium & Enhancement

Deuteron thermal equilibrium (TE) polarization before microwave irradiation:

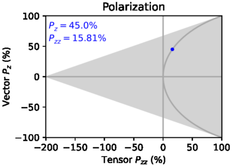
$$P(1) = \frac{4\tanh(\frac{g_i \mu_i B}{2k_B T})}{3 + \tanh^2(\frac{g_i \mu_i B}{2k_B T})} \quad (3)$$

Only 0.1% polarization at 5 T and 1 K.

TE signal can be used for calibration if detected. Signal is then enhanced with microwaves.



Above: Deuteron TE signal from CLAS target. From C. Keith *et al*, NIM A **501** (2003). *Right*: Polarization curve during enhancement.

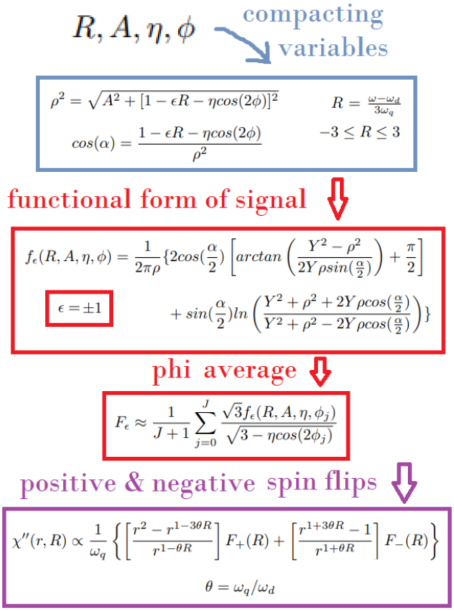


NMR Curve Fitting

- Fit NMR lineshape with procedure from C. Dulya *et al*, NIM A **398** (1997) 109-125
- Includes effects from molecular bond quadrupole terms
- Can naively use peak height ratio r to estimate polarization

$$P_z = \frac{r^2 - 1}{r + r^2 + 1}$$
$$P_{zz} = \frac{r^2 - 2r + 1}{r^2 + r + 1} \quad (4)$$

- Then compare *ratio* and *area* methods for P_{zz} measurement consistency



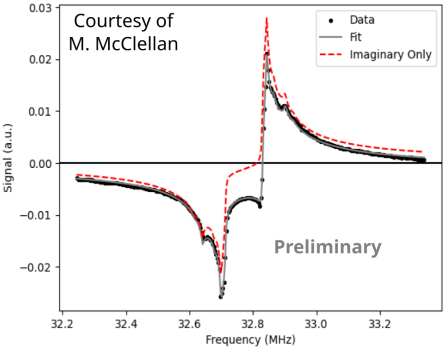
Right: Parts of the curve fitting method suggested by C. Dulya *et al.*

Real & Imaginary Fits

- Can now manually set NMR phase angle ϕ during cooldowns
- Fit using a rotation of the absorptive (χ'') and dispersive (χ') around phase angle:

$$\text{Real} = \chi'' \cos\phi - \chi' \sin\phi$$
$$\text{Imag} = \chi'' \sin\phi + \chi' \cos\phi \quad (5)$$

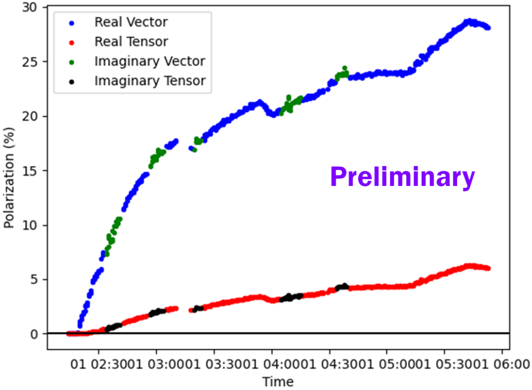
- Can fit a simultaneous mixture of real and imaginary
- First fits with the new method match data well, look very promising!



Above: Fit of recent cooldown data using real and imaginary parts. Fit is compared with an "imaginary only" signal and then fitted for a phase mistune.

Real & Imaginary NMR Signals

- Switch from real to imaginary lineshape by tuning phase
- Use fitting for real and imaginary lineshapes differently
- Demonstrated resilience to having phase not tuned perfectly
- Real and imaginary measurements match each other well!



Above: Data from recent UNH cooldown with both real and imaginary line data for both vector and tensor polarization. Figure courtesy of M. McClellan.