A Target Insert Design for the UNH Solid Polarized Target Lab

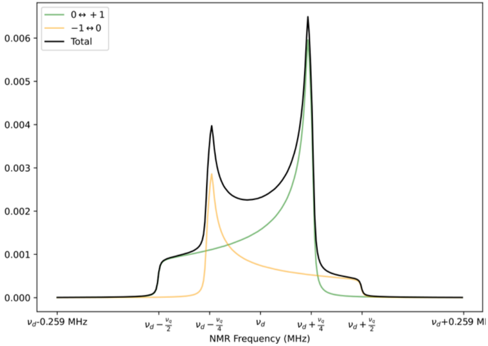
Allison J. Zec
(she/her)

Univ. of New Hampshire

2024-09-24

Deuteron DNP

- Deuterated chemically-doped/irradiated materials (alcohols primarily)
- 5 T magnetic field, 1 K temperature, 140 GHz microwaves
- 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. Simulation courtest of E. Long and M. McClellan.

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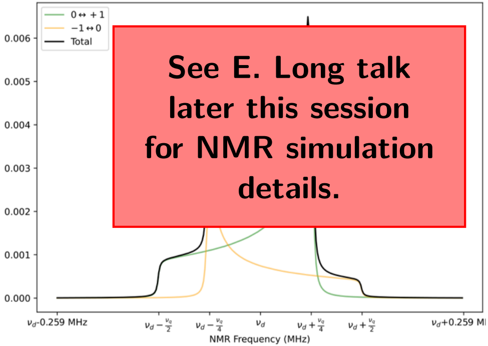


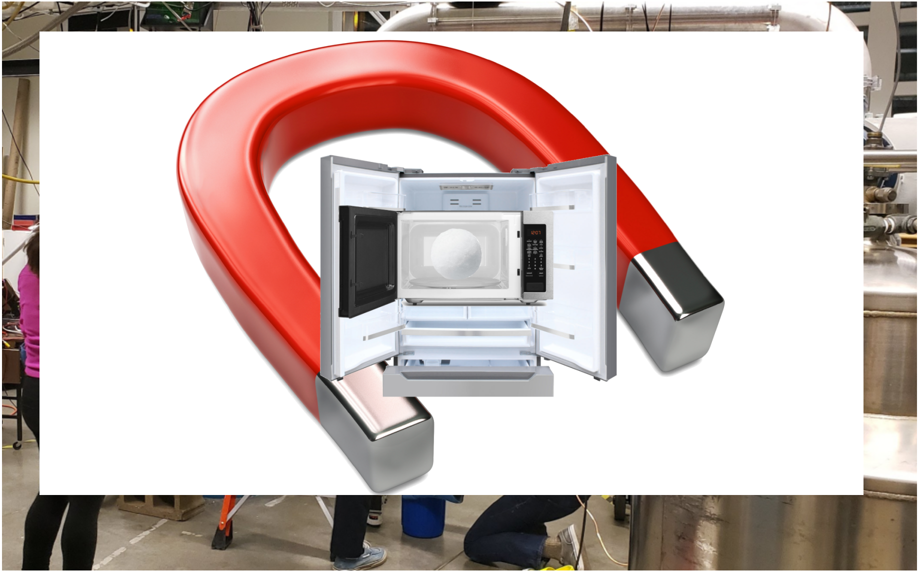
See E. Long talk later this session for NMR simulation details.

Above: Simulated deuteron lineshape showing the contributions from both the $-1 \rightarrow 0$ transition and the $0 \rightarrow 1$ transition. Simulation courtest of E. Long and M. McClellan.

UNH Polarized Target Lab

The UNH polarized target group is hard at work!

UNH Polarized Target Lab



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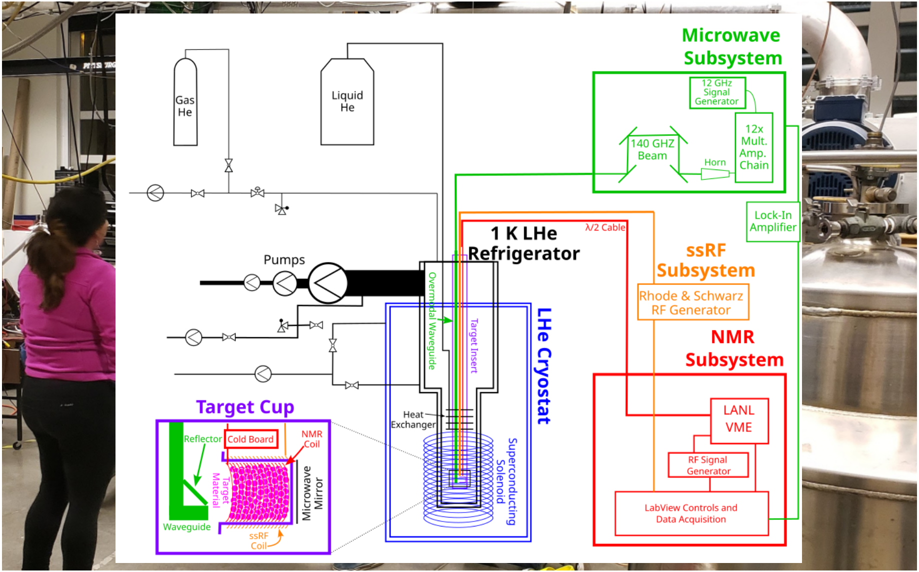
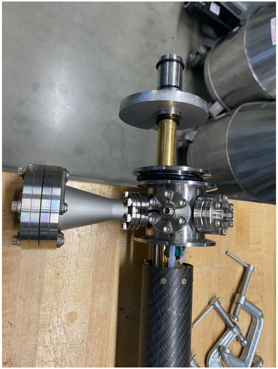
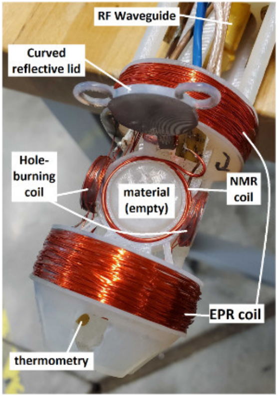


The UNH polarized target group is hard at work!

2022 Target Stick

- Designed 2021-2022, assembled in spring 2022
- 3D printed target ladder using FormLabs “durable” resin
- One target cup, plus ss-RF and EPR capability
- Hand-wound RF-coils
- Includes both Temati CCS and Lake Shore Cernox thermometry
- **Used in all UNH cooldowns from 2022 until now**

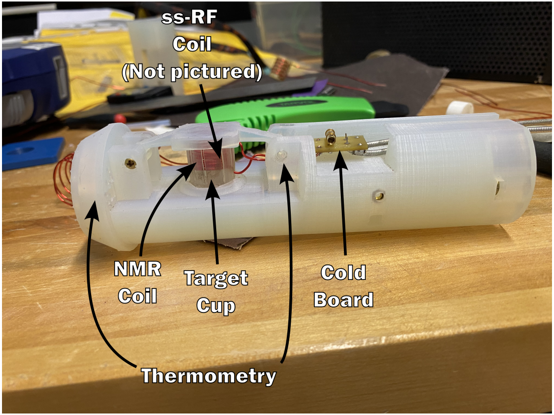




Above left: Top of the 2022 target stick looking down towards the target ladder. Picture shows the 2022 top plate design. **Above right:** 2022 target ladder design with target cup, waveguide, and RF coils labeled.

2024 Target Stick

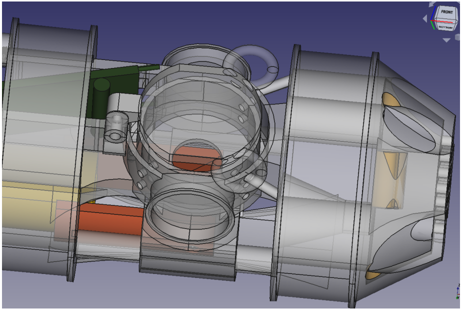
- Designed 2023-2024, still in final stages of assembly
- Ladder also of durable resin
- Also ss-RF and (future) EPR capability
- Mold-wound NMR coils, hand-wound ss-RF and EPR
- Cernox thermometry only
- **Goal: to complete and test this target stick for cooldowns later next month.**



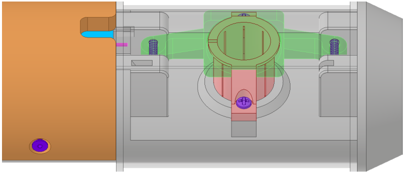
Above: Partially assembled target ladder prototype with the 2024 design. ss-RF coil is not pictured but is wound on the outside of the target cup.

Target Cup Comparison

2022 Design



2024 Design



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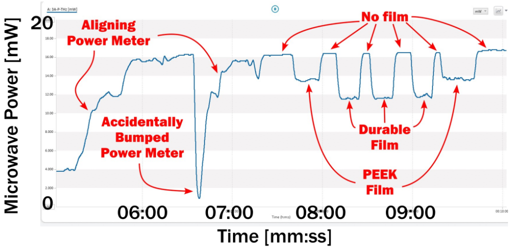
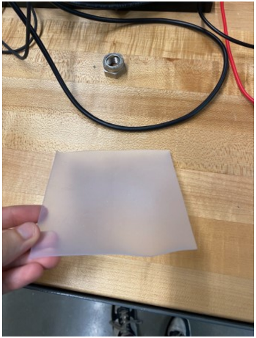
- ID: 20 mm, length: 10 mm
- Target cup fixed in ladder
- NMR coil outside cup
- Loose cup cap (material only in capsules)

- 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

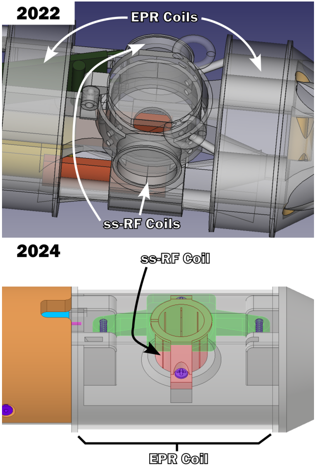
- PCTFE (Kel-F) is best plastic for target ladders, but difficult to acquire right now
- Durable resin or PEEK plastic, which transmited microwaves better?
- 0.5 mm-thick durable film: 35-40% loss at 140 GHz
- 0.5 mm-thick PEEK film: 20-25% loss at 140 GHz
- 2022 design used only durable resin, 2024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



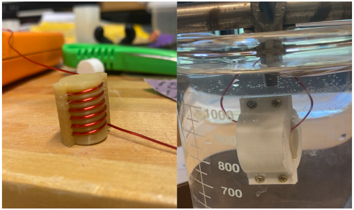
Above: 2022 and 2024 target ladder comparison with ss-RF and EPR coils labeled.

2022 Design:

- All RF coils (NMR, ss-RF, EPR) wound by hand
- NMR, ss-RF, EPR coils all on perpindicular 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

See N. Santiesteban/ D. Ruth talk later this session on RF manipulation!

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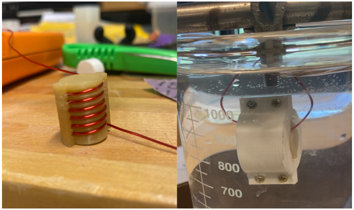

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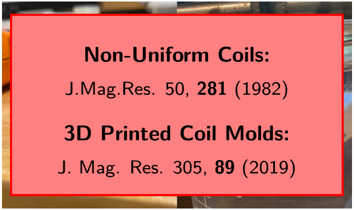

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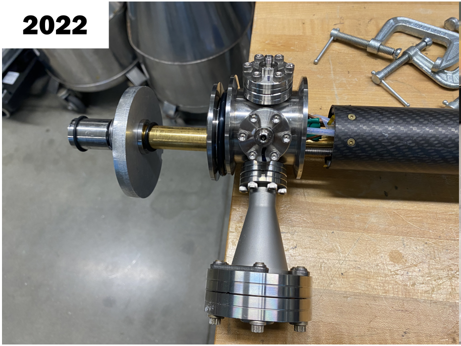
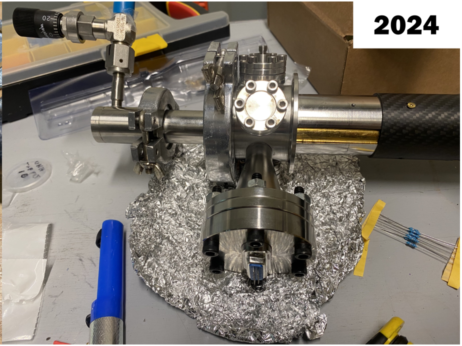
Waveguide & Vacuum Seal





2022

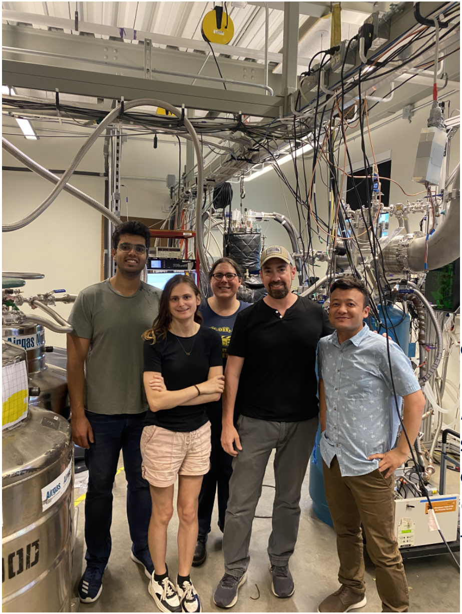
- Waveguide acts as external vacuum seal
- "Piston" on cryostat to run multiple target cells
- 2022 cooldown struggled with vacuum problems

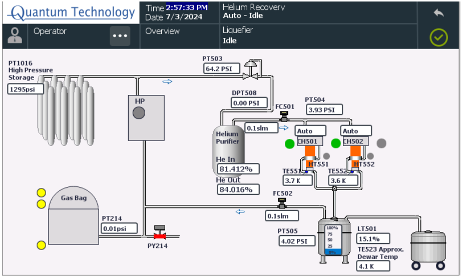
2024

- Waveguide entirely internal to stick
- No piston, new top plate with flanges installed
- Vacuum problems were MUCH less impactful

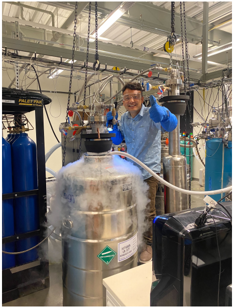
2022 target was also updated with 2024 top plate design!

NEW Helium Reliquefaction System



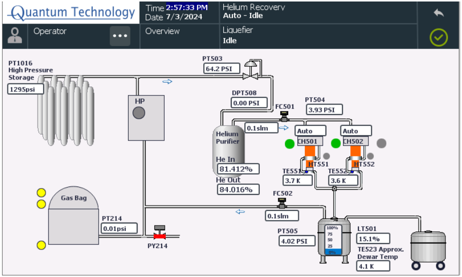


Left: group photo of the reliquefier installation team. **Above:** Reliquifier system software overview. **Right:** Chhetra adds LN2 to our helium purifier dewar.



NEW Helium Reliquefaction System

See C. Lama talk later this session on our operational reliquefier!



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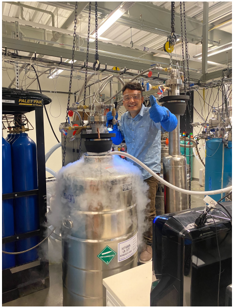
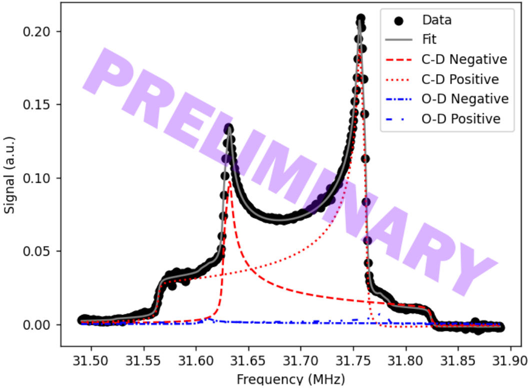


Tensor Polarization at UNH

- 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!
- Reliquefier vastly increases cooldown capacity.
    - Two UNH cooldowns in September 2024 alone!
- **Highest UNH deuteron polarization observed just last week!**



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

This Data (Preliminary)

P: 43-47%
Q: 14-19%

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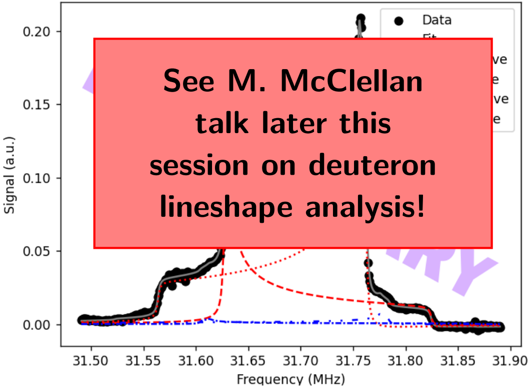

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Summary

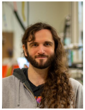
Professors


Karl Slifer

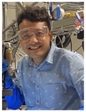

Elena Long


Nathaly Santiesteban

Graduate Students


Michael McClellan


Anchit Arora


Chhetra Lama


Zoe Wolters

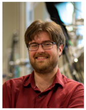

Muhammad Farooq


Olaiya Olokunboyo


Hector Chinchay

Postdocs


Allison Zec


David Ruth

Undergraduate Student


Eli Phippard

2024 UNH Polarized Target Group

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

- **UNH PolTarg is polarizing again!!!**
- Recent data shows >40% vector polarization on irradiated d-butanol
- New target stick with usability & RF-coil improvements
- Improved microwave transmission
- **New reliquefier vastly increases UNH's cooldown capacity!**
  - We have irradiated ND_3, will run with it soon!

Trans & Nonbinary Physicists

TRANS & NON-BINARY PHYSICISTS

The Trans and Nonbinary Physicists Discord server is an online community for transgender and nonbinary physicists — from enthusiasts to professors! — to socialize, network, and support one another. All are welcome, and so far we have over 200 members from across the world!

Follow

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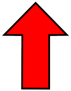
Questions, comments, concerns, observations?

Backup Slides

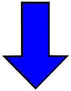
What Deuterons Do That Protons Don't

Proton

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

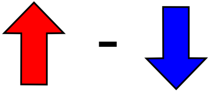


$m = +\frac{1}{2}$



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

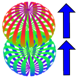
"Typical" Vector Polarization



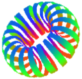
$$P_z = p_+ - p_-$$

Deuteron

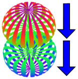
Spin-1 System



$m = +1$

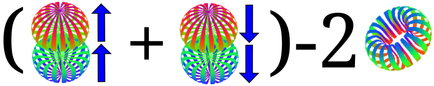


$m = 0$



$m = -1$

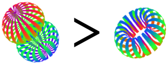
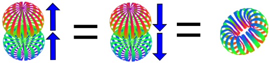
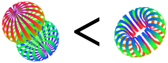
Vector **and** Tensor Polarization

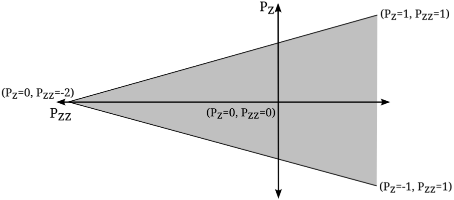


$$P_{zz} = (p_+ + p_-) - 2p_0$$

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

Tensor Polarization Properties

If...	**Then...**
	$0 < P_{zz} \leq 1$
	$P_{zz} = 0$
	$-2 \leq P_{zz} < 0$



- P_z ranges from -1 to +1
- P_{zz} ranges from -2 to +1
- In deuterons both P_z and P_{zz} can be nonzero simultaneously

Tensor Polarization Properties

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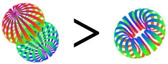
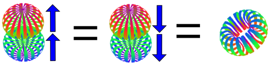
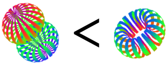
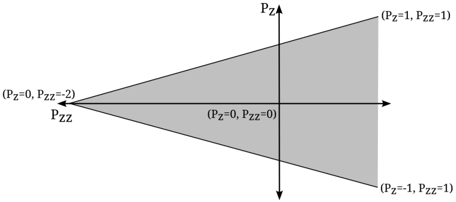
	$0 < P_{zz} \leq 1$
	$P_{zz} = 0$
	$-2 \leq P_{zz} < 0$



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

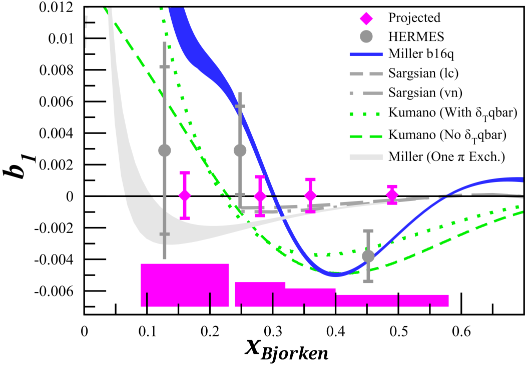
b_1 Experiment

- 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

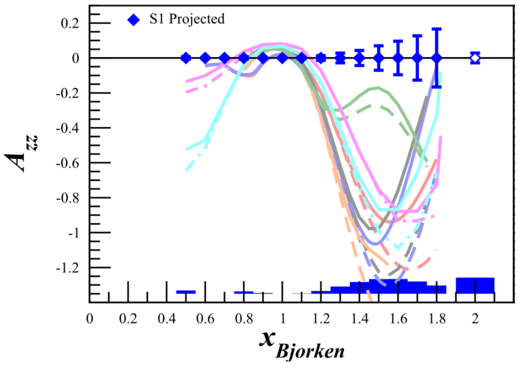
- First-of-its-kind quasielastic A_{zz} measurement
- Implications for SRC physics and deuteron wavefunction
- Widest range of x covered by a single measurement
- Measurement of T_{20} included!

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

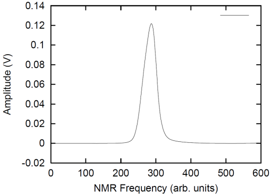


E. Long *et al*, JLab C12-15-005

BACKUP: DNP

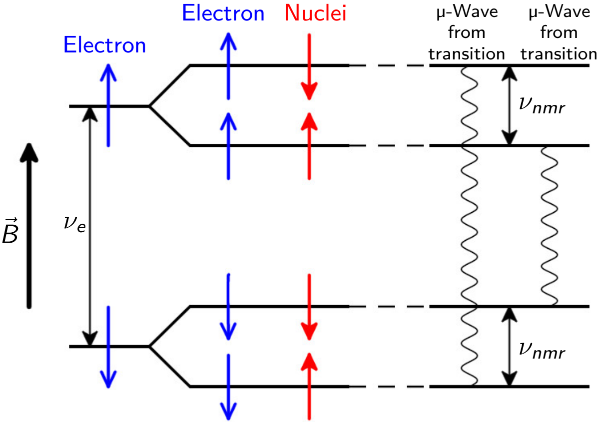
Dynamic Nuclear Polarization (DNP)

- 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

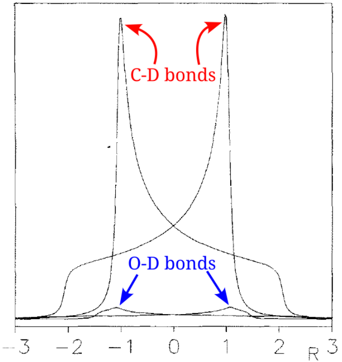
C.D. Keith *et al*, NIM A **501** (2003)



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

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)

BACKUP: Tensor Polarization Analysis

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

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

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

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

R, A, η, ϕ — compacting variables

$$\rho^2 = \sqrt{A^2 + [1 - \epsilon R - \eta cos(2\phi)]^2} \qquad R = \frac{\omega - \omega_d}{3\omega_q}$$
$$cos(\alpha) = \frac{1 - \epsilon R - \eta cos(2\phi)}{\rho^2} \qquad -3 \leq R \leq 3$$

functional form of signal

$$f_\epsilon(R, A, \eta, \phi) = \frac{1}{2\pi\rho}\{2cos(\frac{\alpha}{2})\left[arctan\left(\frac{Y^2 - \rho^2}{2Y\rho sin(\frac{\alpha}{2})}\right) + \frac{\pi}{2}\right] + sin(\frac{\alpha}{2})ln\left(\frac{Y^2 + \rho^2 + 2Y\rho cos(\frac{\alpha}{2})}{Y^2 + \rho^2 - 2Y\rho cos(\frac{\alpha}{2})}\right)\}$$

$\epsilon = \pm 1$

phi average

$$F_\epsilon \approx \frac{1}{J+1}\sum_{j=0}^{J}\frac{\sqrt{3} f_\epsilon(R, A, \eta, \phi_j)}{\sqrt{3 - \eta cos(2\phi_j)}}$$

positive & negative spin flips

$$\chi''(r, R) \propto \frac{1}{\omega_q}\left\{\left[\frac{r^2 - r^{1-3\theta R}}{r^{1-\theta R}}\right] F_+(R) + \left[\frac{r^{1+3\theta R} - 1}{r^{1+\theta R}}\right] F_-(R)\right\}$$

$$\theta = \omega_q / \omega_d$$

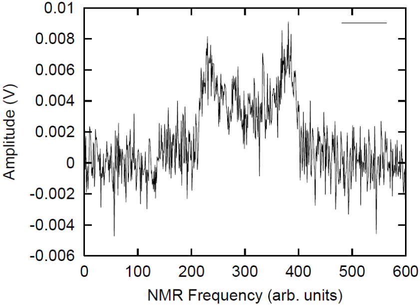
Thermal Equilibrium & Enhancement

Deuteron thermal equilibrium (TE) polarization before microwave irradiation:

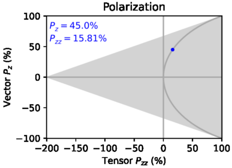
$$P(1) = \frac{4\tanh(\frac{g_i \mu_i B}{2k_B T})}{3 + \tanh^2(\frac{g_i \mu_i B}{2k_B T})} \qquad (2)$$

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.

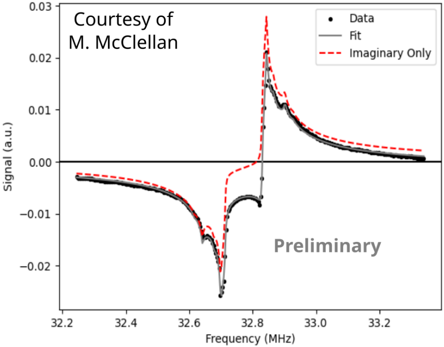


Real & Imaginary Fits

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

$$\text{Real} = \chi'' \cos\phi - \chi' \sin\phi$$
$$\text{Imag} = \chi'' \sin\phi + \chi' \cos\phi \quad (3)$$

- 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.