Solid Tensor-Polarized Targets for Tests of Nuclear Structure

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New Hampshire

Deuterons and 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

$$P_z = p_+ - p_-$$

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

Deuteron
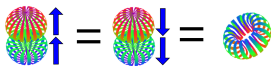
Spin-1 System

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

Vector **and** Tensor Polarization

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

Tensor Polarization Properties

If...

Then...
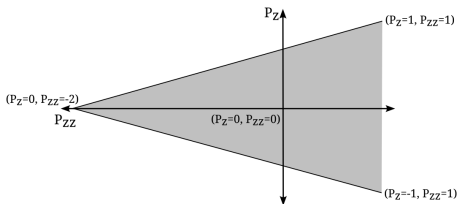
$$0 < P_{zz} \leq 1$$
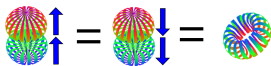
$$P_{zz} = 0$$

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

- 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
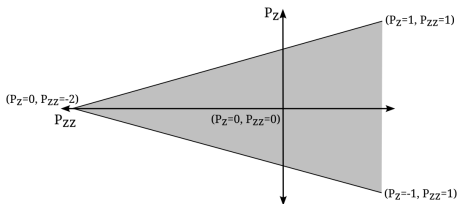
Tensor Polarization Properties

If...

Then...

$$0 < P_{zz} \leq 1$$

$$P_{zz} = 0$$

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

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

Tensor Observables

$$\frac{d^2\sigma}{dk d\Omega} = \sigma_0 \left[1 + h_e(P_z A_\parallel + P_{zz} A_T^{ed}) + P_z A_V^d + \frac{1}{2} P_{zz} \, A_{zz} \right] \tag{1}$$

where σ_0 is unpolarized cross-section, h_e is electron beam helicity, and $A_\parallel$, A_T^{ed}, A_V^d, and A_{zz} are asymmetries dependent on polarization angles.

W. Leidemann, E.L. Tomusiak, H. Arenhovel, Phys. Rev. C **43** 1022 (1991)

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If you can integrate over beam helicity, then $A_\parallel$ and A_T^{ed} are suppressed

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If you can integrate over beam helicity, then $A_\parallel$ and A_T^{ed} are suppressed

If you can flip between vector polarization signs then A_V^d is suppressed

Effect of tensor asymmetry remains

W. Leidemann, E.L. Tomusiak, H. Arenhövel, Phys. Rev. C **43** 1022 (1991)

Quasielastic Tensor Asymmetry

## For $0.8 \leq x \leq 1.8$

$\sigma_p =$ polarized cross section
$\sigma_0 =$ unpolarized cross section

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

- **Currently no quasielastic tensor asymmetry measurements!**
- Asymmetry in $1.0 < x < 1.8$ range predicted as high as 100%
- Difficult to measure with just vector polarized deuterons

M. Sargsian, M. Strikman arXiv:1409.6056
E. Long *et al*, JLab C12-15-005

$E_e = 8.8$ GeV, $Q^2 = 1.5$ GeV^2

Light-cone calculation

AV18

Virtual Nucleon Calculation
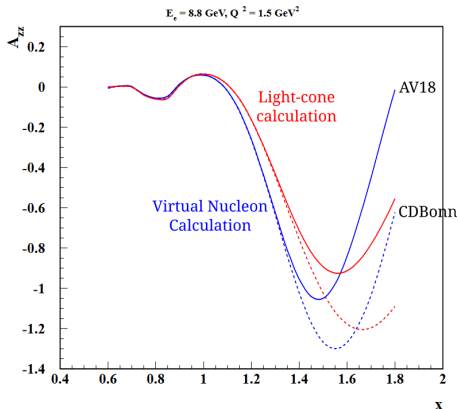
CDBonn

Above: Two theory models: AV18 (solid) and CDBonn (dashed) for two different calculation frameworks predicting the quasielastic value of A_{zz}.

Deep Inelastic Tensor Structure Functions

$$W_{\mu\nu} = -\alpha F_1 + \beta F_2 \qquad \text{Unpolarized structure functions}$$
$$+ i\gamma g_1 + i\delta g_2 \qquad \text{Vector polarized structure functions} \qquad (3)$$
$$-\epsilon \boxed{b_1} + \zeta b_2 + \eta b_3 + \kappa b_4 \quad \text{Tensor polarized structure functions}$$
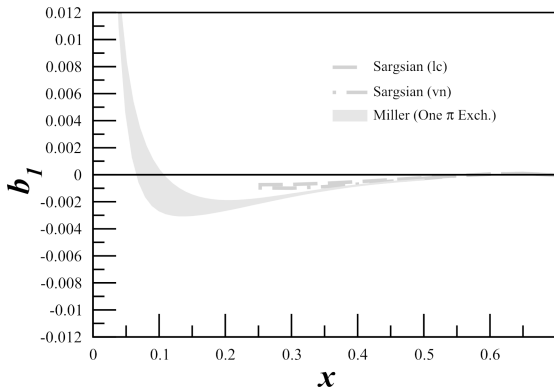
For $x \leq 0.5$

$$b_1 = -\frac{3}{2} F_1 A_{zz} \qquad (4)$$

- Callan-Gross relation with $b_2 = 2x b_1$
- b_1 sole tensor structure function that has been measured
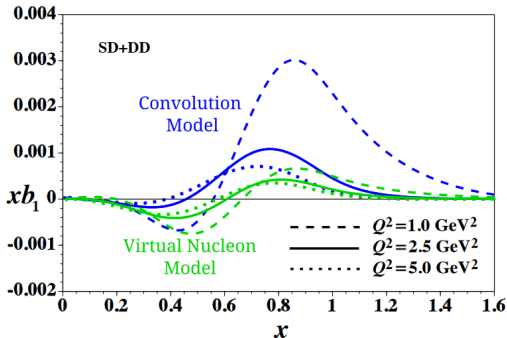
W. Cosyn, Y. Dong, S. Kumano, M. Sargsian *et al*, PRD **95** 074036 (2017)

Current b_1 Data

In traditional deuteron state models b_1 is predicted to be small

K. Slifer *et al*, JLab C12-13-011

In traditional deuteron state models b_1 is predicted to be small

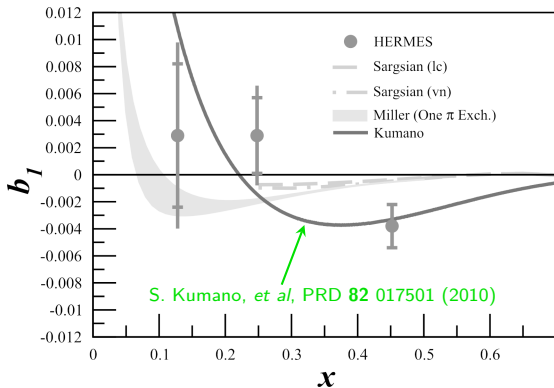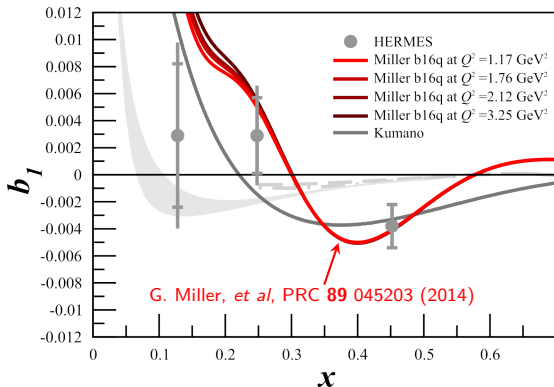. . . but the HERMES experiment measured something different!

A. Airapetian, *et al*, PRL **95** 242001 (2005)
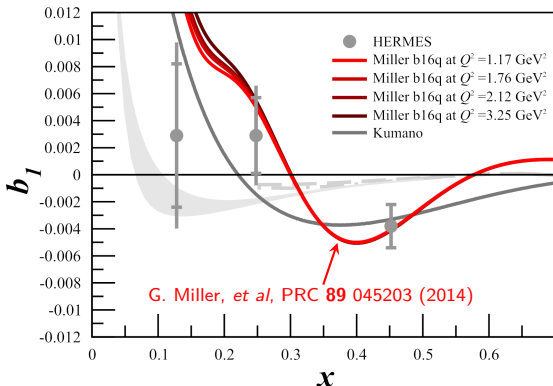
Only $\sim 2\sigma$

K. Slifer *et al*, JLab C12-13-011

In traditional deuteron state models b_1 is predicted to be small

... but the HERMES experiment measured something different!

It could be explained by tensor-polarized anti-quark effects

S. Kumano, *et al*, PRD **82** 017501 (2010)

- HERMES
- Sargsian (lc)
- Sargsian (vn)
- Miller (One π Exch.)
- Kumano

K. Slifer *et al*, JLab C12-13-011

In traditional deuteron state models b_1 is predicted to be small

... but the HERMES experiment measured something different!

It could be explained by tensor-polarized anti-quark effects

... or by six-quark hidden color effects.

- HERMES
- Miller b16q at $Q^2 = 1.17$ GeV^2
- Miller b16q at $Q^2 = 1.76$ GeV^2
- Miller b16q at $Q^2 = 2.12$ GeV^2
- Miller b16q at $Q^2 = 3.25$ GeV^2
- Kumano

G. Miller, *et al*, PRC **89** 045203 (2014)

K. Slifer *et al*, JLab C12-13-011

In traditional deuteron state models b_1 is predicted to be small

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G. Miller, *et al*, PRC **89** 045203 (2014)

Measuring $b_1 < 0$ indicates exotic physics in the tensor structure of the deuteron! So can we improve on HERMES' error bar?

K. Slifer *et al*, JLab C12-13-011

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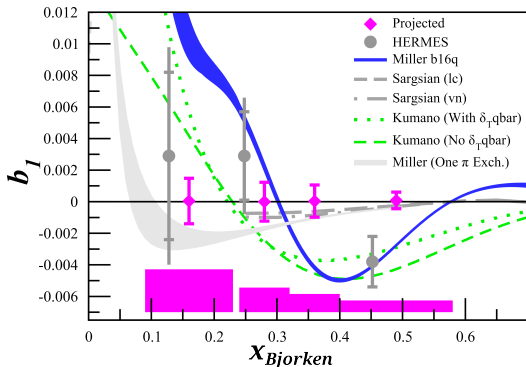
K. Slifer *et al*, JLab C12-13-011   **Spokespersons:** K. Slifer, O.R. Aramayo, J.P. Chen, N. Kalantrians, D. Keller, E. Long, P. Solvignon

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%

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

Tensor Target

b_1 Systematics Estimates

Source	Systematic
Polarimetry	**8.0%**
Dilution/Packing Fraction	**4.0%**
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$$A_{zz} = \frac{2}{f \boxed{P_{zz}}} \left(\frac{\sigma_p}{\sigma_0} - 1 \right)$$

Both experiments require a highly ($\geq$30%) tensor-polarized deuterium target with precise measurement of P_{zz}. How can we achieve that?

UNH Polarized Target Lab

Dynamic Nuclear Polarization (DNP)

- Using μwaves, drive spin transitions of unpaired electrons
- Electrons transfer spin to nuclei
- Nuclear absorption spectrum gives polarimetry info
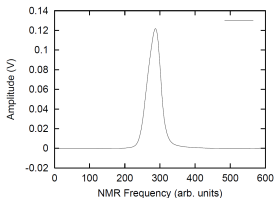
Above: Characteristic lineshape of the proton

C.D. Keith *et al*, NIM A **501** (2003)
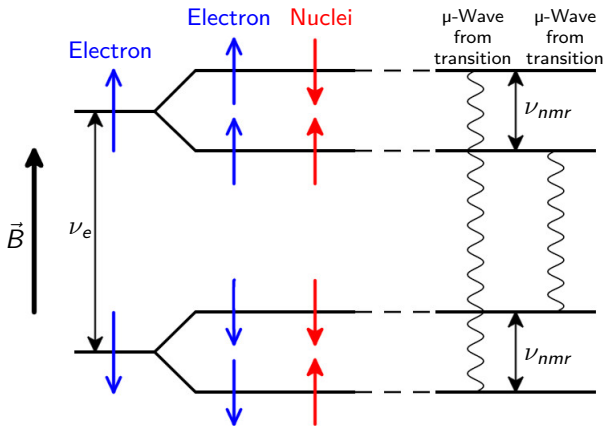
Above: Diagram of the energy level transitions in the DNP process. Adapted from *Annu. Rev. Nucl. Part. Sci. 1997. 47:67–109*

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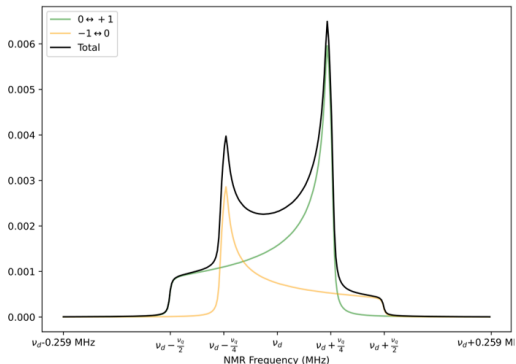
Above: Simulated deuteron lineshape showing the contributions from both the $-1 \rightarrow 0$ transition and the $0 \rightarrow 1$ transition.

The UNH polarized target group is hard at work!

The UNH polarized target group is hard at work!
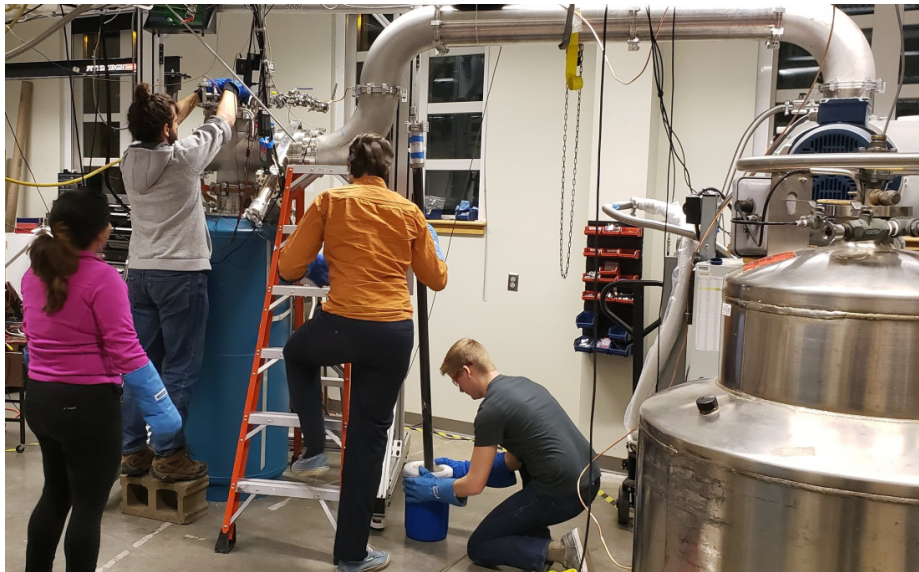
The UNH polarized target group is hard at work!

UNH Polarized Target Lab

- Target material produced and stored on-site
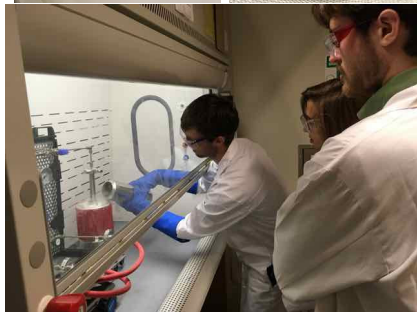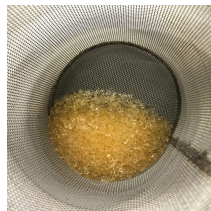
Top Left: Frozen NH_3; *Top Right*: Frozen butanol;
Bottom: Students at work producing target material.

UNH Polarized Target Lab

- Target material produced and stored on-site
- Solid-state microwave system & overmodal waveguide
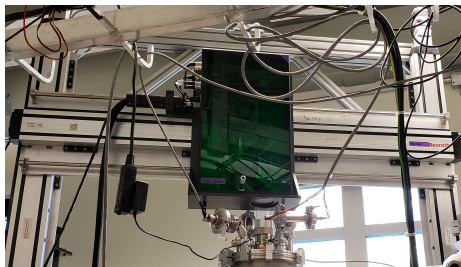
Top: UNH solid-state microwave system; *Bottom*: Bottom part of waveguide with reflector

UNH Polarized Target Lab

- Target material produced and stored on-site
- Solid-state microwave system & overmodal waveguide
- 1 K LHe refrigerator w/ 2.4 W cooling power
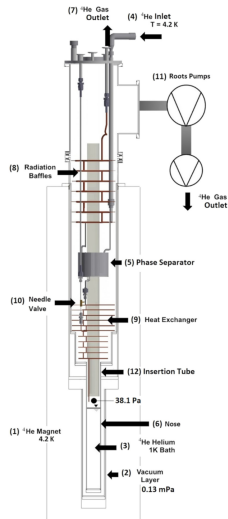
Left: UNH LHe refrigerator; *Right*: Refrigerator diagram adapted from NIM A **976** (2020) 164277

UNH Polarized Target Lab

- Target material produced and stored on-site
- Solid-state microwave system & overmodal waveguide
- 1 K LHe refrigerator w/ 2.4 W cooling power
- Superconducting 5 T Nb-Sn solenoidal magnet
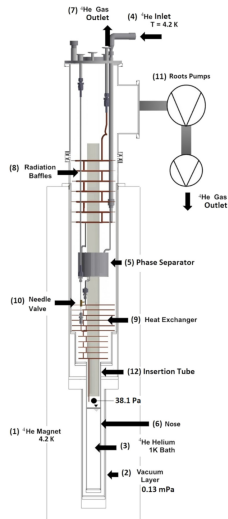
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- Target material produced and stored on-site
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- 3D printed target insert assembled on-site
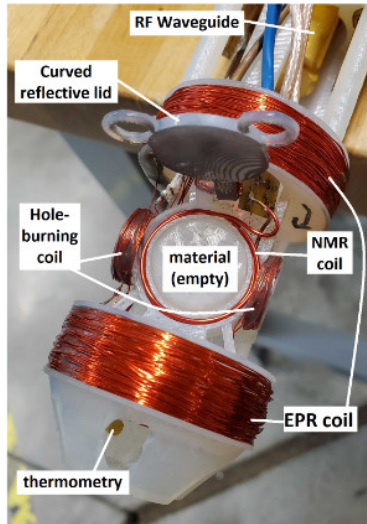
Labeled picture of most-recently-used UNH target ladder

UNH Polarized Target Lab

- Target material produced and stored on-site
- Solid-state microwave system & overmodal waveguide
- 1 K LHe refrigerator w/ 2.4 W cooling power
- Superconducting 5 T Nb-Sn solenoidal magnet
- 3D printed target insert assembled on-site
- NMR system is LANL Q-meter design
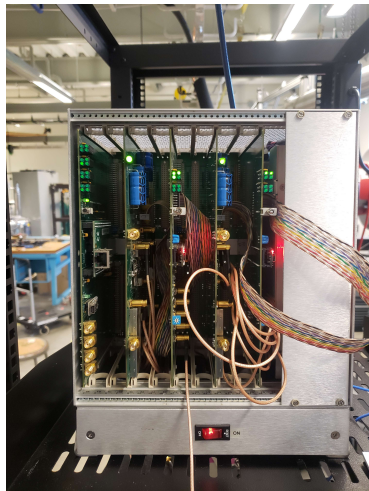
LANL Q-meter VME in UNH lab. Design from P. McGaughey, *et al*, NIM A **995** (2021) 165045

Tensor Polarization Measurement

Measuring Tensor Polarization

Vector Polarization Measurement

$$P_z = C(I_+ + I_-) \qquad (5)$$
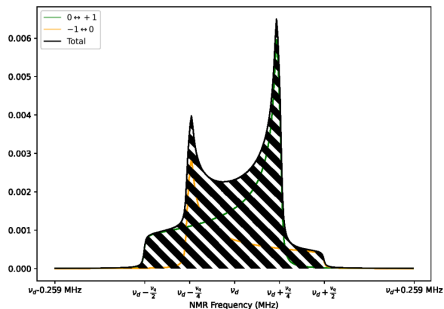
Tensor Polarization Measurement

$$P_{zz} = C(I_+ - I_-) \qquad (6)$$
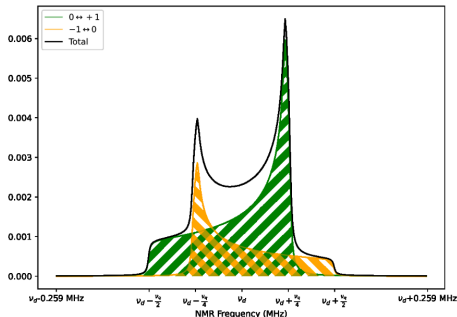
where C is a dimensionless calibration constant, $I_+ = n_+ - n_0$, and $I_- = n_0 - n_-$

D. Keller NIM A **981** (2020) 164504

Tensor Polarization Measurement

- Fit with Dulya procedure closely matches data from recent UNH cooldown
- Reconstruct spin-flip and quadrupole curves from fit parameters
- With reconstruction can do more in-depth polarization analysis

May 2022 Cooldown

$P_z = 28.2\%$
$P_{zz} = 6.1\%$
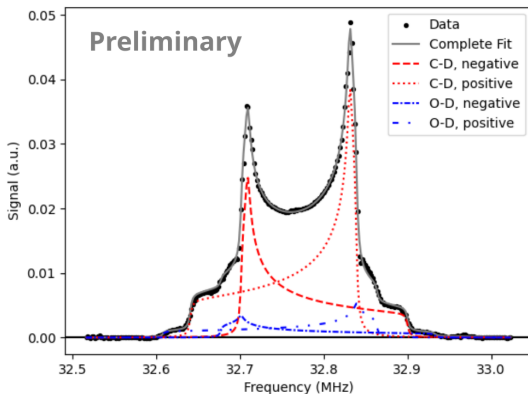
Above: Curve fit of NMR lineshape from recent target cooldown at UNH.
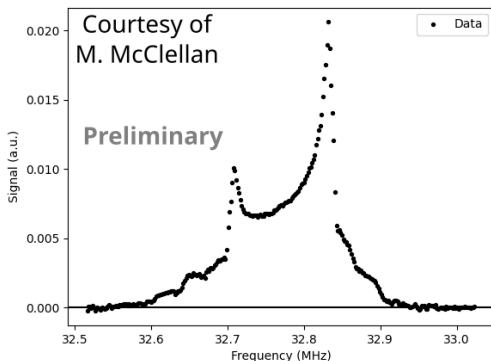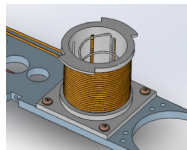
Above: NMR signal which includes ssRF. Effect can be seen in a raising of one transition signal above 32.8 MHz, and a lowering of the signal below 32.8 MHz.
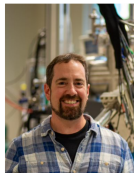
Right: Design of a target cell with an ss-RF coil. Figure from D. Keller, et al. NIM A **981** 164504 (2020)

- Recent work done with ssRF shows promise, needs further development
  - No polarization results from ssRF runs to report. . . yet
  - In particular can improve ssRF coil design and construction
- UNH group working to irradiate ND_3 for future cooldowns
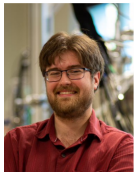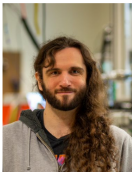
Summary

Professors

Karl Slifer

Elena Long

Nathaly Santiesteban

Graduate Students


David Ruth

Michael McClellan

Zoe Wolters

UNH Polarized Target Group

- Tensor polarized targets present new opportunities for high-luminosity experiments such as b_1 and A_{zz}
- DNP tried-and-true method for target polarization
- UNH NPG has demonstrated tensor polarization capability
- UNH NPG developing new tensor polarization methods
- Improvements to NMR signal fitting method show promise
- Imaginary signal may prove useful for future fitting
- **Polarized ND_3 results in near future!**
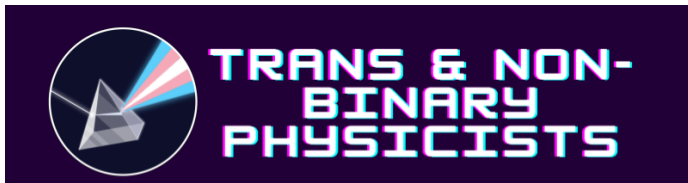
The Trans and Nonbinary Physicists Discord server is an online community for transgender and nonbinary physicists — from enthusiasts to professors! — to socialize, network, and support one another. All are welcome, and so far we have over 200 members from across the world!

Follow

@transphysicists

on twitter!

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Follow
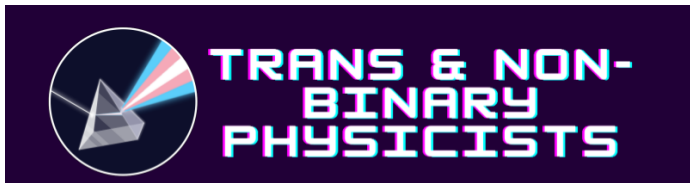
@transphysicists

on twitter!

Questions, comments, concerns, observations?
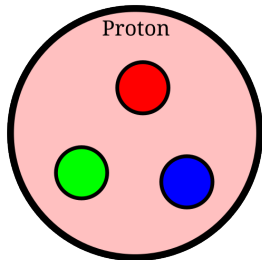
Backup Slides

Deuteron Tensor Polarization and Properties

Protons & Deuterons

Proton

Spin-$\frac{1}{2}$ System
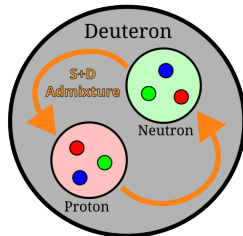
Three valence quarks $+$ gluons and sea quarks

No nucleon-nucleon interactions

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

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

Deuteron

Spin-1 System

Proton-Neutron bound state

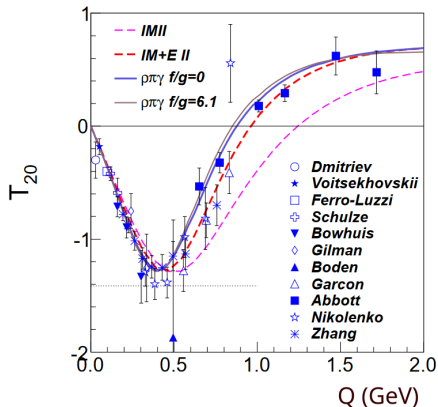Simplest nuclear system: nucleon interaction effects

$m = \pm 1, 0$

Elastic Tensor Analyzing Power

For $1.5 \leq x \leq 2.0$

$$T_{20} \approx \frac{A_{zz}}{\sqrt{2}d_{20}} \quad (7)$$

- Third of three elastic scattering functions of deuteron
- Extracted by measuring A_{zz} near elastic peak
- Current data doesn't constrain models well at high x

M. Kohl Nucl Phys A **805** (2008)

Above: T_{20} with current measurements and theoretical models.
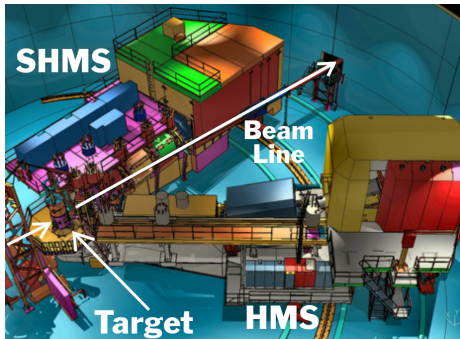
R. Holt, R. Gilman Rept.Prog.Phys. **75** (2012)

JLab

- 12 GeV CEBAF accelerator
- 4 experimental halls running simultaneously
- Beam current up to 200 µA

Hall C

- Two spectrometers
  - HMS (up to 7.3 GeV momentum)
    - Scattering angle $10° \leq \theta' \leq 85°$
  - SHMS (up to 11 GeV momentum)
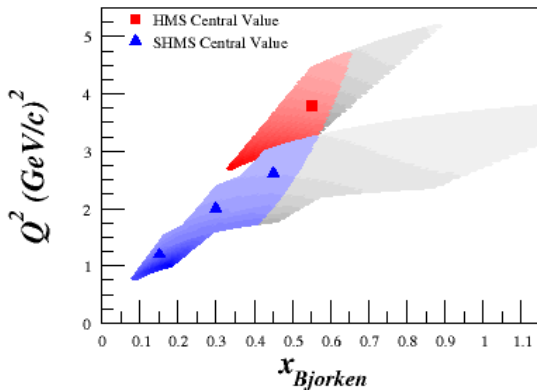   - Scattering angle $5.5° \leq \theta' \leq 40°$
- High-rate detector package

- Approved for 30 days of physics running + 10.8 days overhead

- 11 GeV beam incident on polarized target

- 9.2% systematic error on A_{zz}

- Foward scattering angles

	x_{Bj}	Q^2 [GeV^2]	E'_0 [GeV]	$\theta_{e'}$ [°]
SHMS	0.15	1.21	6.70	7.35
SHMS	0.30	2.00	7.45	8.96
SHMS	0.452	2.58	7.96	9.85
HMS	0.55	3.81	7.31	12.50

E12-13-011

The Deuteron Tensor Structure Function b_1

K. Slifer *et al*, JLab C12-13-011

A_{zz} Kinematics

- Approved for 34 days of physics running + 10.3 days overhead
  - 25 days 8.8 GeV beam
  - 8 days 6.6 GeV beam
  - 1 day of 2.2 GeV beam
- 9.2% systematic error on A_{zz}, 7.4% on T_{20}
- Forward scattering angles

	E_0 [GeV]	Q^2 [GeV^2]	E_0' [GeV]	$\theta_{e'}$ [°]
SHMS (S1)	8.8	1.5	8.36	8.2
HMS (H1)	8.8	2.9	7.26	12.2
SHMS (S2)	6.6	0.7	6.35	7.5
HMS (H2)	6.6	1.8	5.96	12.3
SHMS (S3)	2.2	0.2	2.15	10.9
HMS (H3)	2.2	0.3	2.11	14.9

E12-15-005

Quasi-Elastic and Elastic Deuteron Tensor Asymmetries
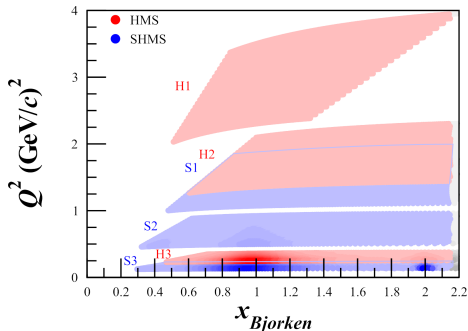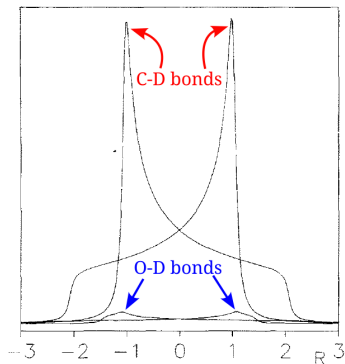

E. Long *et al*, JLab C12-15-005

BACKUP: Tensor Polarization & DNP

ND₃ and Other Target Materials

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

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

- 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

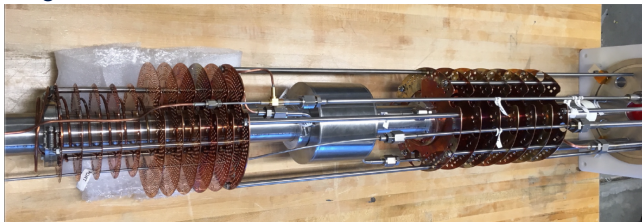| Material	Dopant & method	Polarizable nucleons % by weight
ND_3 d-ammonia	$N\dot{D}_2$ Irradiation	$\sim$30%
C_4D_9OD d-butanol	TEMPO Chemical	23.7%

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

BACKUP: UNH Polarized Target System

LHe Refrigerator and Magnet

- 1K evaporative LHe refrigerator
  - Built in-house at UNH
- Phase separator removes gaseous helium
- 2.4 W of cooling power

- LHe vapor pressure measured near refrigerator bottom
- Target cell at refrigerator nose
- Superconducting 5 T Nb-Sn solenoidal magent

Right: Diagram of the polarized target cryostat & refrigerator. Adapted from NIM A **976** (2020) 164277. *Below:* UNH LHe refrigerator

(7) ⁴He Gas Outlet
(4) ⁴He Inlet T = 4.2 K
(11) Roots Pumps
⁴He Gas Outlet
(8) Radiation Baffles
(5) Phase Separator
(10) Needle Valve
(9) Heat Exchanger
(12) Insertion Tube
38.1 Pa
(1) ⁴He Magnet 4.2 K
(6) Nose
(3)
⁴He Helium 1K Bath
(2) Vacuum Layer 0.13 mPa
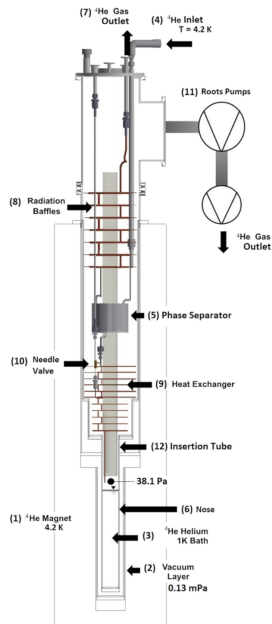
Solid-State Microwave System

- 12 GHz signal generator outputs 140 GHz mmwaves
- Sits directly above magnet
- Over 100 mW power between 132 and 142 GHz

Microwave Power vs Output Frequency
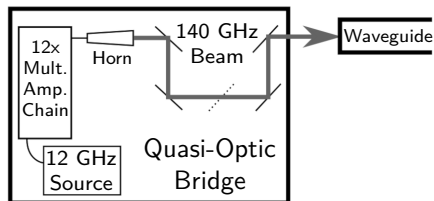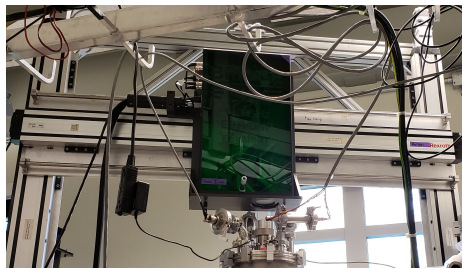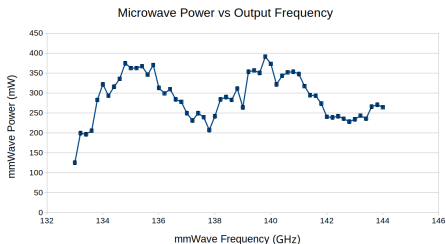
Above right: Photo of microwave system.

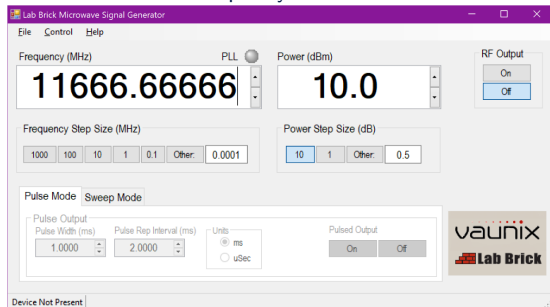*Right:* Diagram of microwave usage. *Above:* microwave power test results.

Solid-State Microwave System

- Microwaves sit on robot with moves for precise positioning
- No cooling required
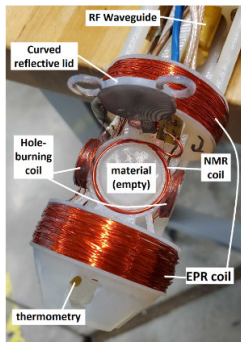
- Up to 400 mW output power
- Frequency hopping up to 10 kHz

Right: Rendering of microwaves on robot

Below: Microwaves frequency control software

- 2 m-long target stick holds target material in magnet/LHe bath
- Can be removed/replaced during operations
- Gold-plated waveguide transmits mmwave power to target cell
- 3D-printed target stick holds material plus NMR coils

*Above Right:* Target stick as seen from the top.
Below Right: Bottom end of RF waveguide.
Left: Bottom of 3d-printed target ladder including target cup and coils used during polarization.
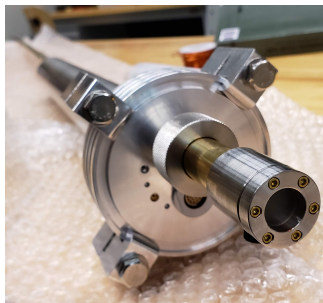
Material Production

- On-site target material production at UNH
- Can produce:
  - Solid NH_3/ND_3
  - Chemically-doped solid alcohol
- Dedicated fume hoods for working with NH_3
- Material storage also at UNH
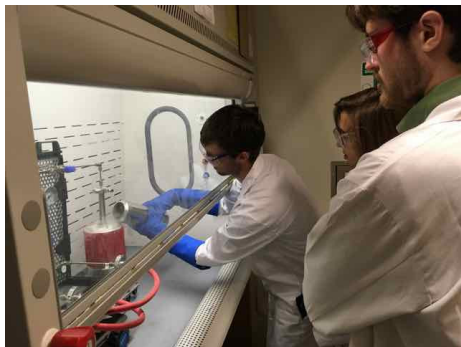
Above: Students producing cryogenic target material. *Left:* Frozen NH_3 produced and stored at UNH. *Right:* Frozen chemically-doped butanol produced at UNH.
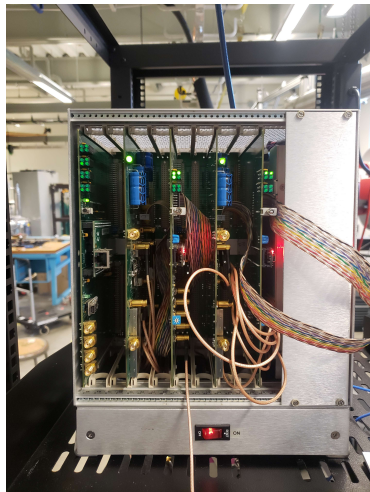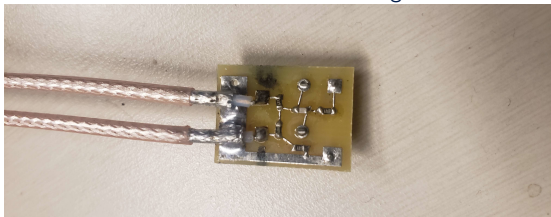
NMR System

- NMR signal at deuteron spin transition central frequency (≈ 30 MHz)
  - System is a LANL Q-Meter design
- NMR system sweeps deuteron frequency range at 20 Hz
- RF "cold board" produces NMR signal from VME output
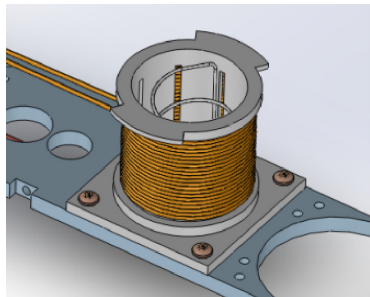
Right: VME crate from which NMR system runs.

*Below:* UNH cold board inserted into target ladder.

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

ssRF ("Hole Burning")

- Additional RF coils drive spin flips

- Manipulates area of NMR curve

- Small frequency range

- UVA lab achieved 28.8% P_{zz} with ssRF technique

- UNH pol targ. w/ ssRF: $P_{zz} = 15.5\% \pm 5\%$

Right: ssRF coil schematic. Figure from D. Keller, et al. NIM A **981** 164504 (2020) *Below:* NMR lineshapes without and with ssRF applied (UNH data).
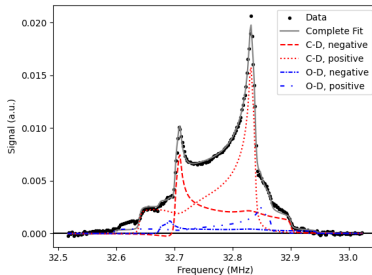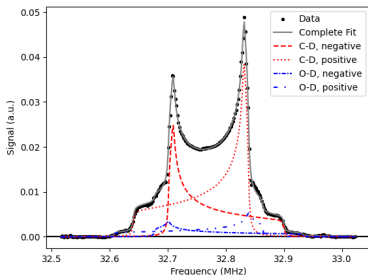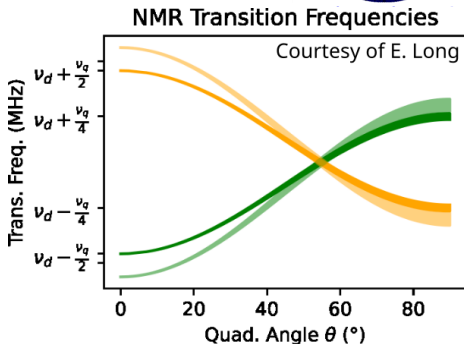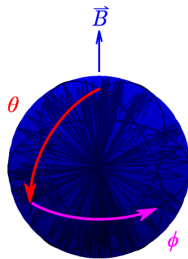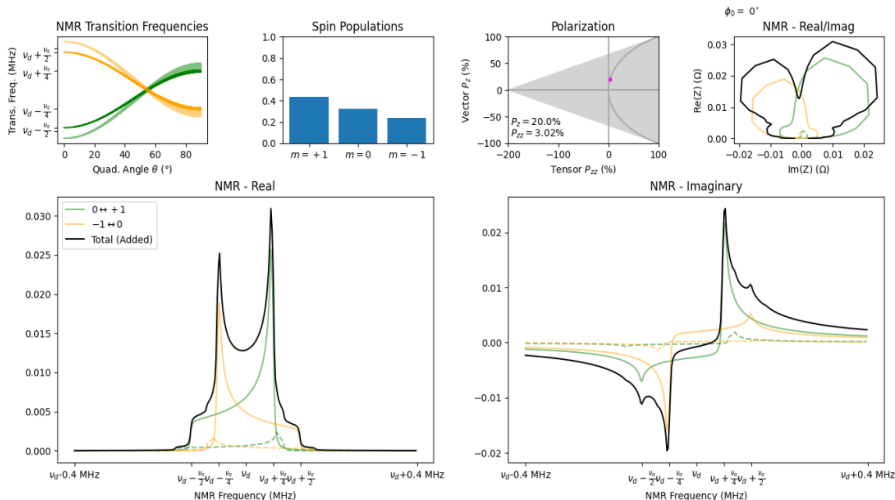
UNH NMR Simulation

From Spin Flips To Lineshape

Right: Quadrupole angles randomly distributed in B-field. *Below*: Spin transition frequencies for each angle θ and each transition.

- Simulation derived from Cohen & Reif model (1957)
- Assume random distribution of quadrupole angles θ from 0°-90°
- Then calculates transition frequency based on angle and energy level
- Performs 125,000 spin flips into 300 angle bins, giving NMR signal
- Simulation can reproduce results from UVA polarized target lab, as well as previous UNH cooldowns

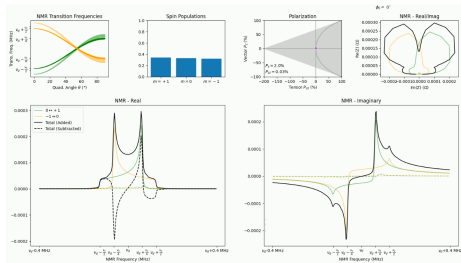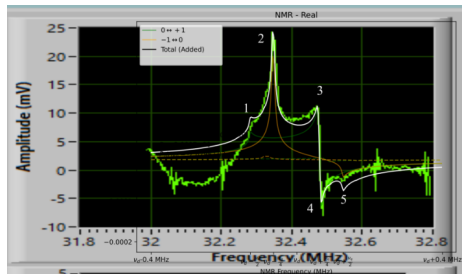NMR Transition Frequencies

Courtesy of E. Long

Generates real & imaginary components of NMR signal plus spin transition components! (Figure courtesy M. McClellan)

NMR Lineshape: Real & Imaginary

- Simulation can be used to retroactively understand previous cooldowns
- First UNH deuteron "ugly" NMR signal now understood to be from a mistuned phase

Above: Lineshape of first deuteron NMR signal recorded by UNH group (Fall 2020). *Left:* Simulation showing matching real and imaginary components.

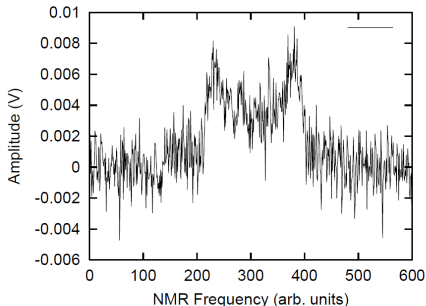# BACKUP: Tensor Polarization Analysis

Thermal Equilibrium & Enhancement

Deuteron thermal equilibrium (TE) polarization before microwave irradiation:
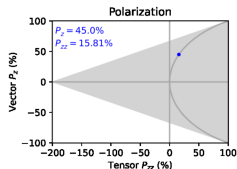
$$P(1) = \frac{4 \tanh\left(\frac{g_i \mu_i B}{2 k_B T}\right)}{3 + \tanh^2\left(\frac{g_i \mu_i B}{2 k_B T}\right)} \qquad (8)$$

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

$$P_z = \frac{r^2 - 1}{r + r^2 + 1}$$

$$P_{zz} = \frac{r^2 - 2r + 1}{r^2 + r + 1}$$

(9)

- 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 ⬇

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

$$\epsilon = \pm 1$$

$$+ \sin(\frac{\alpha}{2})\ln\left(\frac{Y^2 + \rho^2 + 2Y\rho\cos(\frac{\alpha}{2})}{Y^2 + \rho^2 - 2Y\rho\cos(\frac{\alpha}{2})}\right)\}$$

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 ⬇

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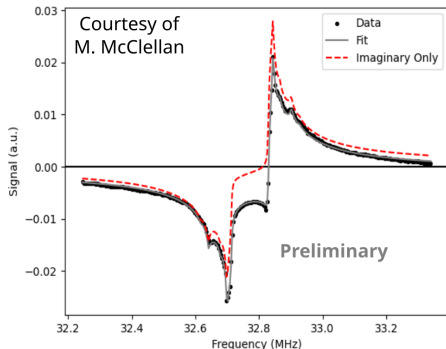
$$\theta = \omega_q/\omega_d$$

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

$$\text{Real} = \chi'' \cos\phi - \chi' \sin\phi$$
$$\text{Imag} = \chi'' \sin\phi + \chi' \cos\phi$$

(10)

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

Courtesy of M. McClellan

Preliminary

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.

Tensor Polarization

"Typical" vector polarization:

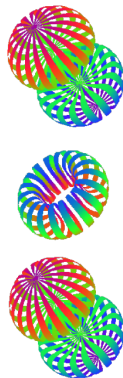$$P_z = N_+ - N_- \qquad (11)$$

where $-1 \leq P_z \leq 1$
... but with an m=0 state we have tensor polarization:

$$P_{zz} = (N_+ + N_-) - 2N_0 \qquad (12)$$

where $-2 \leq P_{zz} \leq 1$

Goal

Create target with high tensor polarization for high-luminosity experiments

Spin-1 System

m = +1

m = 0

m = -1