Status of the Hall C Tensor Experiment Program

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(she/her)

Univ. of New Hampshire

2023-06-29

Deuterons and Tensor Polarization

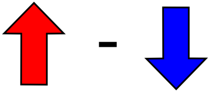
What Deuterons Do That Protons Don't

Proton

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

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

"Typical" Vector Polarization

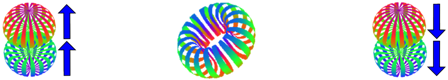


$$P_z = p_+ - p_-$$

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

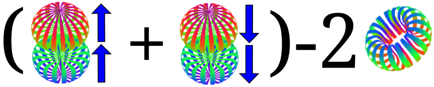
Deuteron

Spin-1 System



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

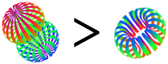
Vector **and** Tensor Polarization



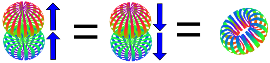
$$P_{zz} = (p_+ + p_-) - 2p_0$$

Tensor Polarization Properties

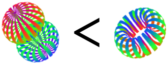
If. . . **Then. . .**



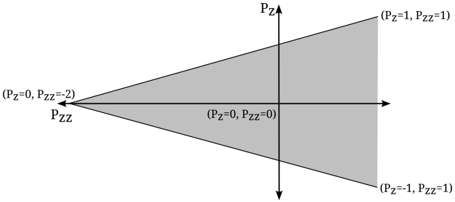
$0 < P_{zz} \leq 1$



$P_{zz} = 0$



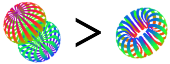
$-2 \leq P_{zz} < 0$



- 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

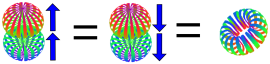
Tensor Polarization Properties

If...

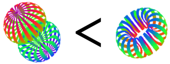


Then...

$0 < P_{zz} \leq 1$



$P_{zz} = 0$



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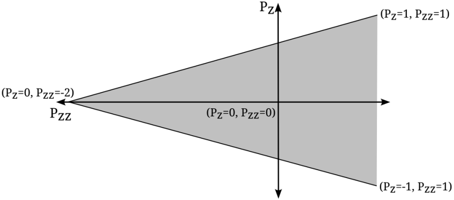

A high-luminosity tensor-polarized target has promise as a novel probe of nuclear physics

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 flip between vector polarization signs then A_V^d is suppressed

Effect of tensor asymmetry remains

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

Quasielastic Tensor Asymmetry

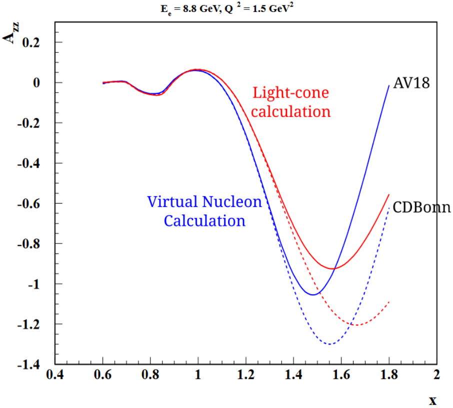
For $\mathbf{0.8 \leq x \leq 1.8}$

σ_p =polarized cross section
σ_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



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

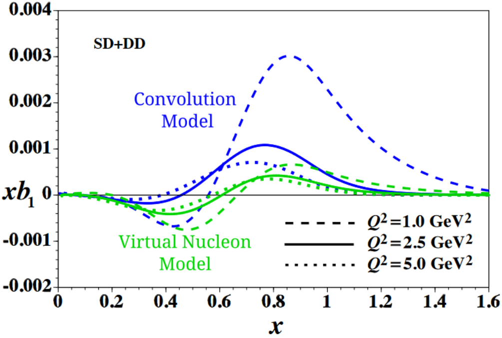
Deep Inelastic Tensor Structure Functions

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

For $x \leq 0.5$

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

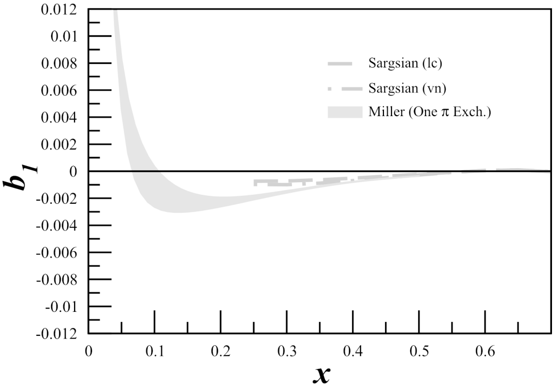
- Callan-Gross relation with $b_2 = 2xb_1$
- b_1 sole tensor structure function that has been measured



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

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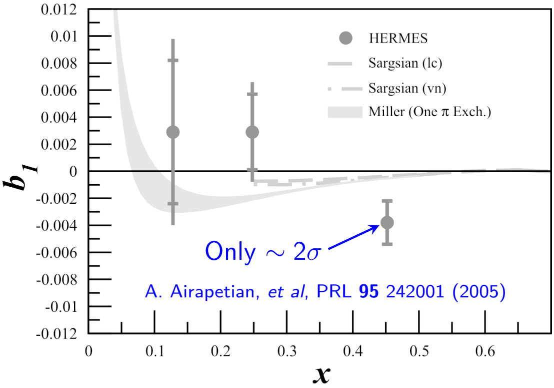
. . . but the HERMES experiment measured something different!



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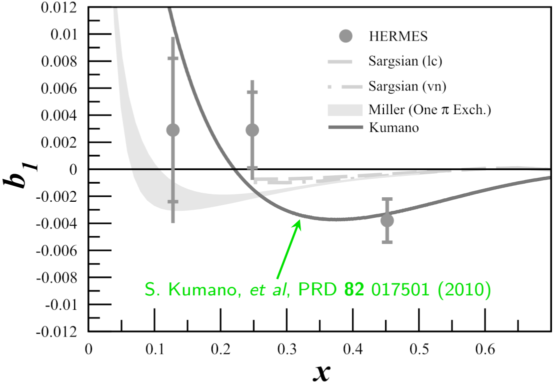
It could be explained by tensor-polarized anti-quark effects



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

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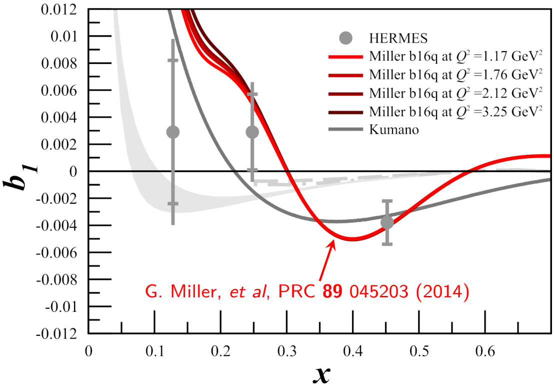
...or by six-quark hidden color effects.



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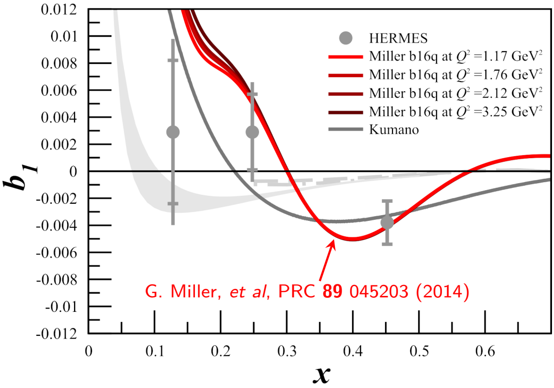


Measuring $b_1 < 0$ indicates exotic physics in the tensor structure of the deuteron! So can we improve on HERMES' error bar?

The Tensor Experiments

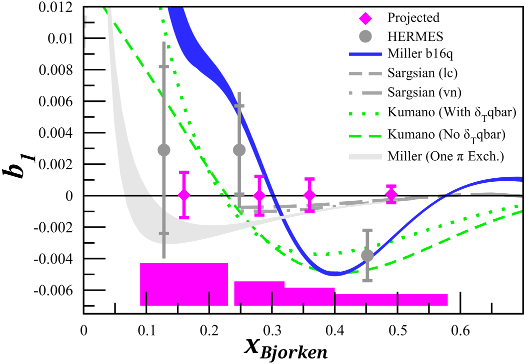
b_1 Experiment

- 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

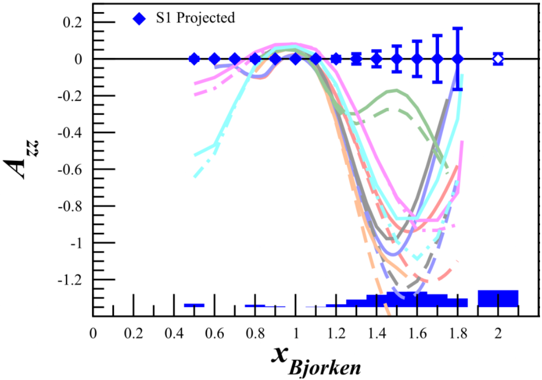
- First-of-its-kind quasielastic A_{zz} measurement
- Implications for SRC physics and deuteron wavefunction
- Widest range of x covered by a single measurement
- Measurement of T_{20} included!

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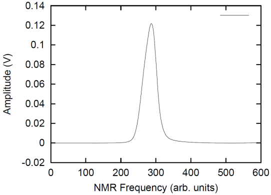
$$A_{zz} = \frac{2}{f\boxed{P_{zz}}}\left(\frac{\sigma_p}{\sigma_0} - 1\right)$$

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

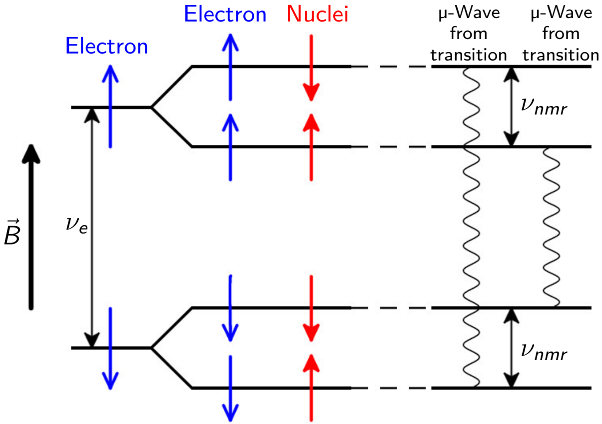
Dynamic Nuclear Polarization (DNP)

- 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

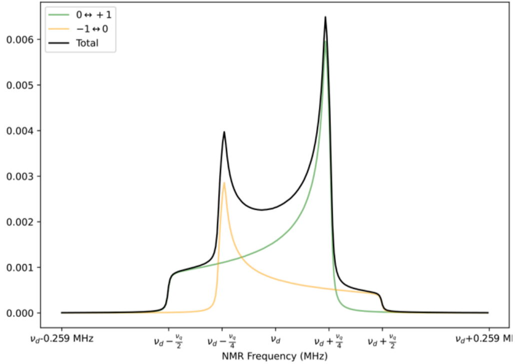
C.D. Keith *et al*, NIM A **501** (2003)



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

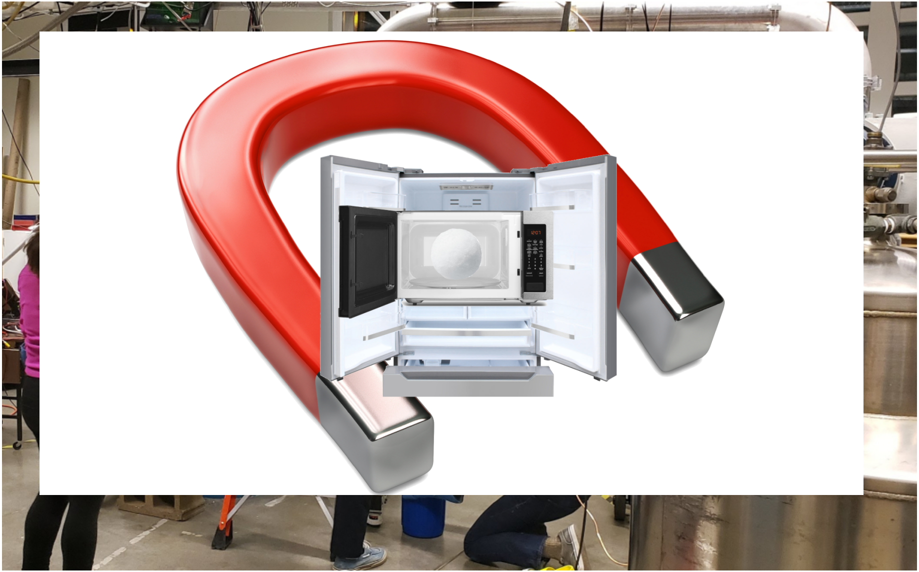


Above: Simulated deuteron lineshape showing the contributions from both the $-1 \rightarrow 0$ transition and the $0 \rightarrow 1$ transition.

UNH Polarized Target Lab

The UNH polarized target group is hard at work!

UNH Polarized Target Lab



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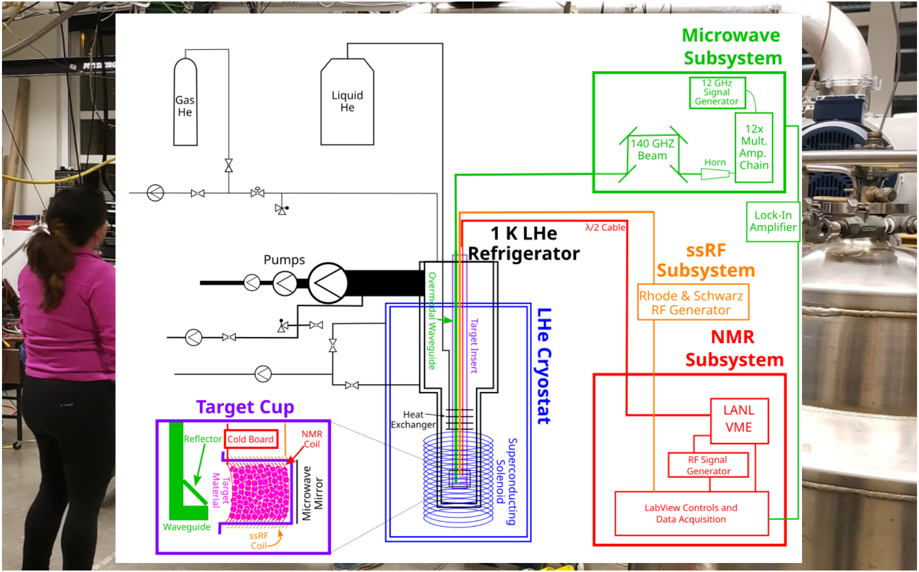


The UNH polarized target group is hard at work!

Target & Experiment Status

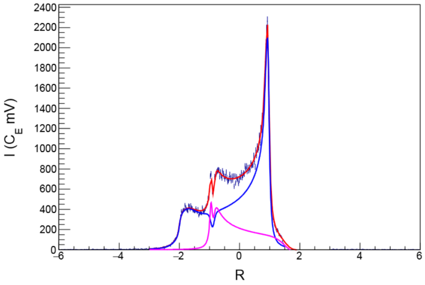
Tensor Polarization Measurement (UVA)

- "Semi-Selective RF"
  - Also called "hole-burning"
- Additional RF coils apply narrow-band signal near deuteron transition frequency
- Result is one side of deuteron lineshape decreased while the opposite side is increased by half
- Decreases vector polarization, increases tensor

Max. UVA P_{zz} with ss-RF

$P_{zz} = 31.1\% \pm 8.5\%$ (rel)

Results from D. Keller, D. Crabb and D. Day NIM A **981** 164504



Above: Hole-burned deuteron NMR signal from UVA cooldown. Fit parameters give 28.8% polarization for this lineshape.

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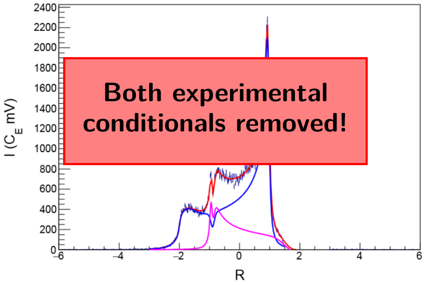


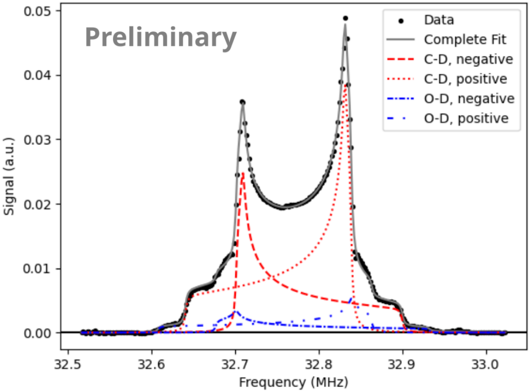
Above: Hole-burned deuteron NMR signal from UVA cooldown. Fit parameters give 28.8% polarization for this lineshape.

Tensor Polarization Measurement (UNH)

- Fit with Dulya procedure closely matches data from recent UNH cooldown
  - C. Dulya et al, NIM A 398 (1997) 109-125
- Reconstruct spin-flip and quadrupole curves from fit parameters
- With reconstruction can do more in-depth polarization analysis

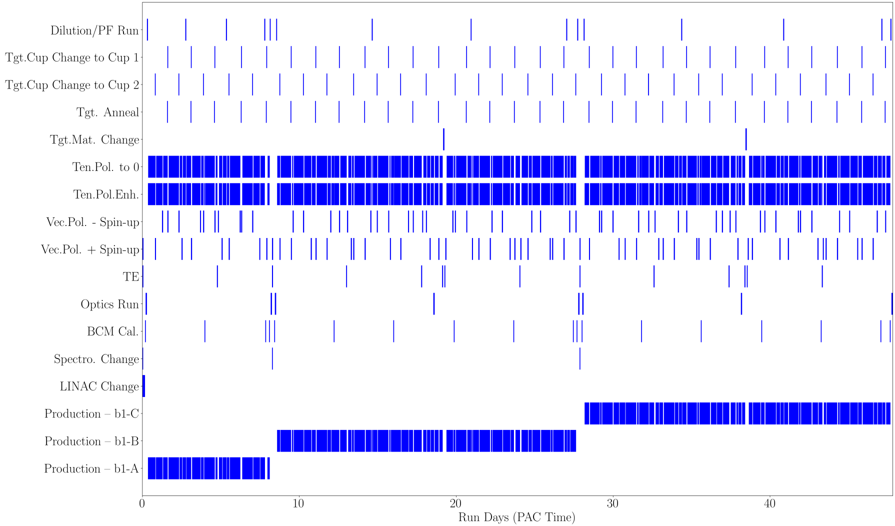
May 2022 Cooldown

$$P_z = 28.2\%$$
$$P_{zz} = 6.1\%$$

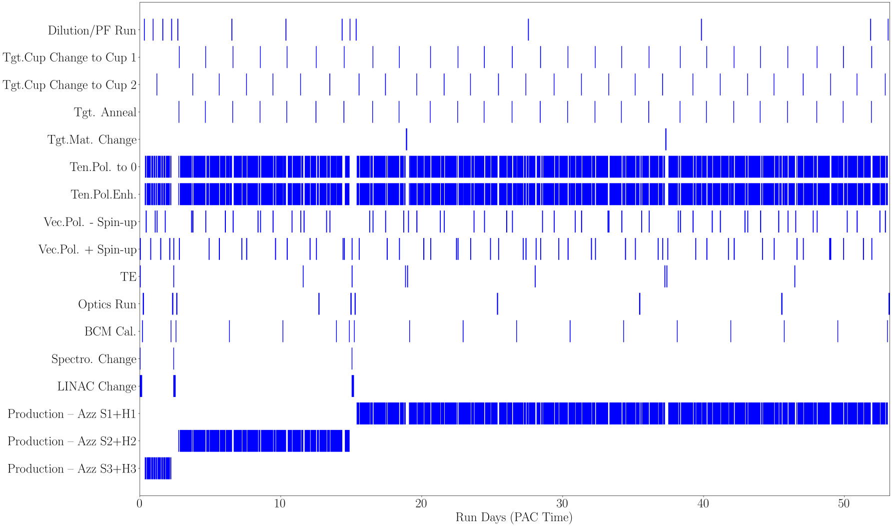


Above: Curve fit of NMR lineshape from recent target cooldown at UNH.

b_1 Experiment Preview



A_{zz} Experiment Preview



Summary

Professors

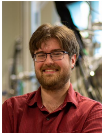

Karl Slifer


Elena Long


Nathaly Santiesteban

Postdocs


Allison Zec


David Ruth

Graduate Students


Michael McClellan

Anchit Arora


Zoe Wolters

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

- Tensor experiment program progressing
- Refining DNP to do tensor enhancement
- Experimental conditionals removed!
- Experimental run still pending. . .
- UNH group polarizing more (publications upcoming. . .)
- **Polarized ND_3 results in near future!**

Trans & Nonbinary 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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on twitter!

Trans & Nonbinary Physicists

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Questions, comments, concerns, observations?

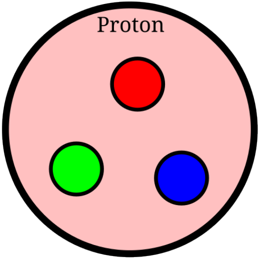
Backup Slides

Deuteron Tensor Polarization and Properties

Protons & Deuterons

Proton

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



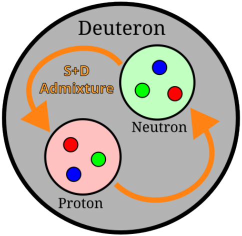
Three valence quarks + gluons and sea quarks

No nucleon-nucleon interactions

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

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)

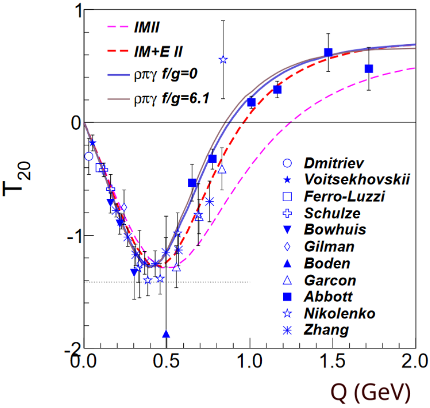
Elastic Tensor Analyzing Power

For $\mathbf{1.5} \leq \boldsymbol{x} \leq \mathbf{2.0}$

$$T_{20} \approx \frac{A_{zz}}{\sqrt{2}d_{20}} \tag{5}$$

- 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)

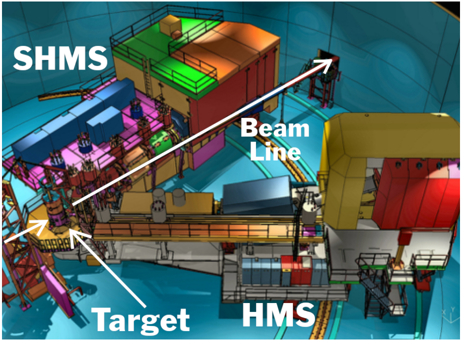
JLab & Hall C

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



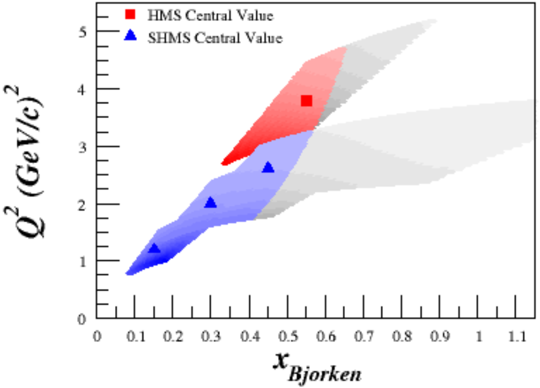
b_1 Kinematics

- 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

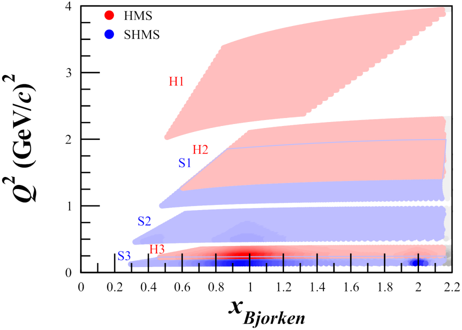
A_{zz} Kinematics

- 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

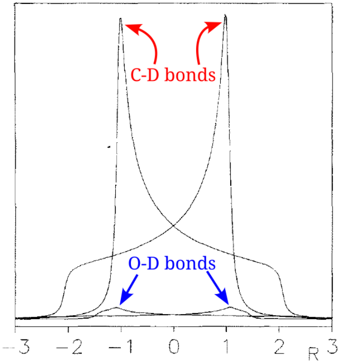


E. Long *et al*, JLab C12-15-005

BACKUP: Tensor Polarization & DNP

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%

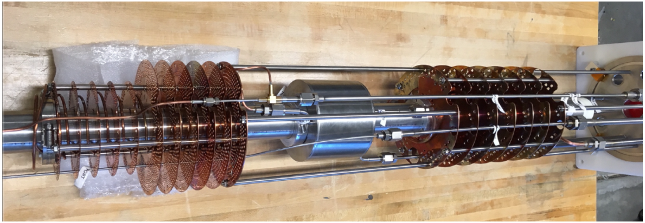
D. Crabb, W. Meyer, Annu. Rev. Nucl. Part. Sci **47** 67-109 (1997)

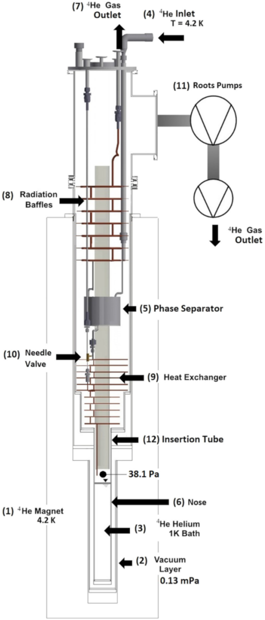
BACKUP: UNH Polarized Target System

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

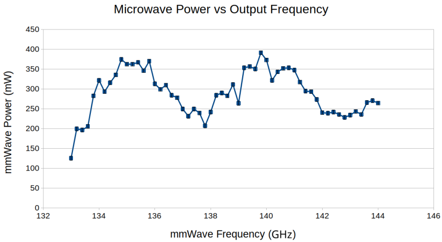
Right: Diagram of the polarized target cryostat & refrigerator. Adapted from NIM A **976** (2020) 164277. *Below:* UNH LHe refrigerator



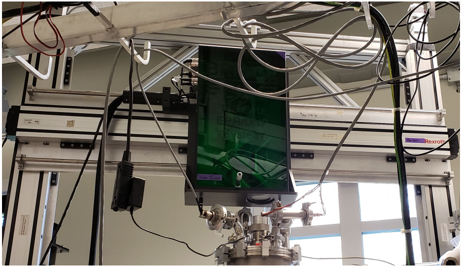


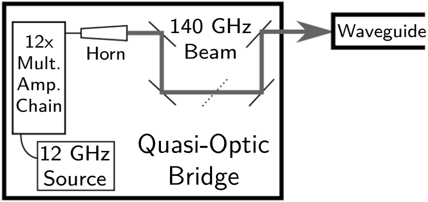
Solid-State Microwave System

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



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



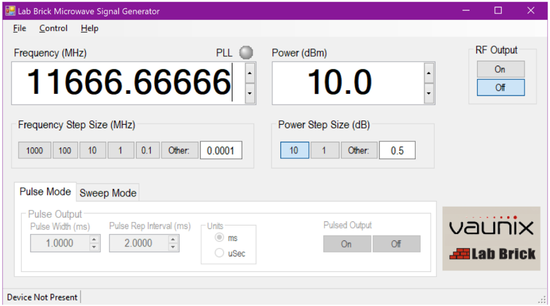


Solid-State Microwave System

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

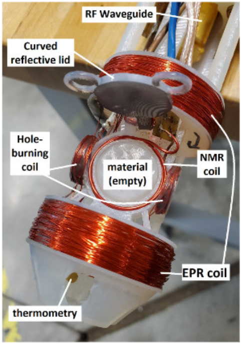
Right: Rendering of microwaves on robot

Below: Microwaves frequency control software

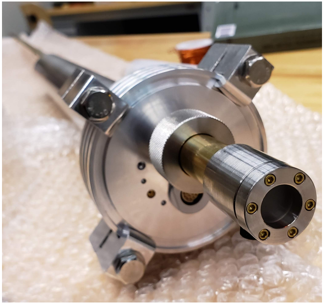


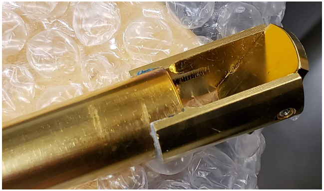
Waveguide & Target Stick

- 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

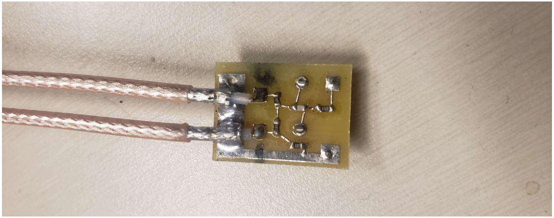
- On-site target material production at UNH
- Can produce:
  - Solid NH_3/ND_3
  - Chemically-doped solid alcohol
- Dedicated fume hoods for working with NH_3
- Material storage also at UNH

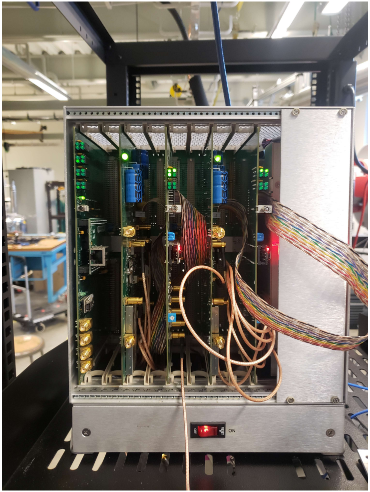
Above: Students producing cryogenic target material. *Left:* Frozen NH_3 produced and stored at UNH. *Right:* Frozen chemically-doped butanol produced at UNH.

NMR System

- NMR signal at deuteron spin transition central frequency ($\approx$ 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.



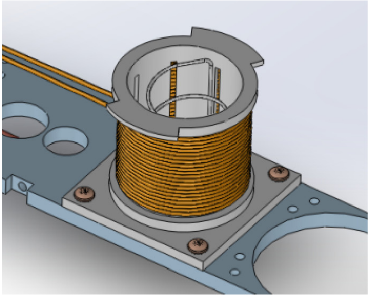


P. McGaughey, *et al*, NIM A **995** (2021) 165045

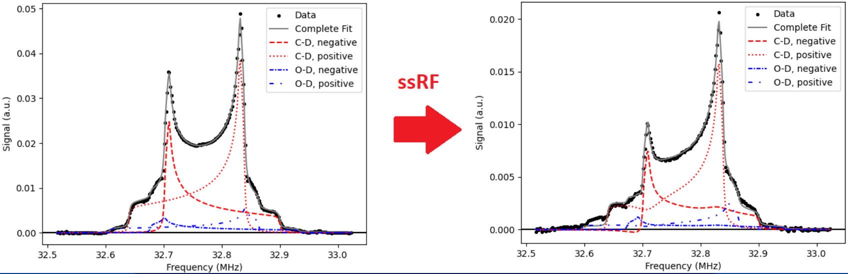
ssRF ("Hole Burning")

- 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%±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).

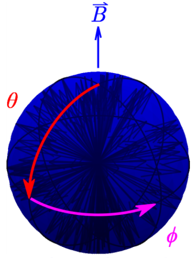


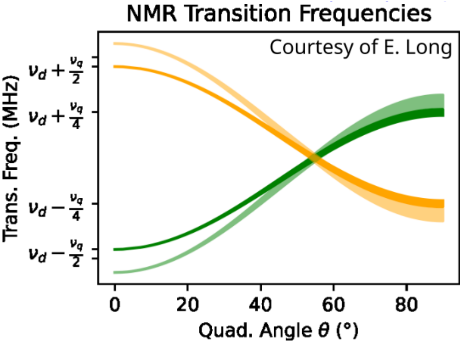
UNH NMR Simulation

From Spin Flips To Lineshape

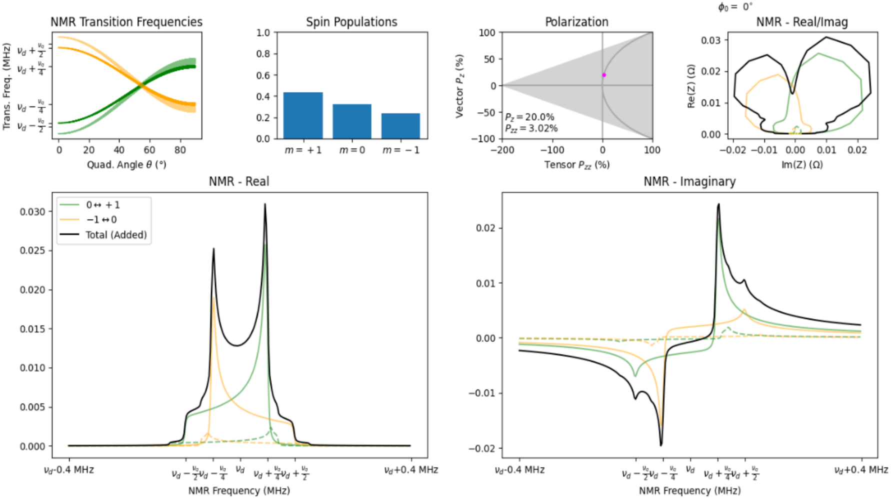
- Simulation derived from Cohen & Reif model (1957)
- Assume random distribution of quadrupole angles θ from 0°-90°
- Then calculates transition frequency based on angle and energy level
- Performs 125,000 spin flips into 300 angle bins, giving NMR signal
- Simulation can reproduce results from UVA polarized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

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





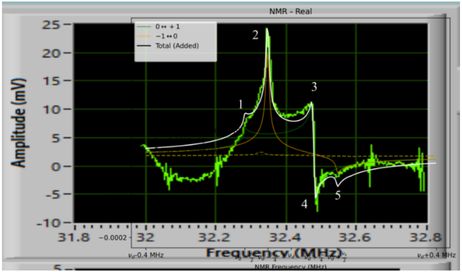
Simulated NMR Spectrum



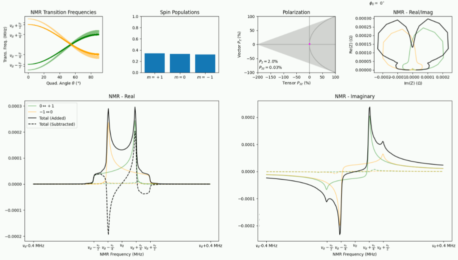
Generates real & imaginary components of NMR signal plus spin transition components! (Figure courtesy M. McClellan)

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

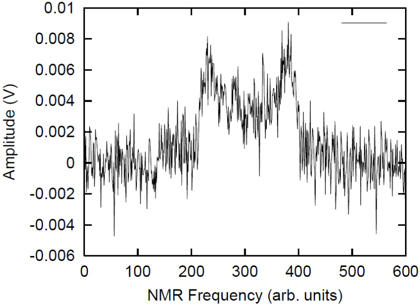
Thermal Equilibrium & Enhancement

Deuteron thermal equilibrium (TE) polarization before microwave irradiation:

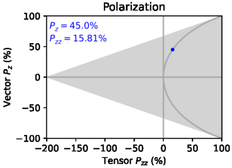
$$P(1) = \frac{4\tanh(\frac{g_i \mu_i B}{2k_B T})}{3 + \tanh^2(\frac{g_i \mu_i B}{2k_B T})} \qquad (6)$$

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

$$P_z = \frac{r^2 - 1}{r + r^2 + 1} \qquad P_{zz} = \frac{r^2 - 2r + 1}{r^2 + r + 1} \tag{7}$$

- 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

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

$$cos(\alpha) = \frac{1 - \epsilon R - \eta cos(2\phi)}{\rho^2} \qquad -3 \le R \le 3$$

functional form of signal

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

$$\boxed{\epsilon = \pm 1}$$

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

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

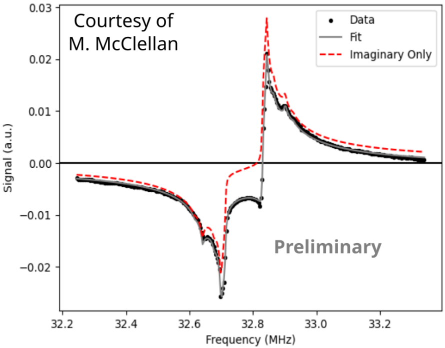
$$\theta = \omega_q/\omega_d$$

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:

$$\begin{aligned} \text{Real} &= \chi'' \cos\phi - \chi' \sin\phi \\ \text{Imag} &= \chi'' \sin\phi + \chi' \cos\phi \end{aligned} \tag{8}$$

- 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.

Tensor Polarization

"Typical" vector polarization:

$$P_z = N_+ - N_- \tag{9}$$

where $-1 \leq P_z \leq 1$

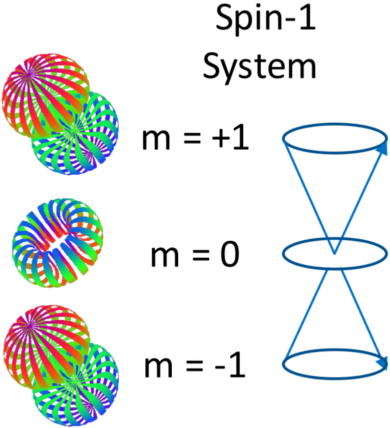
...but with an m=0 state we have tensor polarization:

$$P_{zz} = (N_+ + N_-) - 2N_0 \tag{10}$$

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

Goal

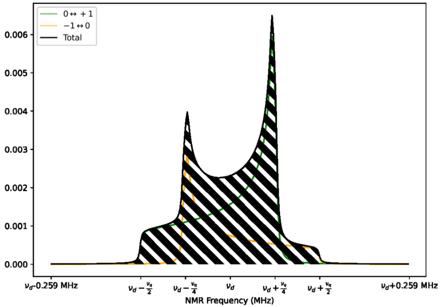
Create target with high tensor polarization for high-luminosity experiments



Measuring Tensor Polarization

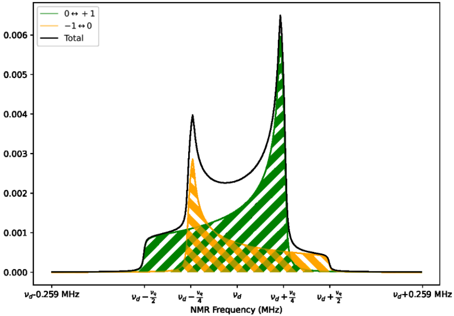
Vector Polarization Measurement

$$P_z = C(I_+ + I_-) \tag{11}$$



Tensor Polarization Measurement

$$P_{zz} = C(I_+ - I_-) \tag{12}$$



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

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