Achieving High Deuteron Tensor Polarization For Polarized Target Experiments

Allison J. Zec
(she/her)

Univ. of New Hampshire

2023-09-26

Deuterons and the Tensor Experiments

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
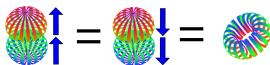

$$P_{zz} = (p_+ + p_-) - 2p_0$$

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

Tensor Polarization Properties

If. . .

 $>$

 $=$ $=$

 $<$

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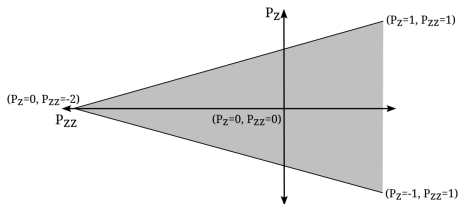
$$0 < P_{zz} \leq 1$$

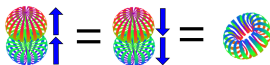$$P_{zz} = 0$$

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

- 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
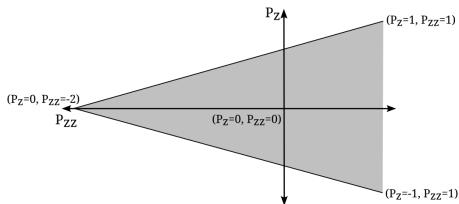
Tensor Polarization Properties

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
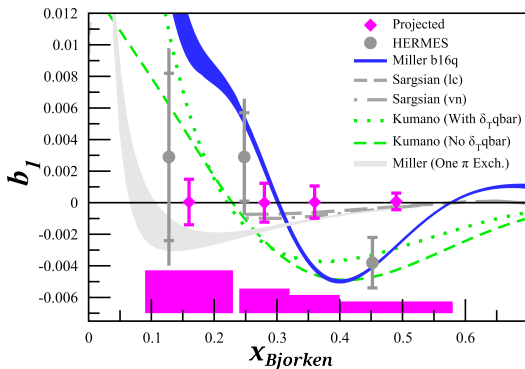
b_1 Experiment

- 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
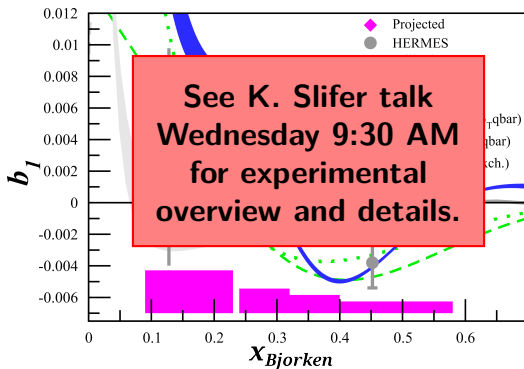
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E12-13-011

The Deuteron Tensor Structure Function b_1

See K. Slifer talk Wednesday 9:30 AM for experimental overview and details.

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
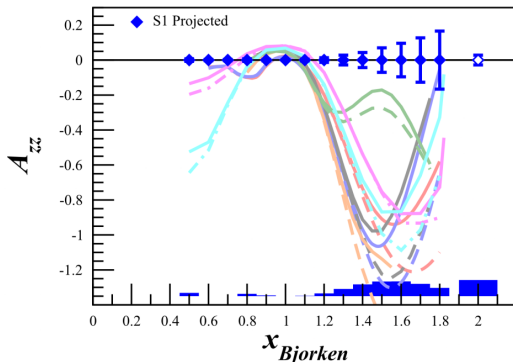
A_{zz} Experiment

- 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
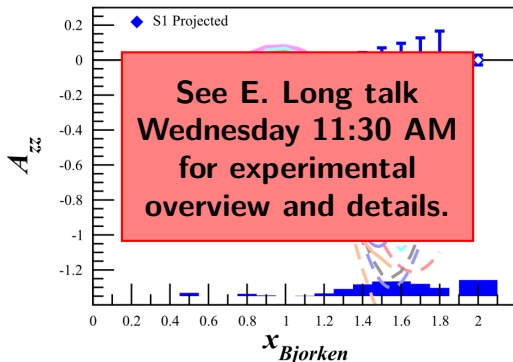
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Approved by JLab with A-physics rating!

E12-15-005

Quasi-Elastic and Elastic Deuteron Tensor Asymmetries

See E. Long talk Wednesday 11:30 AM for experimental overview and details.

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

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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?

Tensor Targets: Granite State Style

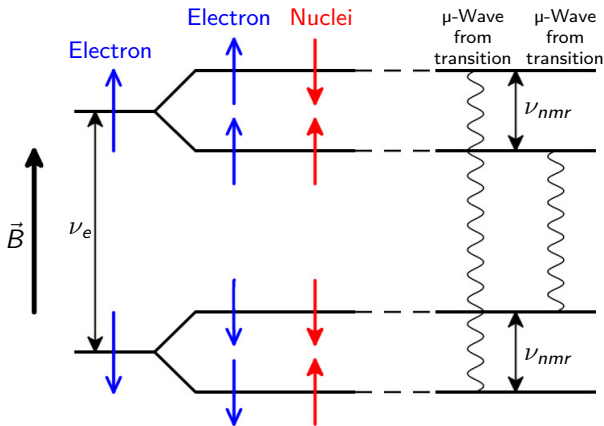# Dynamic Nuclear Polarization (DNP)

- Using μwaves, drive spin transitions of unpaired electrons
- Electrons transfer spin to nuclei
- Nuclear absorption spectrum gives polarimetry info
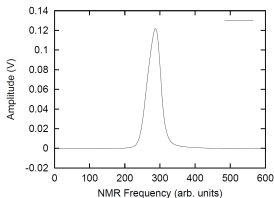
*Above:* Characteristic lineshape of the proton
C.D. Keith *et al*, NIM A **501** (2003)

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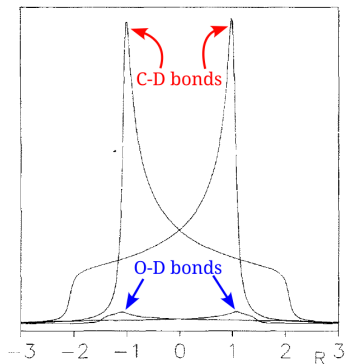
Deuteron Polarization

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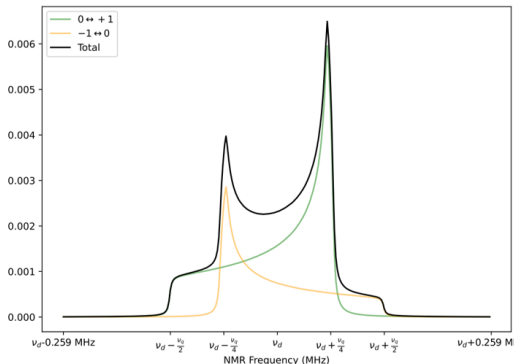
Above: Simulated deuteron lineshape showing the contributions from both the $-1 \rightarrow 0$ transition and the $0 \rightarrow 1$ transition.

ND$_3$ and Other Target Materials

- 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

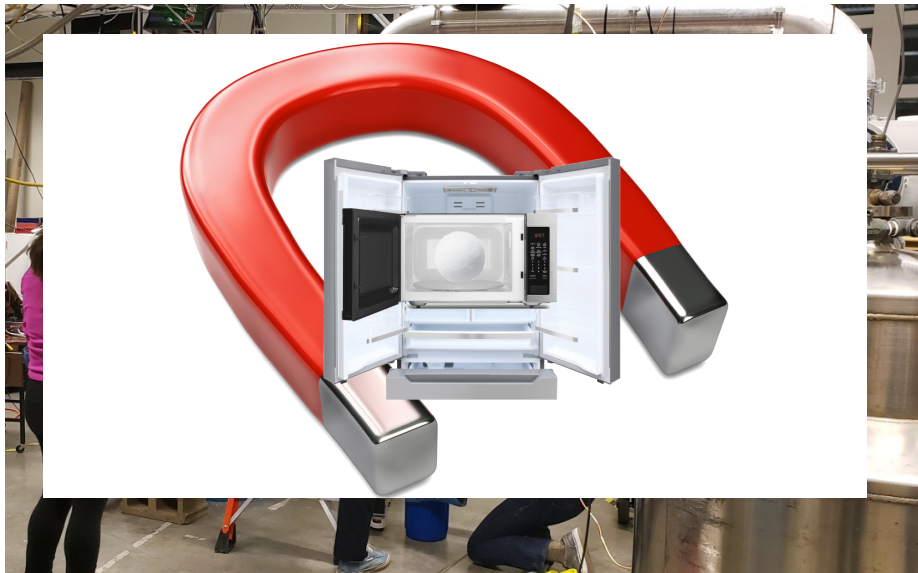| Material	Dopant & method	Polarizable nucleons % by weight
ND$_3$ d-ammonia	ND$_2$ Irradiation	~30%
C$_4$D$_9$OD d-butanol	TEMPO Chemical	23.7%

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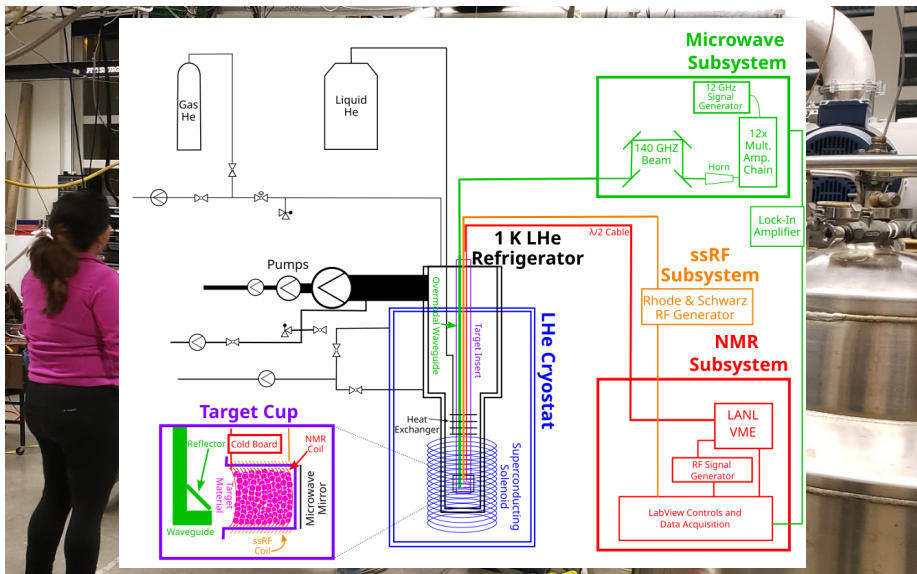
UNH Polarized Target Lab

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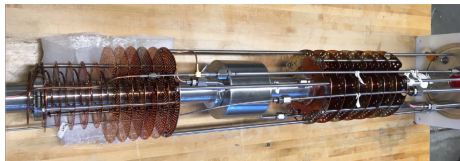
The UNH polarized target group is hard at work!
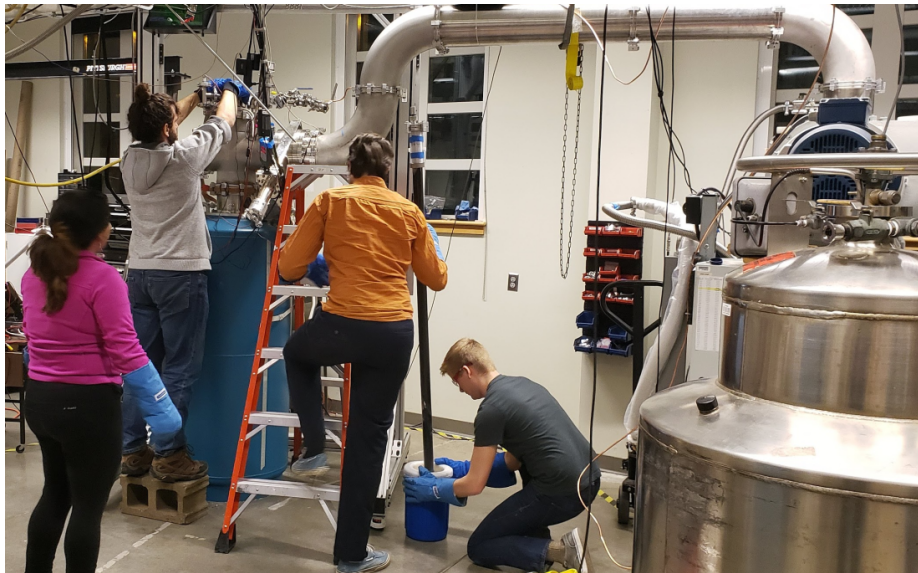
The UNH polarized target group is hard at work!

UNH Polarized Target Lab

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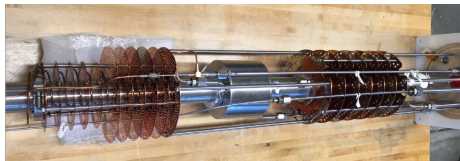D. M. Aliaga *et al.* NIM 976 (2020) 164277

Refrigerator and Magnet

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

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

Refrigerator and Magnet

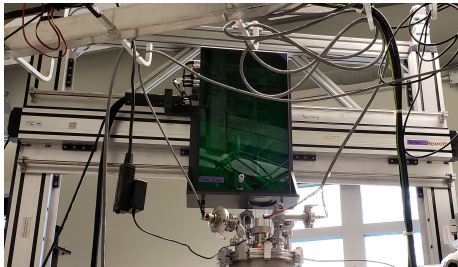| 1 K LHe evaporative fridge, with 2.4 W cooling power | 5 T Nb-Sn superconducting solenoidal magnet |

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

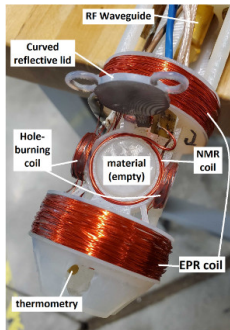Designed, printed and assembled in-house. Also houses overmodal microwave waveguide.

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

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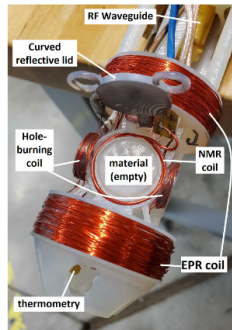
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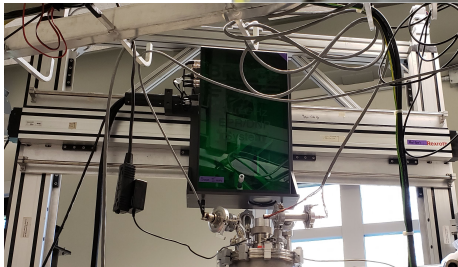
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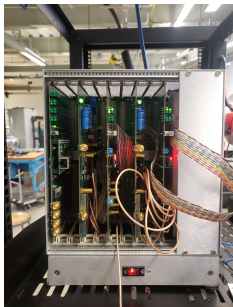*Right: 3D-printed target insert ladder with coils wound and no target material.*

Below left: frozen unirradiated NH$_3$.
Below right: frozen doped butanol.

Target Material

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

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.
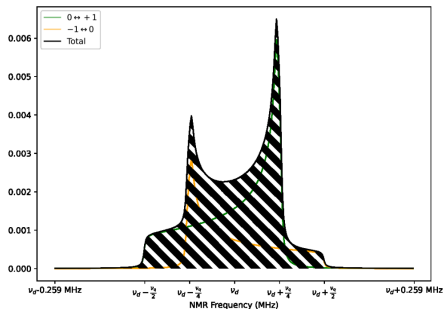*Below right: frozen doped butanol.*

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Tensor Polarization Measurements
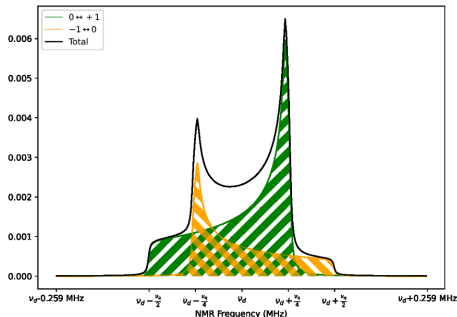
Measuring Tensor Polarization

Vector Polarization Measurement

$$P_z = C(I_+ + I_-) \qquad (1)$$

Tensor Polarization Measurement

$$P_{zz} = C(I_+ - I_-) \qquad (2)$$

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

Figures courtesy of E. Long

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

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

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

(3)

- 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

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

$$\epsilon = \pm 1$$

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

phi average

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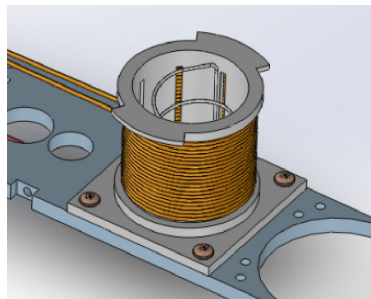
positive & negative spin flips

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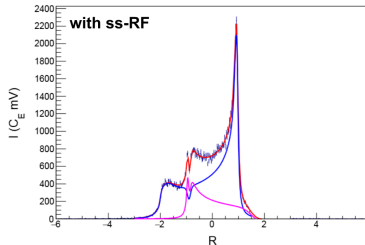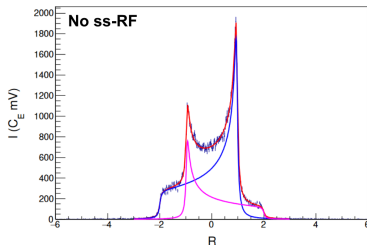
$$\theta = \omega_q/\omega_d$$

Tensor Polarization Measurement (UVA)

- UVA-pioneered tensor enhancement technique
- Additional RF coils drive spin flips
- Manipulates area of NMR curve

- Small frequency range
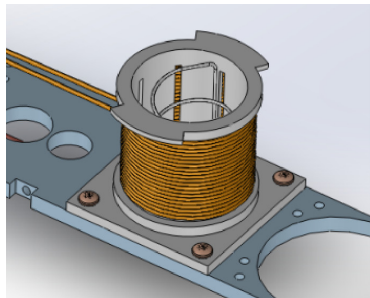- UVA lab achieved $P_{zz}=31.1\pm8.5\%$ with ssRF technique

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

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

No ss-RF

with ss-RF

b_1 and A_{zz} experimental conditionals removed!
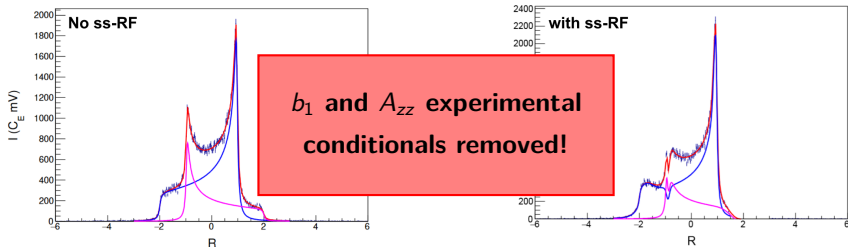
Tensor Polarization (UNH)

- 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
- Fit method works very well for UNH data!
- **New helium reliquifier system will enhance UNH's ability to run and get physics data!**
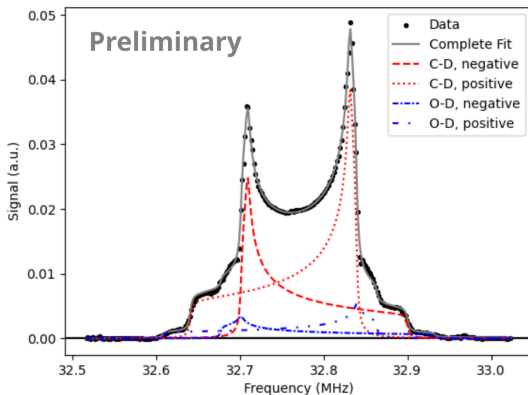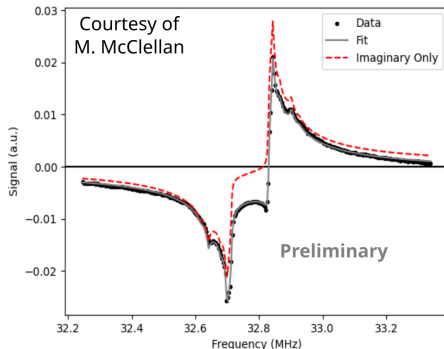

Above: Curve fit of NMR lineshape from recent target cooldown at UNH.

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:

$$\text{Real} = \chi'' \cos\phi - \chi' \sin\phi$$
$$\text{Imag} = \chi'' \sin\phi + \chi' \cos\phi \qquad (4)$$

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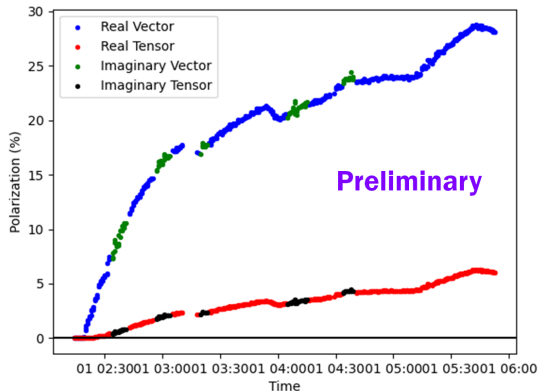
Above: Data from recent UNH cooldown with both real and imaginary line data for both vector and tensor polarization. Figure courtesy of M. McClellan.
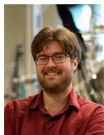
Summary

Professors
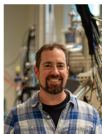
Karl Slifer

Elena Long
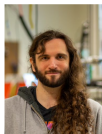
Nathaly Santiesteban

Postdocs

Allison Zec

David Ruth
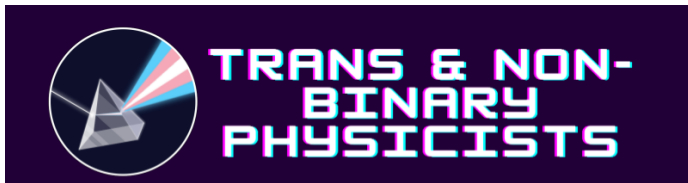
Graduate Students

Michael McClellan

Anchit Arora

Zoe Wolters

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

- Tensor target experiments approved!
- Conditionals removed for both experiments
- target development at UNH and UVA
- Improvements with ss-RF for better tensor polarization
- UNH group polarizing more (publications upcoming. . .)
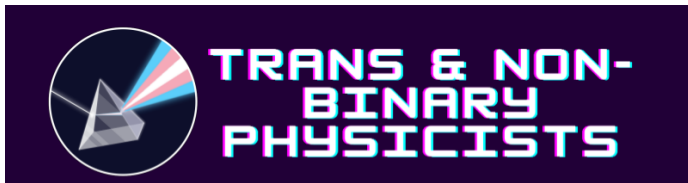- Exciting new developments upcoming!

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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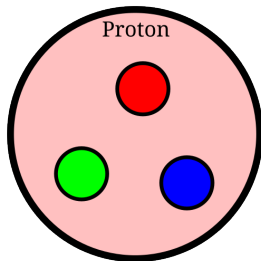**@transphysicists**

on twitter!

Questions, comments, concerns, observations?

Backup Slides

Proton

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

Three valence quarks + gluons and sea quarks

No nucleon-nucleon interactions
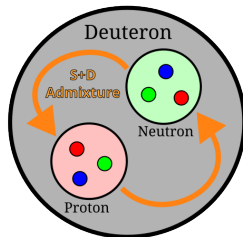
$m = \pm\frac{1}{2}$

Deuteron

Spin-1 System

Proton-Neutron bound state

Simplest nuclear system: nucleon interaction effects

$m = \pm 1, 0$

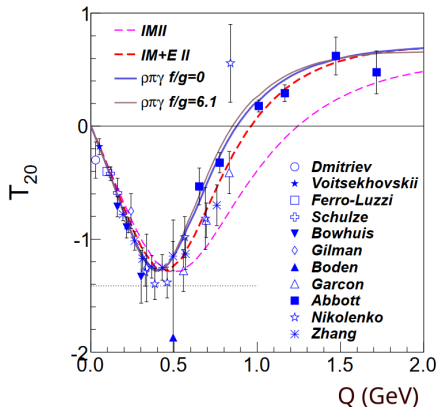S. Kumano, IOP Proc. Tens. Pol. Targ. (2014)

Elastic Tensor Analyzing Power

For $1.5 \leq x \leq 2.0$

$$T_{20} \approx \frac{A_{zz}}{\sqrt{2}d_{20}} \qquad (5)$$

- 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.

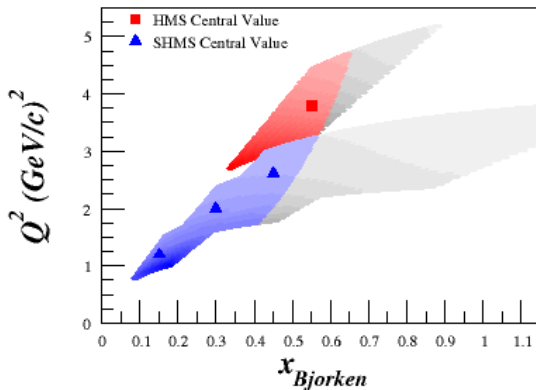R. Holt, R. Gilman Rept.Prog.Phys. **75** (2012)

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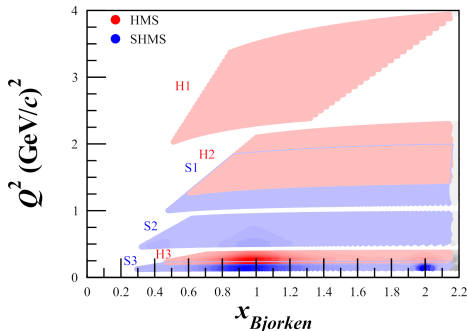
E. Long *et al*, JLab C12-15-005

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

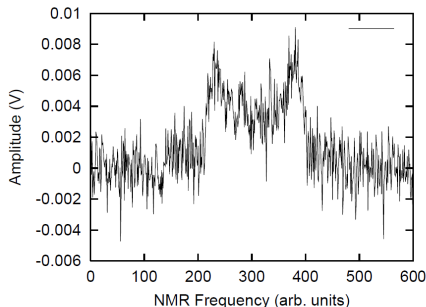# BACKUP: Tensor Polarization Analysis

Thermal Equilibrium & Enhancement

Deuteron thermal equilibrium (TE) polarization before microwave irradiation:

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

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.