Prospects for Tensor-Polarized DVCS

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2023-08-10

Deuterons and the Current Tensor Program

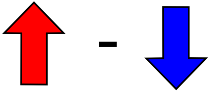
What Deuterons Do That Protons Don't

Proton

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

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

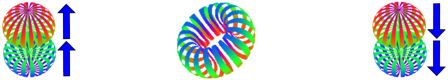
"Typical" Vector Polarization



$P_z = p_+ - p_-$

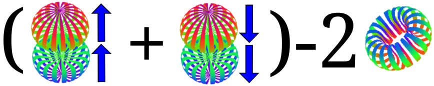
Deuteron

Spin-1 System



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

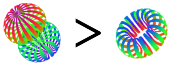
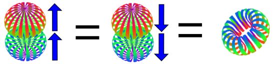
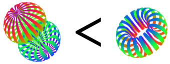
Vector **and** Tensor Polarization

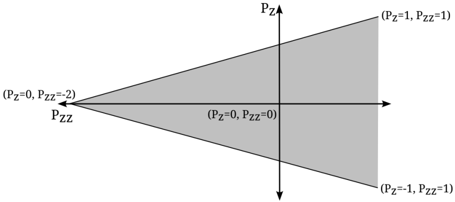


$P_{zz} = (p_+ + p_-) - 2p_0$

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

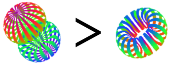
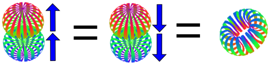
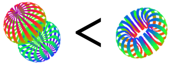
Tensor Polarization Properties

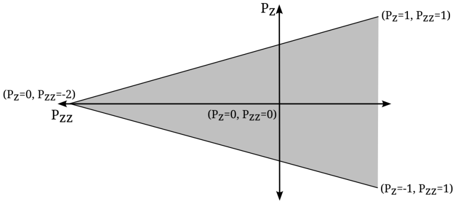
If...	**Then...**
	$0 < P_{zz} \leq 1$
	$P_{zz} = 0$
	$-2 \leq P_{zz} < 0$



- 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

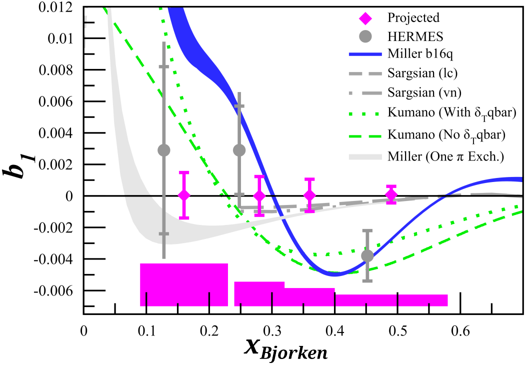
Approved Experiment: b_1

- 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

Approved Experiment: A_{zz}

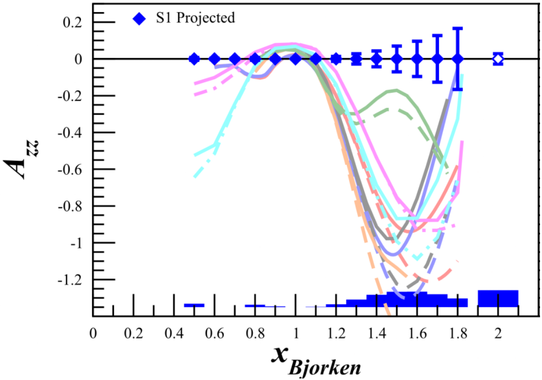
- First-of-its-kind quasielastic A_{zz} measurement
- Implications for SRC physics and deuteron wavefunction
- Widest range of x covered by a single measurement
- Measurement of T_{20} included!

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

Propsects: Deuterons, GPDs and DVCS

Spin-1 GPDs

Vector and Axial Elements for Deuteron GPDs

$$V_{\lambda'\lambda} = -(\epsilon'^* \cdot \epsilon) H_1 + \frac{(\epsilon \cdot n)(\epsilon'^* \cdot P) + (\epsilon'^* \cdot n)(\epsilon \cdot P)}{P \cdot n} H_2 - \frac{(\epsilon \cdot P)(\epsilon'^* \cdot P)}{2M_D^2} H_3$$
$$+ \frac{(\epsilon \cdot n)(\epsilon'^* \cdot P) - (\epsilon'^* \cdot n)(\epsilon \cdot P)}{P \cdot n} H_4 + \left[4M_D^2 \frac{(\epsilon \cdot n)(\epsilon'^* \cdot n)}{(P \cdot n)^2 + \frac{1}{3}(\epsilon'^* \cdot \epsilon)} \right] H_5 \quad (1)$$

$$A_{\lambda'\lambda} = -i \frac{\epsilon_{\mu\alpha\beta\gamma} n^\mu \epsilon'^{*\alpha} \epsilon^\beta P^\gamma}{P \cdot n} \tilde{H}_1$$
$$+ i \frac{\epsilon_{\mu\alpha\beta\gamma} n^\mu \Delta^\alpha \epsilon^\beta}{P \cdot n} \frac{\epsilon^\gamma (\epsilon'^* \cdot P) + \epsilon'^{*\gamma} (\epsilon \cdot P)}{M_D^2} \tilde{H}_2$$
$$+ i \frac{\epsilon_{\mu\alpha\beta\gamma} n^\mu \Delta^\alpha P^\beta}{P \cdot n} \frac{\epsilon^\gamma (\epsilon'^* \cdot P) - \epsilon'^{*\gamma} (\epsilon \cdot P)}{M_D^2} \tilde{H}_3 \quad (2)$$
$$+ i \frac{\epsilon_{\mu\alpha\beta\gamma} n^\mu \Delta^\alpha P^\beta}{P \cdot n} \frac{\epsilon^\gamma (\epsilon'^* \cdot n) + \epsilon'^{*\gamma} (\epsilon \cdot n)}{P \cdot n} \tilde{H}_4$$

where $P = (p + p')/2$, ϵ is the target deuteron polarization and ϵ' is the recoil deuteron polarization

E. Berger, F. Cano, M. Diehl, B. Pire PRL 87 (2001) 142302

Spin-1 GPDs

Relevant Sum Rules

$$\int_{-1}^{1} dx H_i(x,\xi,t) = G_i(t) \qquad (i=1,2,3) \qquad (3)$$

$$\int_{-1}^{1} dx \tilde{H}_i(x,\xi,t) = \tilde{G}_i(t) \qquad (i=1,2) \qquad (4)$$

$$\int_{-1}^{1} dx H_4(x,\xi,t) = \int_{-1}^{1} \tilde{H}_3(x,\xi,t) = 0 \qquad (5)$$

$$\int_{-1}^{1} dx H_5(x,\xi,t) = \int_{-1}^{1} \tilde{H}_4(x,\xi,t) = 0 \qquad (6)$$

Time-Reversal Behavior

$$H_i(x,\xi,t) = H_i(x,-\xi,t) \quad (i=1,2,3,5) \qquad (7)$$

$$\tilde{H}(x,\xi,t) = \tilde{H}_i(x,-\xi,t) \quad (i=1,2,4) \qquad (8)$$

$$H_4(x,\xi,t) = -H_4(x,-\xi,t) \qquad (9)$$

$$\tilde{H}_3(x,\xi,t) = -\tilde{H}_3(x,\xi,t) \qquad (10)$$

E. Berger, F. Cano, M. Diehl, B. Pire PRL 87 (2001) 142302
M. Diehl Phys. Rept. 388 (2003) 41-277

Form Factors & the Forward Limit

Form Factors | **Forward Limit**

$$\int_{-1}^{1} dx H_1(x,\xi,t) = G_C(t) + \frac{tG_Q(t)}{6M_D^2} \qquad \Rightarrow \int_{-1}^{1} dx H_1(x,0,0) = Z \tag{11}$$

$$\int_{-1}^{1} dx H_2(x,\xi,t) = G_M(t) \qquad \Rightarrow \int_{-1}^{1} dx H_2(x,0,0) = Z\mu_D \tag{12}$$

$$\int_{-1}^{1} dx H_3(x,\xi,t) = \frac{1}{1-\frac{t}{4M_D^2}}\left[G_M(t) - G_C(t) + \left(1-\frac{t}{6M_d^2}\right)G_Q(t)\right]$$
$$\Rightarrow \boxed{\int_{-1}^{1} dx H_3(x,0,0) = Z(\mu_D + \mathcal{Q}_D - 1)} \tag{13}$$

S Liuti, K Kathuria 2014 J. Phys. Conf. Ser. 543 012005; A. Kirchner, D. Müller Eur.Phys.J. C32 (2003) 347-375

$H_1 \Rightarrow$ momentum, $H_2 \Rightarrow$ ang. mom., $H_3 \Rightarrow$ quadrupole. $\mathcal{Q}_D$ is the deuteron quadrupole moment

Forward Limit and b_1

First tensor structure function b_1

$$\int_0^1 dx b_1 = 2 \sum_{i=u,d,s} e_i^2 \int_0^1 dx \delta\bar{q}_i(x) \quad (14)$$

for unpolarized sea quarks:

$$\int_0^1 dx b_1(x) = 0 \qquad (15)$$

F. E. Close, S. Kumano PRD 42 (1990) 2377
A. Kirchner, D. Müller Eur.Phys.J. C32 (2003) 347-375

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A. Kirchner, D. Müller Eur.Phys.J. C32 (2003) 347-375

Tensor GPD H_5

In forward limit:

$$H_5(x, 0, 0) \equiv b_1(x) \quad (16)$$

with

$$b_1(x) = \frac{1}{2} \sum_q e_q^2 \left[q^0(x) - \frac{q^1(x) + q^{-1}(x)}{2} \right] \quad (17)$$

where $q^i(x)$ are quark densities

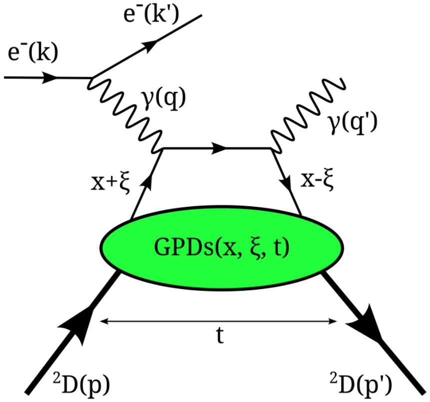
S. Liuti, K. Kathuria 2014 J. Phys. Conf. Ser. 543 012005

Coherent Deuteron DVCS

$$eD \to e\gamma D$$

- Cross-section dependent on $\mathcal{M}_{BH}$ and $\mathcal{M}_{DVCS}$ and interference terms
- Rates not yet examined
- Unpolarized deuteron DVCS: **E08-25**
- Two approved inclusive tensor experiments: $\boldsymbol{b_1}$ and $\boldsymbol{A_{zz}}$
- New experimental group for exclusive measurement of A_{zz}
- **No current proposals for DVCS with a tensor-polarized target!**

M. Benali *et. al.* Nat. Phys. 16 (2020) 191-198



Above: Handbag diagram for coherent deuteron DVCS

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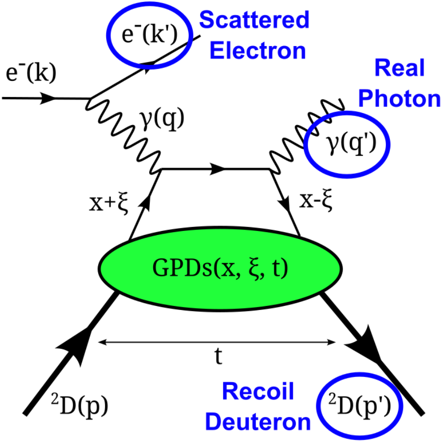
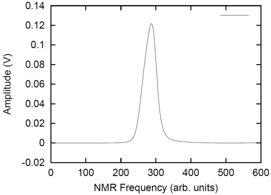


Above: Handbag diagram for coherent deuteron DVCS, with outgoing particles labeled.

UNH Polarized Targets

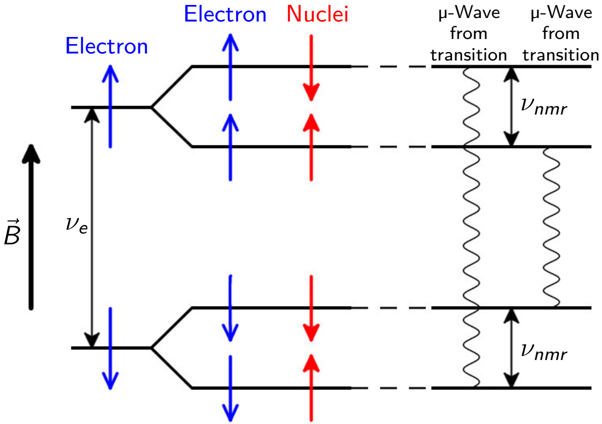
Dynamic Nuclear Polarization (DNP)

- 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

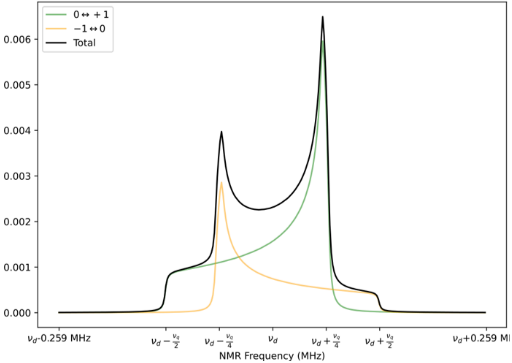
C.D. Keith *et al*, NIM A **501** (2003)



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
- ***P_{zz}* extracted from area difference of transition curves!**



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

$$P_z = \frac{r^2 - 1}{r + r^2 + 1}$$
$$P_{zz} = \frac{r^2 - 2r + 1}{r^2 + r + 1} \qquad (18)$$

- 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

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

$\epsilon = \pm 1$

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

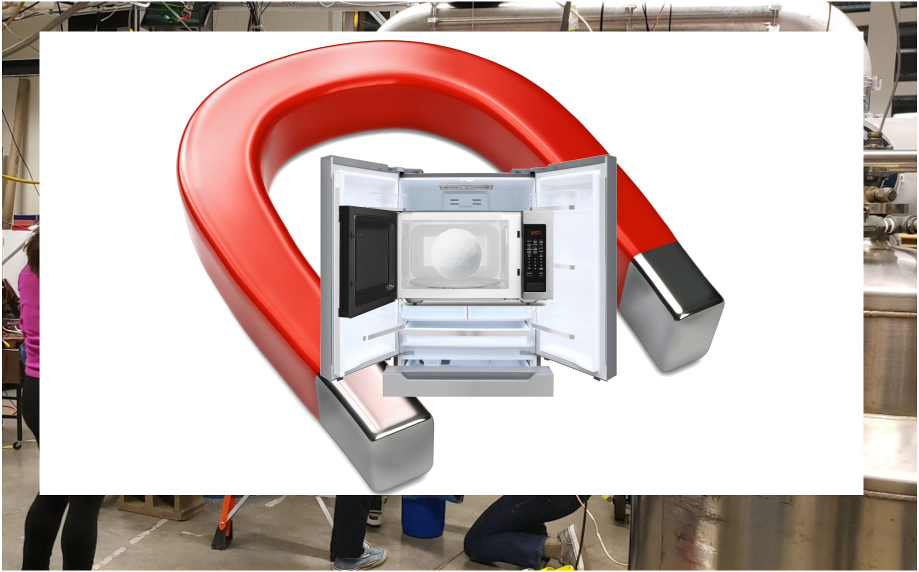
$$\chi''(r, R) \propto \frac{1}{\omega_q}\left\{\left[\frac{r^2 - r^{1-3\theta R}}{r^{1-\theta R}}\right]F_+(R) + \left[\frac{r^{1+3\theta R} - 1}{r^{1+\theta R}}\right]F_-(R)\right\}$$

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

UNH Polarized Target Lab

The UNH polarized target group is hard at work!

UNH Polarized Target Lab



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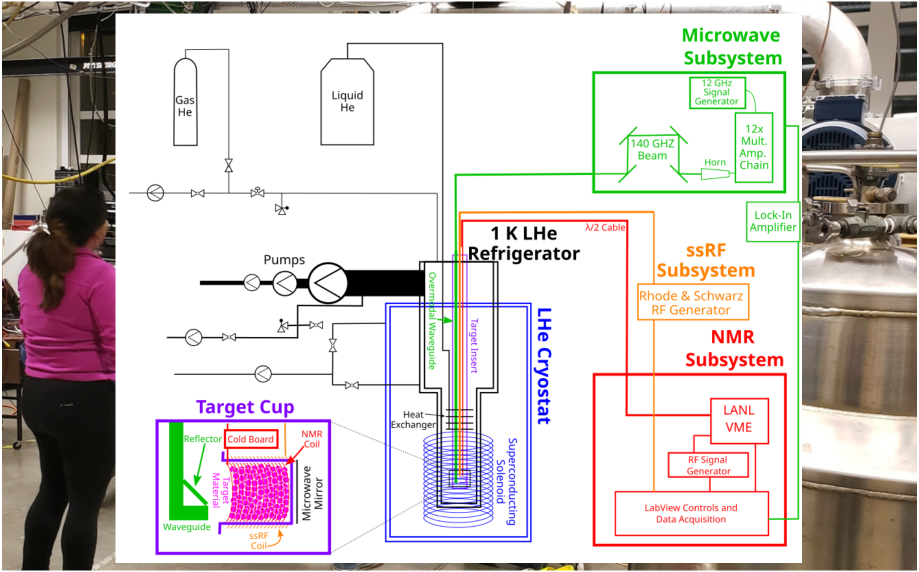
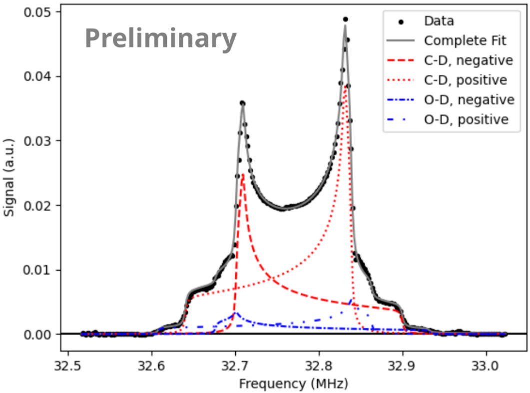


The UNH polarized target group is hard at work!

Tensor Target & Development

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!

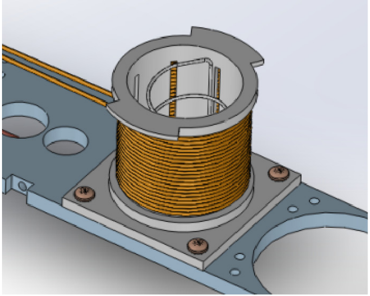


Above: Curve fit of NMR lineshape from recent target cooldown at UNH.

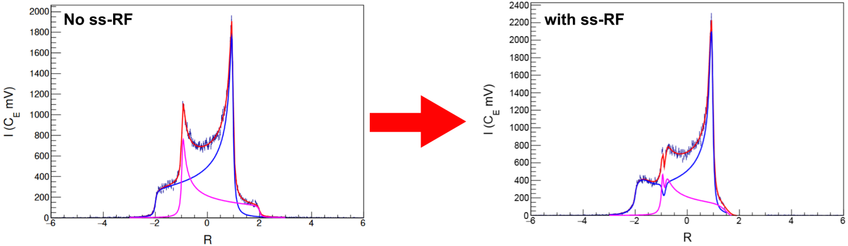
Tensor Polarization Measurement (UVA)

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

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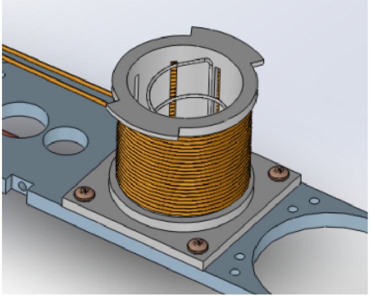

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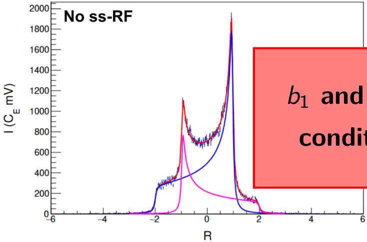
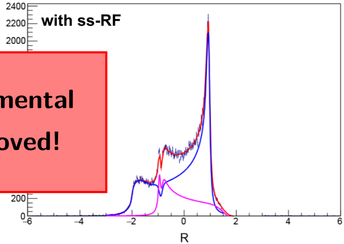
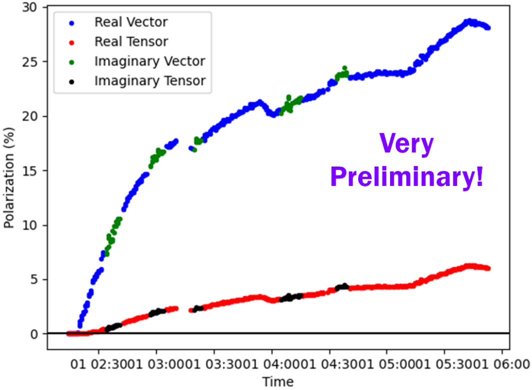


b_1 and A_{zz} experimental conditionals removed!



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

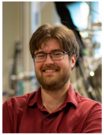
Karl Slifer

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!

- Inclusive tensor program approved!
- Tensor-polarized DVCS has implications for H_3 and H_5 GPDs
- Possible DVCS expansion to tensor experiment program, **actively seeking collaborators!**
- Target development for current tensor experiments
- UNH group polarizing more (publications upcoming. . .)
- Exciting new developments upcoming!

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

@transphysicists

on twitter!

Trans & Nonbinary Physicists

TRANS & NON-BINARY PHYSICISTS

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Questions, comments, concerns, observations?

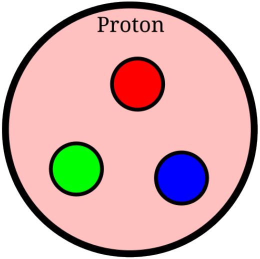
Backup Slides

Deuteron Tensor Polarization and Properties

Protons & Deuterons

Proton

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



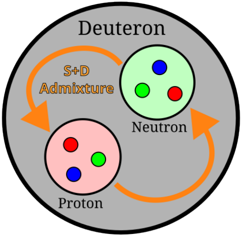
Three valence quarks + gluons and sea quarks

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)

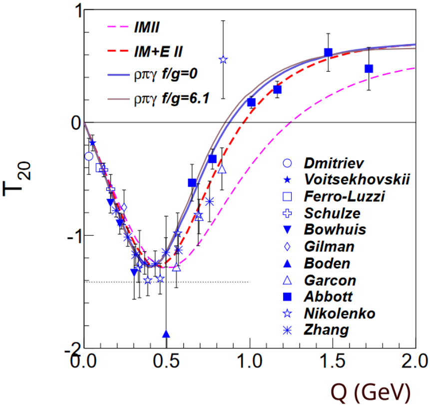
Elastic Tensor Analyzing Power

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

$$T_{20} \approx \frac{A_{zz}}{\sqrt{2}d_{20}} \qquad (19)$$

- 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)

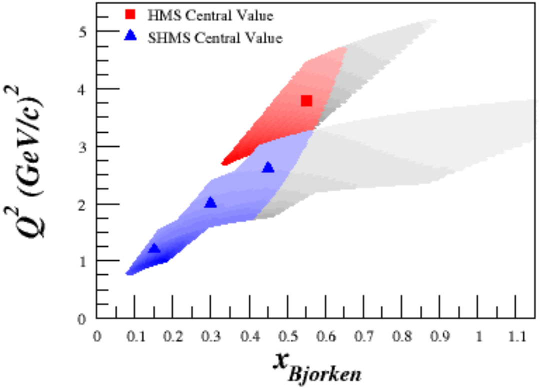
b_1 Kinematics

- 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

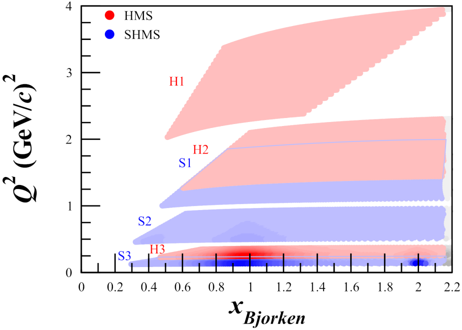
A_{zz} Kinematics

- 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

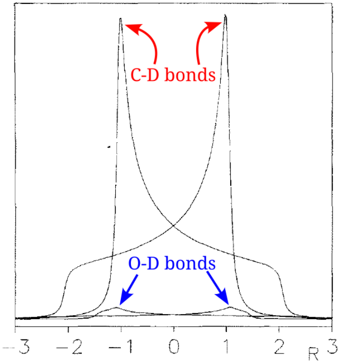


E. Long *et al*, JLab C12-15-005

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%

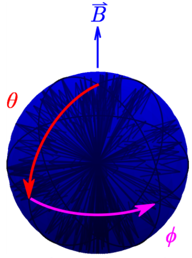
D. Crabb, W. Meyer, Annu. Rev. Nucl. Part. Sci **47** 67-109 (1997)

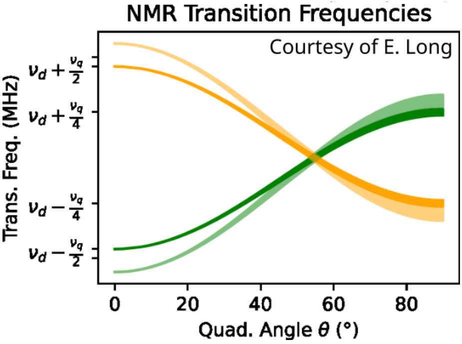
BACKUP: UNH NMR Simulation

From Spin Flips To Lineshape

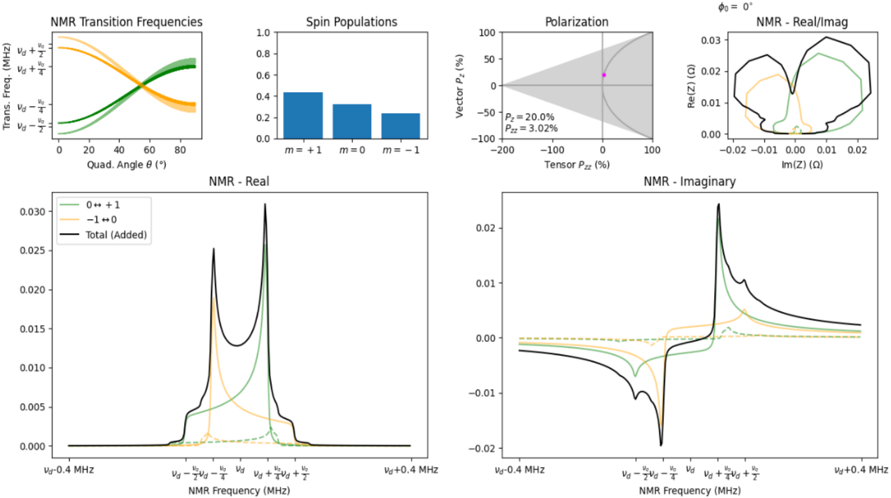
- Simulation derived from Cohen & Reif model (1957)
- Assume random distribution of quadrupole angles θ from 0°-90°
- Then calculates transition frequency based on angle and energy level
- Performs 125,000 spin flips into 300 angle bins, giving NMR signal
- Simulation can reproduce results from UVA polarized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





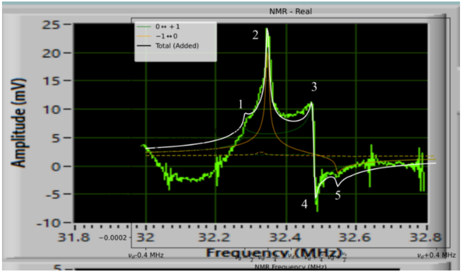
Simulated NMR Spectrum

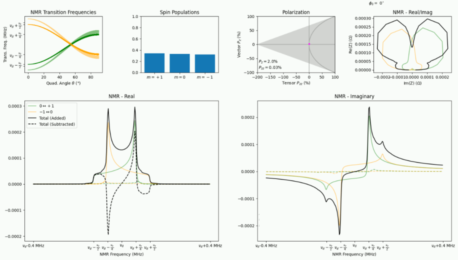


Generates real & imaginary components of NMR signal plus spin transition components! (Figure courtesy M. McClellan)

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

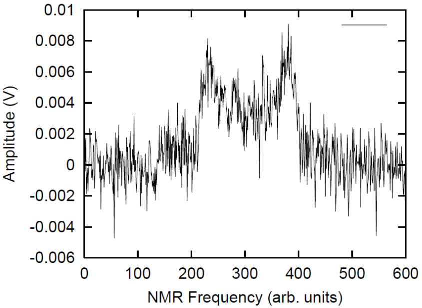
Thermal Equilibrium & Enhancement

Deuteron thermal equilibrium (TE) polarization before microwave irradiation:

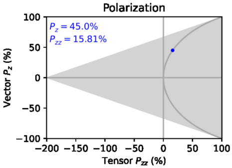
$$P(1) = \frac{4\tanh(\frac{g_i \mu_i B}{2k_B T})}{3 + \tanh^2(\frac{g_i \mu_i B}{2k_B T})} \tag{20}$$

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.

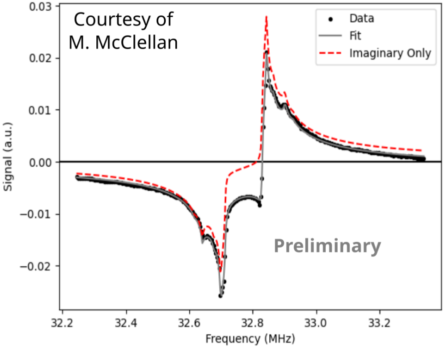


Real & Imaginary Fits

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

$$\begin{aligned} \text{Real} &= \chi'' \cos\phi - \chi' \sin\phi \\ \text{Imag} &= \chi'' \sin\phi + \chi' \cos\phi \end{aligned} \tag{21}$$

- 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.