PR12-15-005: Measurement of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries

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Deuteron

Simplest composite nuclear system

However, understanding of deuteron at short distances remains unsatisfying

 A well-constrained theoretical model is necessary for understanding tensor interactions underlying short-range correlations and *pn*-dominance

Short-range deuteron structure can be probed using choice in kinematics (x > 1) and by enhancing the *D*-state through tensor polarization

This proposal uses a combination of both techniques



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

Tensor Polarization

For tensor polarization, need spin-1 particles



Animations by SC Pieper, et al, http://www.phy.anl.gov/theory/movie-run.html

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of nuclear physics

Deuteron Wavefunction

Is the deuteron wavefunction hard or soft?

- AV18 is an example of a moderate-hard WF
- CDBonn is an example of a soft WF

Unpolarized deuterons need to be probed at k > 400 MeV to distinguish between hard and soft WFs

• Not practical

Currently no unambiguous experimental evidence for which is more valid

Tensor polarization enhances the *D*-state, allowing hard and soft WFs to be distinguished at lower momenta



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Deuteron Wavefunction

First calculated in the '70s, A_{zz} can be used in to discriminate between hard and soft wavefunctions

$$A_{ZZ} = \frac{2}{f P_{ZZ}} \left(\frac{\sigma_p - \sigma_u}{\sigma_u} \right)$$

In the impulse approximation, A_{zz} is directly related to the *S*-and *D*-states

$$A_{zz} \propto \frac{\frac{1}{2}w^2(k) - u(k)w(k)\sqrt{2}}{u^2(k) + w^2(k)}$$

Modern calculations indicate a large separation of hard and soft WFs begins just above the quasi-elastic peak at x > 1.4

L.L. Frankfurt, M.I. Strikman, Phys. Rept. 76 (1981) 215



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Relativistic NN Bound System



Relativistic calculations needed to understand underlying physics in short-range correlations at high momenta

Light Cone (LC) and Virtual Nucleon (VN) calculations are often used

Large momenta (> 500 MeV/c) needed to discriminate with unpolarized deuterons

With tensor polarized A_{zz} significant difference at much lower momenta (> 300 MeV/c) and x > 1.1

M Sargsian, Tensor Spin Observables Workshop (2014)

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Final State Interactions

To determine nucleonic components of the deuteron WF, FSI must be understood

Minimum and maximum effects from FSI have been calculated by W. Cosyn

Even with FSI, large discrepancy based on WF input



First Measurement of Quasi-Elastic A_{zz}



Sensitive to effects that are very difficult to measure with unpolarized deuterons

Huge 10-120% asymmetry

Measuring A_{zz} over a range in x and Q^2 provides insight to

- Nature of NN Forces
- Hard/Soft Wavefunctions
- Relativistic NN Dynamics
- On-Shell/Off-Shell Effect FSI

Decades of theoretical interest that we can only now probe with a high-luminosity tensor-polarized target

Importance ranges from understanding short-range correlations to the equations of state of neutron stars

First Measurement of Quasi-Elastic A_{zz}

A measurement of quasi-elastic A_{zz} will fill a gap in tensor polarized deuteron experiments

DIS $\rightarrow b_1 \propto F_1 A_{zz}$ HERMES, upcoming at JLab	$QE \rightarrow A_{ZZ}$ <u>No current or planned</u> <u>measurements</u>	Elastic $\rightarrow T_{20} \propto A_{zz}$ 10 measurements from Bates, JLab, NIKHEF, and VEPP		
< 0.5	0.8 - 1.8	2 x		

summer."

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Theoretical Interest

"A measurement of Azz will provide important information on whether the deuteron wavefunction is hard or soft, as well as on relativistic effects. These are important for the progress of our understanding of the short-range dynamics of nuclear interactions, which have relevance ranging from short-range correlations in nuclei to the equations of state of neutron stars."

" A_{zz} is a unique method to measure the ratio of S- and D-waves in the deuteron at short distances and hence test the spin structure of short-range correlations. It is also the most sensitive observable to test different approaches to the description of relativistic dynamics."

"What interests me most in this proposal is that it can teach us about the nature of the nucleon-nucleon force at short distances and with an observable sensitive to non-nucleonic contributions there is also room for surprising results. Additionally, on the theory side, this measurement would also provide an incentive for additional calculations and studies on top of the testing of various existing models, which is always a good thing."

"This proposal really challenges theorists to better understand the meaning of nuclear wave functions in a situation that demands a relativistic treatment. I plan on working to understand this reaction during the upcoming

"Previous low Q^2 measurements seemed to indicate that the asymmetries are far less sensitive to reaction mechanisms than the cross sections; so while the new calculations are not yet available, it is clear that the asymmetries will produce unique constraints on our understanding of the deuteron."

- W. Van Orden

- G. A. Miller

Part of a Growing Tensor Program

Growing tensor program

- DIS b_1 already approved (E12-13-011)
- Exotic gluon states through Δ (LOI12-14-001)



Physics accessible with a tensor polarized target:

- Deuteron wave function
- Close-Kumano Sum Rule
- Orbital Angular Momentum & Spin Crisis
- Gravitomagnetic Form Factors
- 6-Quark, Hidden Color
- Pionic Effects
- Polarized Sea Quarks
- Short Range Correlations and p-n Dominance
- Differentiate Light Cone and Virtual Nucleon Models
- Final State Interactions
- Gluonic Effects
- …and more!



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Azz Experimental Set-Up

- Hall C with HMS & SHMS
- Identical equipment and technique as b₁ (E12-13-011)





Techniques in R&D:

- 1) Selective Semi-Saturation
- 2) Time Dependence of Sample Rotation
- 3) Material Crystallization
- 4) Alternative Materials

Target Status Update

 Results from UVA are promising, preliminary Pzz=30% recently achieved with full analysis in progress





D Keller, PoS(PSTP 2013) 010 D Keller, HiX Workshop (2014) D Keller, J.Phys.:Conf.Ser. **543**, 012015 (2014) UVA Tensor Enhancement on Butanol (2014)

 UNH target lab is nearing complete, successfully tested magnet & NMR, first He fridge cool-down and proton TE scheduled for end of July





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D Keller, PoS(PSTP 2013) 010 D Keller, HiX Workshop (2014) D Keller, J.Phys.:Conf.Ser. **543**, 012015 (2014) UVA Tensor Enhancement on Butanol (2014)

Target Status Update

Progress made on measuring P_{zz} through NMR line-shape analysis

Solid-state NMR P_{zz} can be confirmed with elastic scattering (T_{20})





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Elastic T_{20} - Calibration & Measurement

Simultaneous measurement of the elastic tensor analyzing power T_{20}

At low Q^2 ,

- $\circ T_{20}$ well known
- P_{zz} can be extracted from T_{20}
- Completely independent P_{zz} measurement from NMR line-shape P_{zz}
- T_{20} in the largest and highest Q^2 range ever done in a single experiment
- $\,\circ\,$ Import cross-check of Hall C high Q^2 data



Kinematics							
$\mathcal{L}_D = 1.2 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$							
I = 80 nA • Similar to RSS, and	o SANE, GEN	E_0 (GeV)	Q^2 (GeV ²)	<i>E'</i> (GeV)	$ heta_{e'}$ (°)	Rates (kHz)	PAC Time (Days)
SHMS	(S1)	8.8	1.5	8.36	8.2	0.38	25
HMS	(H1)	8.8	2.9	7.26	12.2	0.04	25
SHMS	(S2)	6.6	0.7	6.35	7.5	3.57	8
HMS	(H2)	6.6	1.8	5.96	12.3	0.09	8
SHMS	(S3)	2.2	0.2	2.15	10.9	10.5	1
HMS	(H3)	2.2	0.3	2.11	14.9	3.23	1

Kinematics



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Solid = Quasi-elastic Open = Elastic

LL Frankfurt, et al, PRC 48 2451 (1993)

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Solid = Quasi-elastic

Open = Elastic

* More calculation coming soon...

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More than 10x less sensitive to systematics than b_1

Systematics

Source	A_{zz} Systematic	T_{20} Systematic
Polarization	3.0 - 6.0%	3.0 - 6.0%
Dilution factor	6.0%	2.5%
Packing fraction	3.0%	3.0%
Trigger/Tracking Eff.	1.0%	1.0%
Acceptance	0.5%	0.5%
Charge Determination	1.0%	1.0%
Detector resolution and efficiency	1.0%	1.0%
Total	7.6 - 9.2%	5.2 - 7.4%

Overhead

Overhead	Number	Time Per (hr)	(hr)
Polarization/depolarization	38	2.0	76.0
Target anneal	15	4.0	60.0
Target T.E. measurement	6	4.0	24.0
Target material change	4	4.0	16.0
Packing Fraction/Dilution runs	20	1.0	20.0
BCM calibration	9	2.0	18.0
Optics	3	4.0	12.0
Linac change	2	8.0	16.0
Momentum/angle change	3	2.0	6.0
			10.3 days

Challenges and Opportunities

- Tensor polarized target in development with dedication from multiple labs
- Stray SHMS fields will have negligible effect on target
- Data recoverable in rare event of target material shifting
- Very large A_{zz} asymmetry (10-120%)
- \circ Identical equipment and technique as b_1
- $^{\rm o}$ More than an order of magnitude less dependent on systematics than b_1
 - Perfect testing ground for fully understanding and controlling systematics

Summary



Summary



"The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of shortrange *pn* correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program." -JLab PAC42 & PAC43 Theory TACs (C. Weiss, R. Schiavilla, J.W. Van Orden)

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Tensor A_{zz} Collaboration

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Backup Slides



E. Long, *et al*, JLab PR12-15-005

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* More model predictions coming soon...

E. Long, et al, JLab PR12-15-005

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* More model predictions coming soon...

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Polarization Cycle

Each polarization cycle is an independent measurement of A_{zz}

- Annealing and target motion only at the start of a new cycle
- Any issues from annealing or material shifts will be isolated to a single cycle
 - Dilution/packing fraction runs at the beginning and end of each cycle can recover data surrounding a material shift event
- $\,\circ\,$ Doubled the number of cycles for the lowest Q^2 measurement



Target Magnet and Horizontal Bender



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Target Magnet and Horizontal Bender



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Tensor Polarized Target

 Dynamic Nuclear Polarization of ND₃ NMR MICROWAVES • $P_{zz} \sim 30\%$ • 5 Tesla at 1 K REFRIGERATOR PUMPS 3cm Target Length Tensor Polarization by Vector Polarization • *p_f* ~ 0.65 40(%)• $f_{dil} \sim 0.27$ **Tensor Polarization** 30 • UVA Techniques in R&D: REFRIGERATOR A=2 - $(4 ext{-}3P^{\,2})^{\scriptscriptstyle 1/2}$ Selective Semi-Saturation 0 Ē 20Time Dependence of Sample Rotation - MAGNET Material Crystallization Alternative Materials 0 TARGET SAMPLE 30 40 5060 70Vector Polarization (%)



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Tensor Polarized Target





Target Development in Progress

Selective Semi-Saturation

- Fitting measurements only minimally dependent on relaxation rates
- Tensor enhancement unrelated to area lost ($\Delta P_{zz} \neq -3\Delta P_z$)
- Spin diffusion can help spread enhancement
- Solid-state NMR P_{zz} can be confirmed with elastic scattering (T_{20})





Target Magnet and Horizontal Bender



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Target Magnet and Horizontal Bender



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Diluting Asymmetries



Dilution Factor



Connection to Short Range Correlations

Short range correlations caused by tensor force – why not probe it through tensor polarization?



Assumptions:

$$P_{zz} = 30\%$$

$$P_{zz} = 30\%$$

$$p_{f} = 65\%$$

$$Z_{tgt} = 3 \text{ cm}$$
P.E. Bosted, V. Mamyan, arXiv:1203.2262
M. Sargsian, Private Communication
N. Fomin, et al., Phys. Rev. Lett. 108 (2012) 092502
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E. Long, Technical Note, JLAB-TN-13-029

Elastic Tensor Observables



RJ Holt, R Gilman, Rep. Prog. Phys. **75** 086301 (2012)

C Zhang, et al, PRL 107 252501 (2011)

Possible New Target Configuration – Extended or Multiple Cells



$$FOM = n_t f^2 P_{zz}^2$$

b1 PAC condition with
$$z = 3 \text{ cm}$$
 and $P_{zz} = 0.3$,
• $n_t = \left(5.913 \times 10^{22} \frac{1}{\text{ cm}^3}\right) \cdot 3 \text{ cm} = 1.77 \times 10^{23} \frac{1}{\text{ cm}^2}$
• $FOM = f^2 (0.159 \times 10^{23} \frac{1}{\text{ cm}^2})$

With
$$z = 3 \text{ cm}$$
 and $P_{zz} = 0.2$,
• $FOM = f^2 (0.071 \times 10^{23} \frac{1}{\text{ cm}^2})$

With
$$z = 6 \text{ cm and } P_{zz} = 0.2$$
,
• $n_t = 3.54 \times 10^{23} \frac{1}{\text{cm}^2}$
• $FOM = f^2 (0.141 \times 10^{23} \frac{1}{\text{cm}^2})$