Tensor polarized deuteron structure

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Outline

- Introduction: tensor polarization, deuteron
- Inclusive DIS Tensor asymmetry: interpretation
- Tagged DIS tensor asymmetry: nuclear structure

Tensor polarization

- Present for **any** particle with spin ≥ 1
- Additional ($\leftrightarrow$ nucleon) spin degrees of freedom
  $\rightarrow$ experimental challenge [$\rightarrow$ talk Zec]
- Focus is on spin 1
  - Deuteron
  - Vector mesons [$\rightarrow$ talk Feng Li]
- Link with partonic properties [$\rightarrow$ talk Slifer]
- Link with nuclear structure [$\rightarrow$ talks Sargsian, Long]

Deuteron

- Only stable 2 nucleon system (*pn*)
- Small binding energy ~ 2 MeV
- $J^\pi = 1^+$, isospin $0 \rightarrow L = 0, 2$
- $\frac{\mu_d - \mu_p - \mu_n}{\mu_d} = -0.026$
  $\rightarrow$ S-wave dominates
- Quadrupole moment 0.282 fm^2
  - requires D-wave
  - non-central (tensor) *NN*-force

An Electrical Quadrupole Moment of the Deuteron*

Columbia University,
Hunter College (JRZ),
New York, New York,
January 15, 1939.

J. M. B. Kellogg
I. I. Rabi
N. F. Ramsey, Jr.
J. R. Zacharias

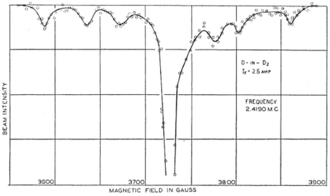


Fig. 2. Resonance minima for D in D_2.

Spin-1 Density Matrix

- Characterizes statistical ensemble of quantum system
- Spin-1: 3×3 matrix
- Multipole decomposition
  $\rightarrow$ 5 **tensor** parameters
- Values determined in polarimetry

$$\rho(\lambda,\lambda') = \begin{bmatrix} \frac{1}{3} + \frac{1}{2}S_L + \frac{1}{2}T_{LL} & \begin{array}{c}\frac{1}{2\sqrt{2}}S_T e^{-i(\phi_h-\phi_S)} \\ + \frac{1}{\sqrt{2}}T_{LT} e^{-i(\phi_h-\phi_{T_L})}\end{array} & \frac{1}{2}T_{TT} e^{-i(2\phi_h-2\phi_{T_T})} \\ \begin{array}{c}\frac{1}{2\sqrt{2}}S_T e^{i(\phi_h-\phi_S)} \\ + \frac{1}{\sqrt{2}}T_{LT} e^{i(\phi_h-\phi_{T_L})}\end{array} & \frac{1}{3} - T_{LL} & \begin{array}{c}\frac{1}{2\sqrt{2}}S_T e^{-i(\phi_h-\phi_S)} \\ - \frac{1}{\sqrt{2}}T_{LT} e^{-i(\phi_h-\phi_{T_L})}\end{array} \\ \frac{1}{2}T_{TT} e^{i(2\phi_h-2\phi_{T_T})} & \begin{array}{c}\frac{1}{2\sqrt{2}}S_T e^{i(\phi_h-\phi_S)} \\ - \frac{1}{\sqrt{2}}T_{LT} e^{i(\phi_h-\phi_{T_L})}\end{array} & \frac{1}{3} - \frac{1}{2}S_L + \frac{1}{2}T_{LL} \end{bmatrix}$$

- If spin quantization axis = polarization direction
  $\rightarrow$ diagonal matrix
- All pure states have tensor polarization
- $\lambda = 0$ pure state has no vector polarization

Tensor Asymmetries

- Density matrix parameters appear in cross section decomposition
  - multiply independent structure functions
  - **richer** structure for spin 1 compared to nucleon
  - **harder** to disentangle experimentally

$$
\begin{aligned}
F_T = T_{LL} \Big[& F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \Big] \\
& + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\
& + T_{LT} [\cdots] + T_{LT} h [\cdots] \\
& + T_{TT} \Bigg[\cos(2\phi_h - 2\phi_{T_T}) \left(F_{UT_{TT},T}^{\cos(2\phi_h - 2\phi_{T_T})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h - 2\phi_{T_T})} \right) \\
& + \epsilon \cos 2\phi_{T_T} F_{UT_{TT}}^{\cos 2\phi_{T_T}} + \epsilon \cos(4\phi_h - 2\phi_{T_T}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T_T})} \\
& + \sqrt{2\epsilon(1+\epsilon)} \left(\cos(\phi_h - 2\phi_{T_T}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T_T})} + \cos(3\phi_h - 2\phi_{T_T}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T_T})} \right) \Bigg] \\
& + T_{TT} h [\cdots]
\end{aligned}
$$

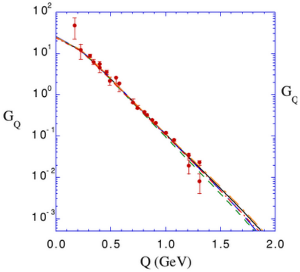
[WC, C. Weiss, in preparation]

- $d\sigma^+ + d\sigma^- - 2d\sigma^0$ selects tensor polarized contributions
  - no electron polarization needed
  - normalized to $d\sigma^{\text{avg}}$: A_{zz}, T_{20}.

- Polarization direction $\rightarrow T_{LL}, T_{LT}, T_{TT}, \phi_{LT}, \phi_{TT}$

Hadronic Matrix Elements

- Same quark/gluon operators: currents & correlators
  $\rightarrow$ FF, pdfs, gpds, ...
- QCD evolution independent of (hadron) spin
- Tensor polarization $\rightarrow$ more independent structures
- Quadrupole FF in elastic *ed*

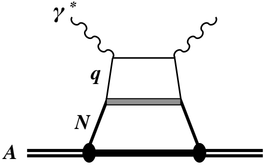


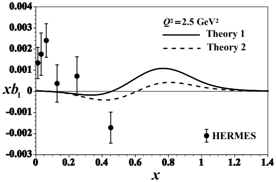
[Gilman, Gross '02]

- Wealth of tensor polarized distributions to be explored
  - experiment, global fits, lattice QCD, model calculations

Inclusive DIS: b_1

- b_1, b_2, b_3, b_4 are tensor polarized **structure functions** [Hoodbhoy, Jaffe, Manohar '88]
- Leading twist $b_1 \rightarrow$ pdf f_{LL}
  $\rightarrow$ difference between unpolarized quark distributions $q^{\lambda=\pm1} - q^{\lambda=0}$
- Kumano-Close sum rule $\int dx\, b_1 = 0$ in parton model
- HERMES measurement, upcoming JLab12
- General convolution model does not describe the data
  - Small b_1 due to D-wave and averaging over all configurations





[WC, Dong, Kumano, Sargsian '17]

- Possible window onto non-nucleonic components (pions, hidden color)
  [G. Miller '13]

From A_{zz} to b_1

- Linear relations (no global fit needed)

- Asymmetry contains **all 4** tensor polarized SF

$$A_{zz} = 2\frac{[T_{LL}]\,(F_{UT_{LL},T} + \epsilon F_{UT_{LL},L}) + [T_{LT}\cos\phi_{T_L}]\sqrt{2\epsilon(1+\epsilon)}\,F_{UT_{LT}}^{\cos\phi_{T_L}} + [T_{TT}\cos 2\phi_{T_T}]\,\epsilon\,F_{UT_{TT}}^{\cos 2\phi_{T_T}}}{F_{UU,T} + \epsilon F_{UU,L}}$$

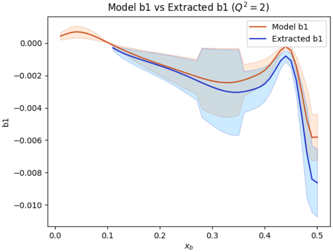
- Experimental extraction uses $A_{zz} = -\frac{2}{3}\frac{b_1}{F_1}$
  $\rightarrow$ only valid
  - In Bjorken limit
  - For deuteron polarized along virtual photon

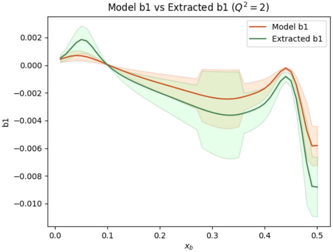
- Difference will depend on **polarization direction** and Q^2

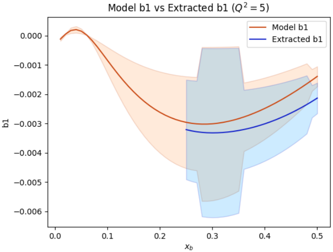
- Additional systematic uncertainty on extraction

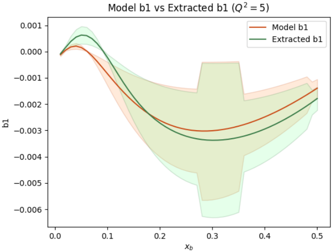
b_1 extraction: estimates

pol. along $\boldsymbol{e}$ | pol. along $\boldsymbol{q}$



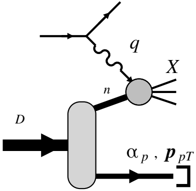




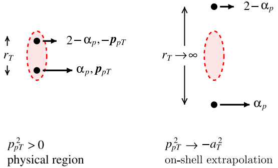


`WC, Alan Sosa, Brandon Roldan Tomei, in preparation`

Deuteron Spectator tagging



$$\alpha_p = 2\frac{p_p^+}{p_d^+} = 2\frac{E_p + p_p^z}{E_d + p_d^z}$$

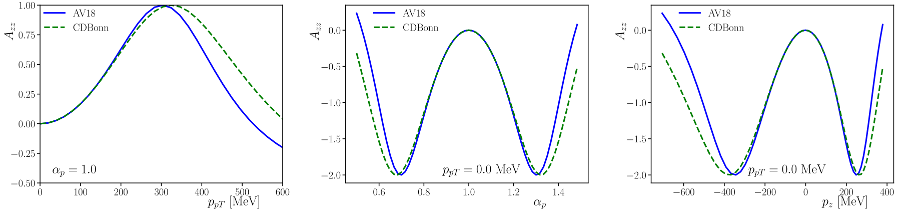


- Detection of nucleon in target fragmentation region: "spectator"
- **Control** over your initial nuclear state
  → Active nucleon identified, create effective targets
- Spectator can **reinteract** with other final-state hadrons
  → "Simple" for deuteron
- Spectator kinematics gives handle on initial state
  → **On-shell extrapolation** for free nucleon
  → Larger momenta for medium modifications
- Well developed pheno for Tagged DIS
  [Sargsian, Strikman '03; Kaptari et al.; WC, Weiss '19+,...]

Tagged A_{zz} for nuclear structure [WC, C. Weiss, in preparation]

- Maximize tensor asymmetry A_{zz} with tagging.
- Tensor polarization is sensitive to unpolarized quark distributions, partonic factor cancels out → **ratio of LF densities** remains

$$A_{zz}(\alpha_p, \boldsymbol{p}_T) = -\frac{\frac{f_0(k) f_2(k)}{\sqrt{2}} + \frac{f_2^2(k)}{4}}{f_0^2(k) + f_2^2(k)} (3\cos 2\theta_k + 1) \qquad \alpha_p = \frac{2p_p^+}{p_D^+} = \left(1 + \frac{k^3}{\sqrt{m^2+k^2}}\right); \quad \boldsymbol{p}_{pT} = \boldsymbol{k}_T$$



- Maximal A_{zz} at $f_2(k) = \sqrt{2} f_0(k)$, not the S wave node!
- Needs quantification of FSI effects

→ **Constraints on deuteron *D*-wave**

Other observables / distributions of interest w tensor pol.

- Gluon helicity flip pdf [Jaffe, Manohar '89]
  - impossible in nucleon
  - probes multinucleon gluons
  - resides in twist-4 SF, hard to extract?
  - existing LOI at JLab
- More complicated final states
  - Hard exclusive channels

    $\rightarrow$ spin-1 GPDS [Berger et al. 04; WC, Pire 18]
  - Semi-inclusive DIS
  - Drell-Yann (NICA, Spinquest)

    $\rightarrow$ spin-1 TMDs [Bacchetta, Mulders 00; Kumano, Song 18+]
  - QE breakup $\rightarrow$ short-range deuteron structure
  - ... add spectator tagging

Conclusions

- Tensor polarization offers new avenues to probe hadronic and nuclear structure
- Proliferation of observables / distributions
  - Theory provides connections, corrections
  - Experimentally challenge to disentangle
- New generation of experiments can be the start of a tensor craze
- Lots of reactions to explore, both from theory and experimental side