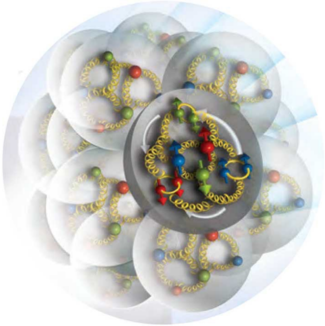
Search for Exotic Glue in Nuclei

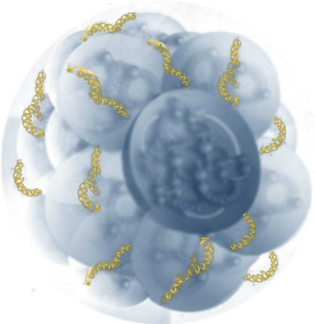
Gluonic Transversity in Polarized DIS

J. Maxwell

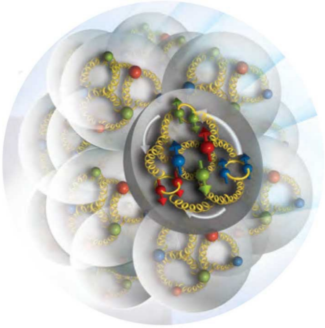
Jefferson Lab
TARGET Group

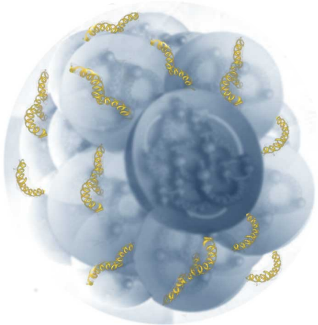
Polarized Ion Sources & Beams for the EIC
Stony Brook, NY
March 10th, 2025





Outline





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   - Lattice Calculations
   - Measurement Approaches
2. Jefferson Lab Measurement
   - JLab Polarized Target
3. Gluonometry at the EIC
   - Polarized Ion Beams

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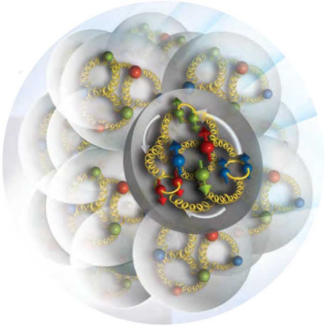
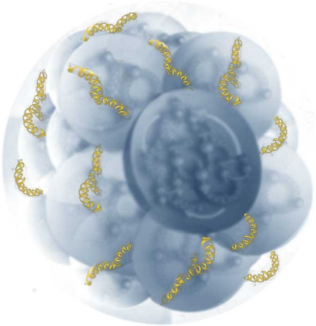
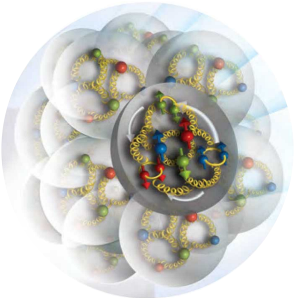




Gluon Structure of Nuclei

- Understanding glue is a key challenge of NP and central goal of EIC



Studying gluons is tricky

- Gluon does not couple to photon
- Probed indirectly by electron scattering from nuclei

- A nuclear glue effect, free from contributions of any nucleon, could offer invaluable view of nuclear structure
- "Nuclear Gluonometry" (Jaffe, Manohar, 1989) offers a probe sensitive **only** to gluonic states in the nucleus: $\Delta(x, Q^2)$

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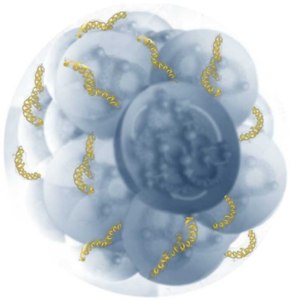

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Gluon Structure of Nuclei

Volume 223, number 2 PHYSICS LETTERS B 8 June 1989

NUCLEAR GLUONOMETRY ☆

R.L. JAFFE and Aneesh MANOHAR
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 24 March 1989

We identify a new leading twist structure function in QCD which can be measured in deep elastic scattering from polarized targets (such as nuclei) with spin $\geqslant 1$. The structure function measures a gluon distribution in the target and vanishes for a bound state of protons and neutrons, thereby providing a clear signature for exotic gluonic components in the target.

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Gluon Structure of Nuclei

PHYSICAL REVIEW D VOLUME 42, NUMBER 5 1 SEPTEMBER 1990

Size and scaling of the double-helicity-flip hadronic structure function

Eric Sather
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

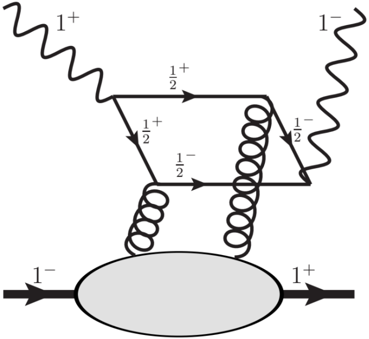
Carl Schmidt
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 24 May 1990)

Recently, Jaffe and Manohar identified a new leading-twist structure function $\Delta(x,Q^2)$, which can be measured in deep-inelastic scattering from polarized targets with spin ≥ 1. We calculate the scaling behavior of $\Delta(x,Q^2)$ in QCD, both by computing the anomalous dimensions of the associated operators and by finding the splitting function for the appropriate parton density. We also estimate the size of the lowest moment of $\Delta(x,Q^2)$ in the bag model. In an appendix we give the complete cross section for electroproduction from a spin-1 target of arbitrary polarization.

- ”Nuclear Gluonometry” (Jaffe, Manohar, 1989) offers a probe sensitive **only** to gluonic states in the nucleus: $\Delta(x, Q^2)$

Double Helicity-Flip Structure Function $\Delta(x, Q^2)$

- As we go from spin-½ to spin-1, we need new leading twist structure functions:
  - Same quark and gluonic operators from spin-½ scattering give b_1, b_2
  - Another tower of gluonic operators that gives rise one more: Δ
- $\Delta(x, Q^2)$: double helicity flip amplitude $A_{+-,-+}$
  - Photon helicity flip of two
  - Unavailable to bound nucleons or pions
  - Purely gluonic observable
- Unpolarized e, transversely polarized nuclei spin ≥ 1
- Moments calculable in Lattice QCD



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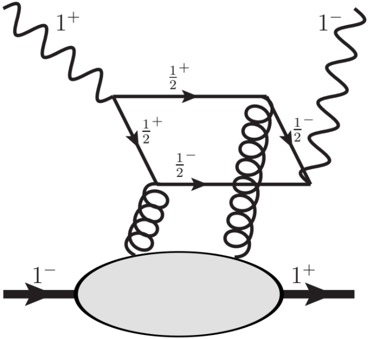


Double Helicity-Flip Structure Function $\Delta(x, Q^2)$

Hadrons: Gluonic Transversity (parton model interpretation)

$$\Delta(x, Q^2) = -\frac{\alpha_s(Q^2)}{2\pi}\mathrm{Tr}\mathcal{Q}^2 x^2 \int_x^1 \frac{dy}{y^3}[g_{\hat{x}}(y, Q^2) - g_{\hat{y}}(y, Q^2)]$$

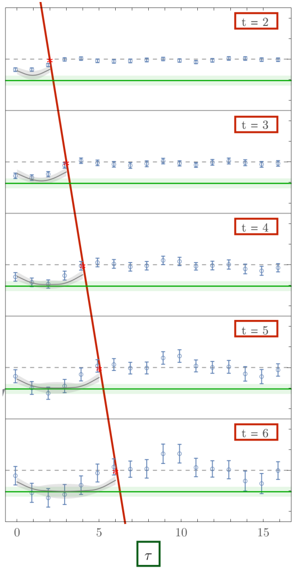
- $g_{\hat{x},\hat{y}}(y, Q^2)$: probability of finding a gluon with momentum fraction y linearly polarized in $\hat{x}$,$\hat{y}$ direction in a target polarized in $\hat{x}$ direction
- "How much more momentum of a transversely polarized particle is carried by gluons aligned rather than perpendicular."

Nuclei: Exotic Glue

- Gluons not associated with individual nucleons in the nucleus

Lattice QCD Guidance for Δ

- In 2016, initial calculations for first moment of Δ on spin-1 $\phi\ (s\bar{s})$
  - $m_\pi = 405$ MeV
  - Gave definitive signal[1]
- Following year, first moment of Δ calculated on non-physical d
  - $m_\pi = 806$ MeV
  - Again definitive signal was seen[2]
- Results have generated significant interest in an observable mostly ignored since 1989



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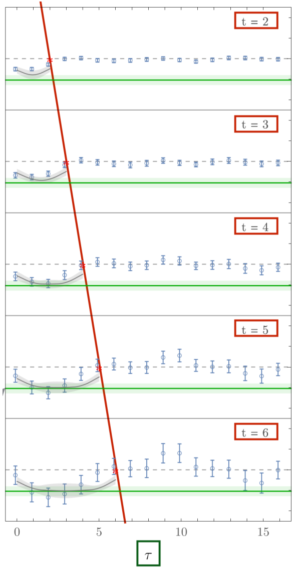

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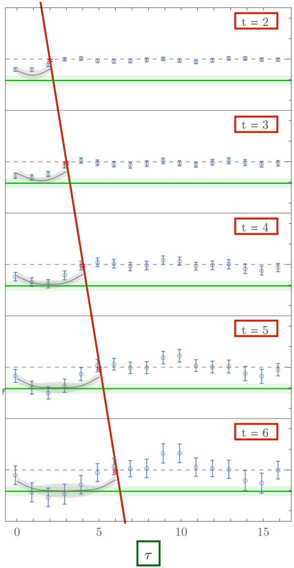

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Measuring $\Delta(x, Q^2)$ via DIS

- Transversely aligned, spin-1 target and unpolarized electron incident from $-z$
- In the Bjorken limit, double helicity component of the hadronic tensor $W^{\Delta=2}_{\mu\nu,\alpha\beta}(E, E')$ becomes (dropping higher twist structure functions)[1]:

$$\lim_{Q^2\to\infty} \frac{d\sigma}{dx\,dy\,d\phi} = \frac{e^4 ME}{4\pi^2 Q^4}\Bigg(xy^2 F_1(x, Q^2) + (1-y)F_2(x, Q^2) - \frac{x(1-y)}{2}\Delta(x, Q^2)\cos 2\phi\Bigg)$$

[1] Jaffe, Manohar, Phys Letters B 223 (2) (1989).

For a spin−1 target polarized at angle θ_m from the z-axis and electron incident from $-z$, target spin $\lambda_m = (1, 0, -1)$:

$$\frac{d\sigma}{dx\,dy\,d\phi}(\lambda_m) = \frac{2y\alpha^2}{Q^2}\left(F_1 + \frac{2}{3}a_m b_1 + \frac{1-y}{xy^2}\left(F_2 + \frac{2}{3}a_m b_2\right)\right.$$
$$\left. - \frac{1-y}{y^2} c_m \sin^2\theta_m \Delta(x, Q^2)\cos(2\phi)\right)$$

with

$$a_m = \frac{1}{4}c_m(3\cos^2\theta_m - 1)$$
$$c_m = 3|\lambda_m| - 2$$

Differences of cross sections: N_+, N_0, N_- for $\lambda_m = (1, 0, -1)$

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$$c_m = 3|\lambda_m| - 2 \quad \Rightarrow \quad c_m = (1, -2, 1)$$

Differences of cross sections: N_+, N_0, N_- for $\lambda_m = (1, 0, -1)$

Average over Polarization: $N_+ + N_- + N_0 \Rightarrow \bar{\sigma}$

- $c_+ + c_0 + c_- = 0$

$$\frac{d\bar{\sigma}}{dx\,dy\,d\phi} = \frac{2y\alpha^2}{Q^2}\left(F_1 + \frac{1-y}{xy^2}F_2\right)$$

- Of course, no Δ dependence
- Δ also cancels out of vector polarization difference $(N_+ - N_0) + (N_0 - N_-) = N_+ - N_-$
  - $c_+ - c_- = 0$

Tensor Polarization: $(N_+ - N_0) - (N_0 - N_-) \Rightarrow \Delta\sigma$

- $c_+ - 2c_0 + c_- = 6$

$$\frac{d\Delta\sigma}{dx\,dy\,d\phi} = \frac{2y\alpha^2}{Q^2}\Bigg((3\cos^2\theta_m - 1)(b_1 + \frac{1-y}{xy^2}b_2) - \frac{1-y}{y^2}6\sin^2\theta_m\Delta(x,Q^2)\cos(2\phi)\Bigg)$$

- Tensor structure functions b_1, b_2 contribute significantly
- Unless! $(3\cos^2\theta_m - 1) = 0 \quad \Rightarrow \quad \theta_m = 54.7^\circ$

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Difference of Polarized and Unpolarized:

$N_+ - \bar{N} = N_+ - \frac{1}{3}(N_+ + N_- + N_0) = \frac{1}{3}(N_+ - N_0) \Rightarrow \hat{\sigma}$

- $c_+ - c_0 = 1$

$$\frac{d\hat{\sigma}}{dx\,dy\,d\phi} = \frac{2y\alpha^2}{Q^2}\left(\frac{1}{6}(3\cos^2\theta_m - 1)(b_1 + \frac{1-y}{xy^2}b_2) - \frac{1-y}{y^2}\sin^2\theta_m \Delta(x, Q^2)\cos(2\phi)\right)$$

- Again tensor structure functions b_1, b_2 contribute significantly unless $\theta_m = 54.7°$

3 ways to measure $\Delta(x, Q^2)$

$$(3\cos^2\theta_m - 1)\left(b_1 + \frac{1-y}{xy^2}b_2\right) - \frac{1-y}{y^2}\sin^2\theta_m \Delta(x, Q^2)\cos(2\phi)$$

1. Leverage $\cos(2\phi)$ to isolate $\Delta(x, Q^2)$ dependence
   - Need azimuthal detector acceptance
2. Form tensor asymmetry: $\mathcal{A} = \frac{1}{A}\frac{N_+ + N_- - 2N_0}{N_+ + N_- + 2N_0}$
   - $\theta_m = 54.7°$ to cancel b_1, b_2 dependence
   - Change polarization to produce N_+, N_- and N_0 yields
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Transverse Polarized Target Nuclei

- Need a spin$\geq$1 nucleus, but this is a **multi-nucleonic** effect
  - Expected larger in compact nuclei (like EMC effect?)
  - Perhaps explains enhanced LQCD signal with larger m_π, more compact d?
- Deuteron? Should be investigated, but may not offer best chance for discovery.
  - Expect two nucleons to good approximation
- Something heavier: Li? $\alpha + d$
- Practical limitations from available polarized targets
  - Long history of polarized p and d in solid targets
  - Lithium Hydride and Deuteride: ^{6}LiH,^{6}LiD, also ^{7}LiH
  - Ammonia: ^{14}NH$_3$,^{14}ND$_3$, also ^{15}NH$_3$
- Or, for eA collider, polarized ion sources
  - D. Alkalis? ^{6}Li, ^{7}Li, ^{23}Na attractive options

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Proposed Measurements of $\Delta(x, Q^2)$

- **Deep Inelastic Scattering** on Polarized N Target:
  JLab Letter of Intent (Maxwell *et al.*, 2018. arXiv: 1803.11206)
- **Drell Yan** on Polarized d Target:
  FNAL (SpinQuest Collaboration, 2022. arXiv:2205.01249)
- J/ψ **production** at NICA

The EIC is the ideal place to search for a $\Delta(x, Q^2)$ signal!
Requires polarized ion sources, with varied species offering more opportunity for discovery.

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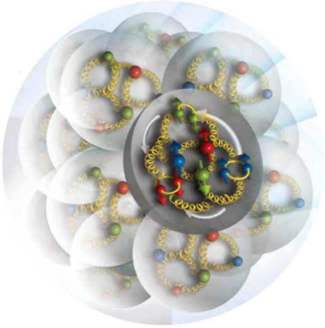

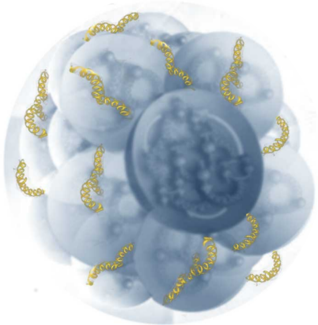

JLab: Fixed, Polarized Target Approach?

$$(3\cos^2\theta_m - 1)\left(b_1 + \frac{1-y}{xy^2}b_2\right) - \frac{1-y}{y^2}\sin^2\theta_m \Delta(x, Q^2)\cos(2\phi)$$

1. Not easy: need out of plane detectors for $\cos(2\phi)$
   - Not standard in Halls A, C. SoLID?
   - No transverse target in Hall B
2. Form tensor asymmetry: $A = \frac{1}{A}\frac{N_+ + N_- - 2N_0}{N_+ + N_- + 2N_0}$
   - Set target field at $\theta_m = 54.7°$
   - Yields at N_+, N_- and N_0 separated in time: systematic headaches
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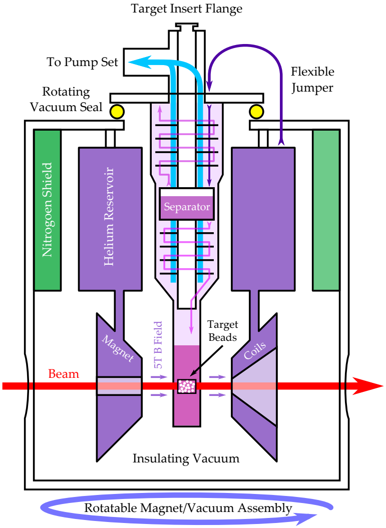
Kinematic Reach with 12 GeV CEBAF in Hall C

- 11 GeV, unpolarized e^- on fixed, polarized $^{14}NH_3$
- Preliminary SHMS Monte Carlo (Gaskell, Arrington)
  - Transverse (not 54.7°!) UVa magnet (M. Jones)

θ	E (GeV)	E' (GeV)	Q^2 (GeV/c^2)	x	Rate (Hz)
10.5	11	5	1.842	0.164	170
10.5	11	4	1.474	0.112	152
10.5	11	3	1.105	0.074	138
10.5	11	2	0.737	0.044	100
15	11	5	3.748	0.333	28
15	11	4	2.999	0.228	30
15	11	3	2.249	0.15	32
15	11	2	1.499	0.089	34

JLab Solid Polarized Target

- Dynamic Nuclear Polarization
  - 5 T field, 1 K ^{4}He evap. fridge
  - Leverage $e-p$ spin coupling
  - μ-waves drive polarizing transitions
  - e relaxes to flip–flop with new p
- Irradiated Ammonia: 95% p, 50% d
  - Beam current <100 nA
  - P decay: anneals and replacement
- Workhorse DIS technique at SLAC, JLab. Upcoming experiments in Halls B, C.
- What material for $\Delta(x, Q^2)$? NH_3?
  - ^{14}N is spin 1



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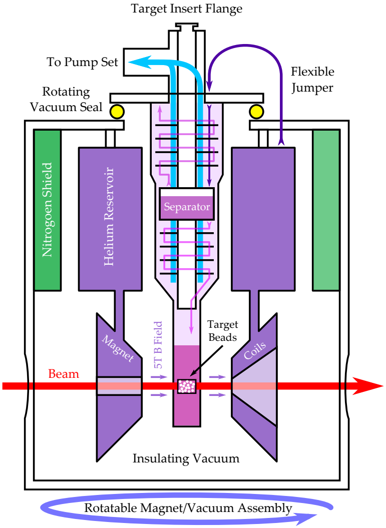


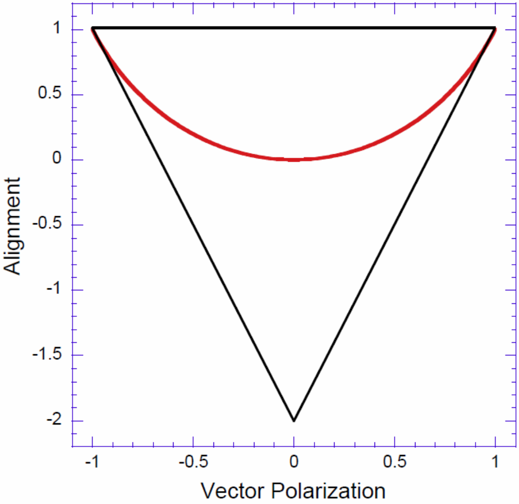
Polarization, Tensor *Alignment* and DNP

$$\begin{aligned} P &= (N_+ - N_0) + (N_0 - N_-) \\ &= N_+ - N_- \\ A &= (N_+ - N_0) - (N_0 - N_-) \\ &= 1 - 3N_0 \end{aligned}$$

- Polarization and alignment can be anywhere in the black triangle
- At *equal spin temperature*, can be only on red curve:

$$A = 2 - \sqrt{4 - 3P^2}.$$

- For $P = 40\% \;\Rightarrow\; A = 13\%$

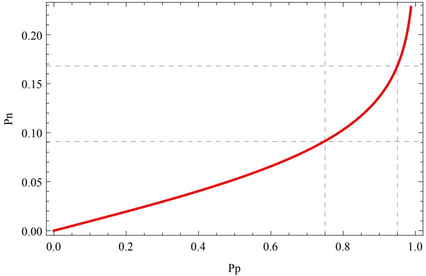


Nitrogen Polarization in Ammonia: Not Easy

- We can also relate polarization of N to p:

$$P_N = \frac{4\,\tanh((\omega_N/\omega_p)\,\mathrm{arctanh}(P_p))}{3+\tanh^2((\omega_N/\omega_p)\,\mathrm{arctanh}(P_p))}$$

- At 95% p: 17% N
  - $P_N = 17\% \Rightarrow A_N = 2\%$
- NMR measurement is difficult
  - Peaks too far apart for one NMR scan (2.4 MHz)
  - Overcome at SMC with 2 sweeps, changing B field[1]



[1] B. Adeva, NIM A 419 (1998).

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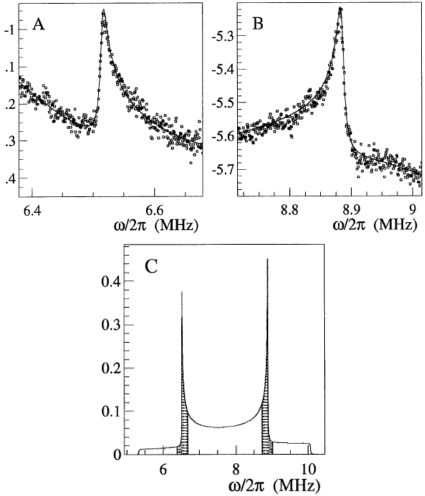
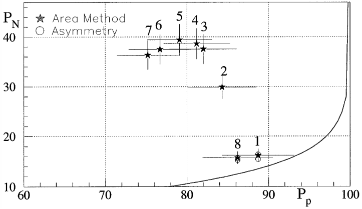
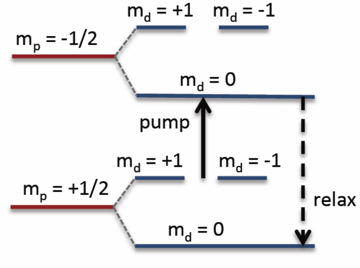


[1] B. Adeva, NIM A 419 (1998).

Techniques to Improve P_N, A_N

- Tricks to help: "RF Hole Burning"[1]
  - Vast separation of NMR peaks in N will help.
- Cross Spin Transfer
  - Move magnetic field to allow cross relaxation of resonances
  - SMC: 40% $P_N \Rightarrow$ 12% A_N
- RF Spin Transfer
  - Same effect in the end
  - Allow dynamic pumping of N while μ-waves pump p





[1] P. Delheij, NIM A 251 (1986).

Jefferson Lab Letter of Intent 12-14-001

- $\sim$30 PAC days with solid polarized target
  - Run with approved measurement of b_1 in Hall C
  - Ballpark 1% statistical error
  - Heavily dependent on achieved polarization
  - Largest systematic uncertainty comes from target polarization measurement 4-5%
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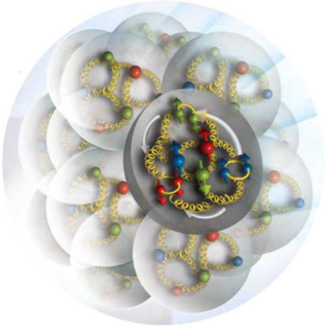
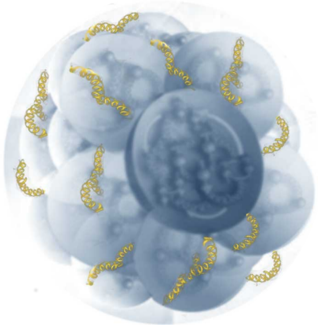
Outline

1. Double Helicity-Flip Structure Function
   - Lattice Calculations
   - Measurement Approaches
2. Jefferson Lab Measurement
   - JLab Polarized Target
3. Gluonometry at the EIC
   - Polarized Ion Beams





Electron–Ion Collider Approach

$$(3\cos^2\theta_m - 1)\left(b_1 + \frac{1-y}{xy^2}b_2\right) - \frac{1-y}{y^2}\sin^2\theta_m \Delta(x,Q^2)\cos(2\phi)$$

1. $\cos(2\phi)$ offers $\Delta(x,Q^2)$ sensitivity
   - Vastly increased kinematic space for search
   - Vector polarization observable
2. ~~Form tensor asymmetry:~~ $\cancel{A = \frac{1}{A}\frac{N_+ + N_- - 2N_0}{N_+ + N_- + 2N_0}}$
   - Set target at $\theta_m = 54.7°$
   - ~~Yields at N_+, N_- and N_0 separated in time: systematic headaches~~
3. ~~Form difference of vector polarized and unpolarized cross sections~~
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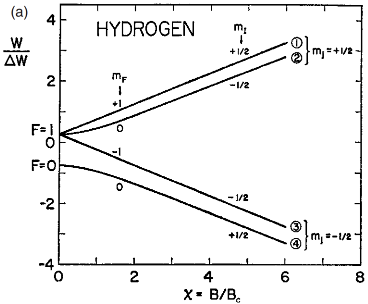
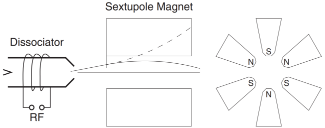
Polarized Gases via Atomic Beam Source

- Spray atoms of choice through a sextupole.
- 4 spin states for H. To isolate 1:
  - Choose 1 2
  - Use RF to flip 2 to 3
  - Second sextupole to choose 1
- 100% Vector P (and/or Tensor!)
- Atomic Beam Source: jets with very low density (10^{16} H/s), good for storage rings
- Storage cells coated with teflon used to increase target density. FILTEX at CERN, and VEPP-3 in Novosibirsk





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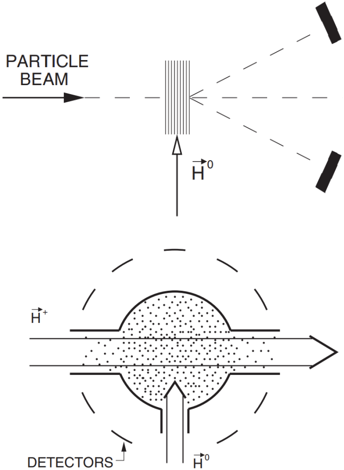

SMOG2 Internal Target (LHCspin)

- Bring Spin Physics to the LHC!
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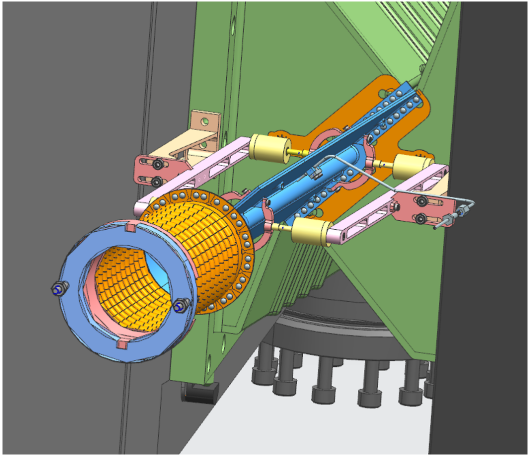

Steffens, PSTP 2022

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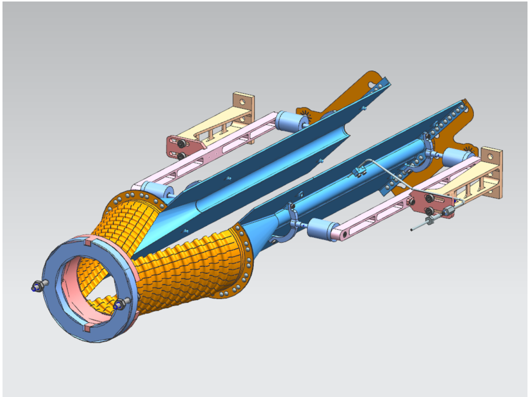

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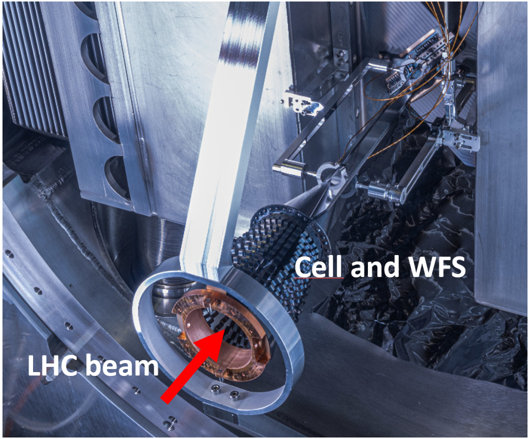
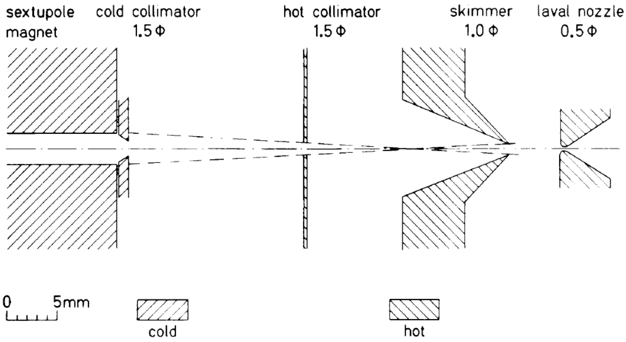


Steffens, PSTP 2022

Spin Polarized Alkali Sources

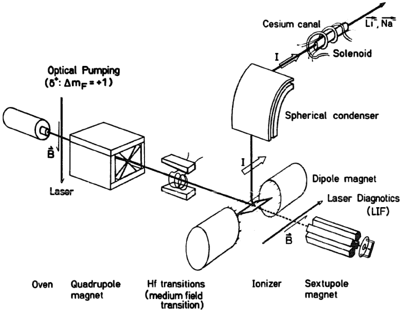
- Heidelberg Atomic Beam Polarized Source (1975)[1]
  - Laval nozzle, Sextupole Stern−Gerlach give $m = +1/2$
  - RF used for adiabatic transitions to fill other states
  - Surface ionization, heated tungsten strip
  - ^{6,7}Li: $0.57 < |P| < 0.65$, 200 nA
  - ^{23}Na: 50% losses to P and current in ionization

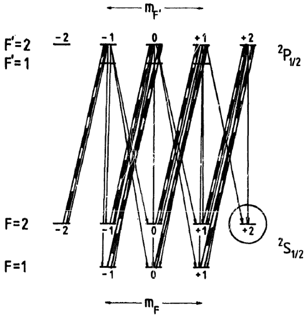


[1] E. Steffens, NIM 143 (1977)

Spin Polarized Alkali Sources

- Improved Heidelberg Source adds OP (1986)[1]
  - Laser pumped, modulated to pump both multiplets
  - ^{6}Li: $A = 85\%$, ^{23}Na: $A = 77\%$
  - Polarization limited due to lack of full ionization





[1] H. Reich, NIM A288 (1989)

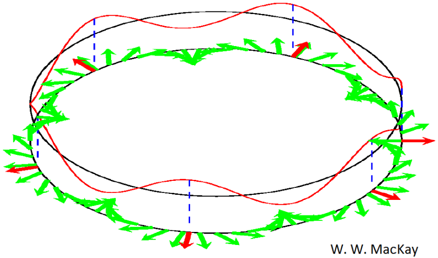
Polarized Ion Beam Possibilities

At EIC, $\Delta(x, Q^2)$ search becomes a problem of available ion sources and their corresponding depolarizing resonances.

Nucleus	Spin	Technique	Pol.	Flux	G
^{2}H	1	OP, ABS	100%	1μA	-0.14
^{6}Li	1	OP, ABS	88%	2.4μA	-0.18
^{7}Li	$\frac{3}{2}$	OP, ABS			1.53
^{10}B	3	Not known			
^{20}F	2	OP, ABS?			
^{23}Na	$\frac{3}{2}$	OP, ABS	77%	6.5 μA	0.53

Spin Manipulation in Ring

- Depolarizing resonances when spin precession frequency = frequency of perturbing B field[1]
- Imperfection: $\nu_s = G\gamma = n$
- Intrinsic: $\nu_s = G\gamma = Pn + \nu_y$
- Anomalous g-factor G



  - ^{7}Li: G of 1.53 (like proton's 1.79) $\Rightarrow$ easy
  - ^{6}Li: G of -0.18 (like deuteron's -0.14) $\Rightarrow$ hard
  - ^{23}Na: G of 0.53 could work at RHIC with more snakes
  - Figure–8 makes for easier manipulation at lower G

[1] Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.

Towards Design of an Optimized EIC Experiment

- Exploration of Δ in x, Q^2, S, & A
  - How does effect change for different nuclear spin ≥ 1?
  - Spin-1/2 species important cross-check
  - How does effect change for different atomic masses?
  - Spin-1 ^{6}Li vs. Spin-3/2 ^{7}Li
- Simulate measurement for Inclusive DIS on Nuclei
- Estimate running time for given statistical uncertainties
  - Species choice informed by simulation
  - Loss of luminosity compared to JLab made up for by lack of dilution, kinematic coverage

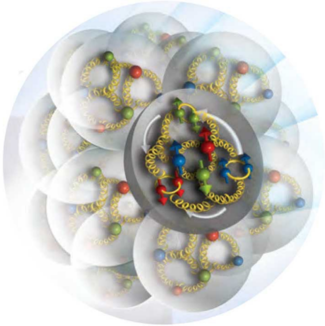
Summary

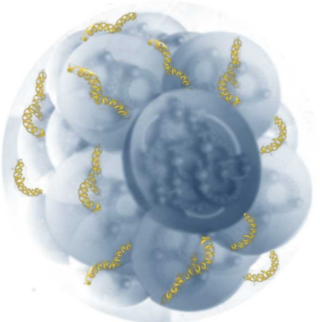
- $\Delta(x, Q^2)$ offers a rare look at gluonic components in the nucleus
  - Significant Lattice QCD result drives interest
  - Need spin ≥ 1, polarized, nuclear target
  - Low x, where glue dominates, region of interest
- Jefferson Lab experiment still in pre-proposal stage
  - $0.05 < x < 0.33$ for exploratory search
  - Polarized Target development needed
  - Fixed target can give the high x needed for moments!
- EIC capable of thorough search
  - Vast low x exploration
  - Spin manipulation of polarized, “heavy” ions crucial
  - Polarized ion sources needed! Li and Na most attractive

JLab Nuclear Gluonometry Collab:

- JLab: M. Jones, C. Keith, J. Maxwell, D. Meekins
- MIT: W. Detmold, R. Jaffe, R. Milner, P. Shanahan
- Univ. of Virginia: D. Crabb, D. Day, D. Keller, O. Rondon
- Oak Ridge: J. Pierce

Thank you for your attention!





5 T Split-Pair Target Magnet

- Can we get $\theta_m = 54.7°$
- Old Hall C Magnet, with largest opening angles, retired in 2012
  - Better than 10^{-4} uniformity in 3x3x3 cm^3 volume
- g_2^p ran with modified Hall B magnet
  - 54.7° not available
  - Alteration needed to get 50°
- New 5 T target magnet needed
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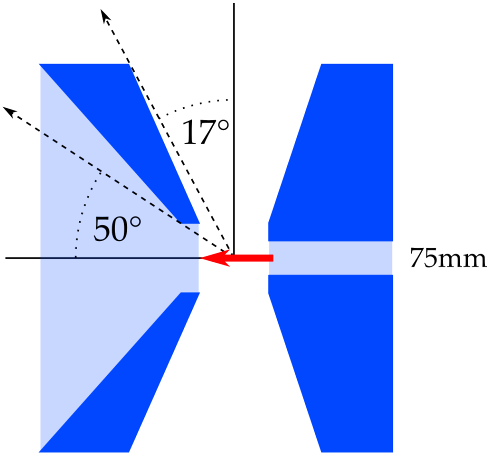

Kinematic Reach at Electron–Ion Collider