Search for Exotic Glue in Nuclei

Gluonic Transversity in Polarized DIS

J. Maxwell

Jefferson Lab

Tensor Spin Observables Workshop
Trento, Italy
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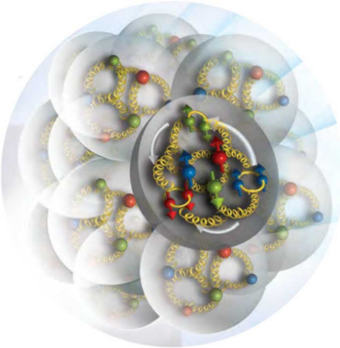
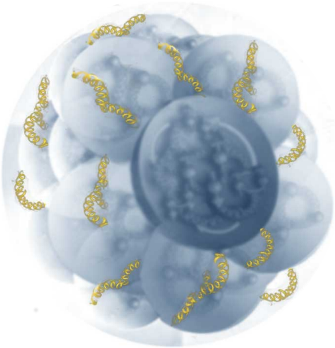
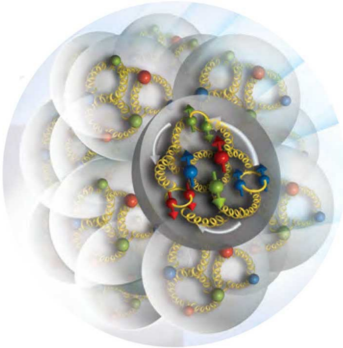
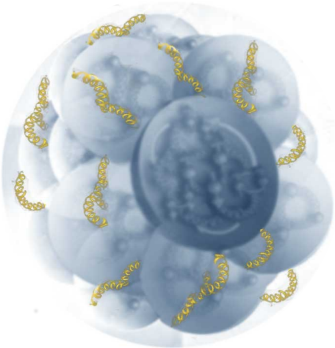




Outline

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





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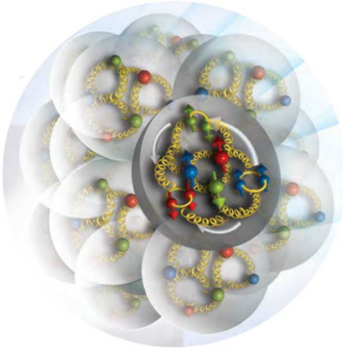
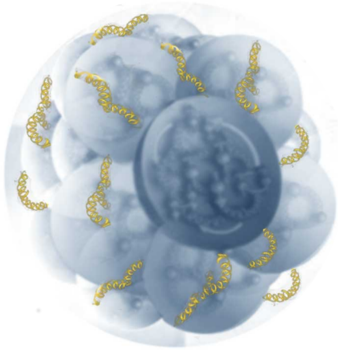
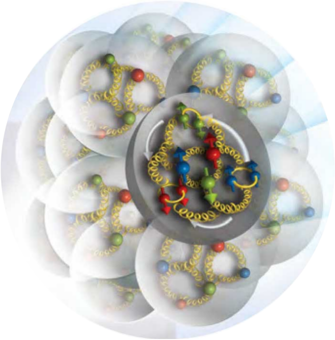




Gluon Structure of Nuclei

- 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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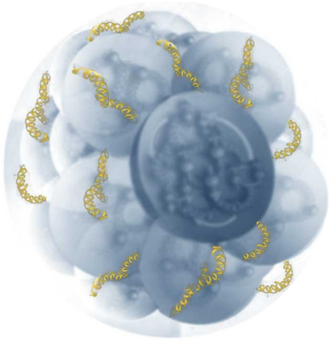

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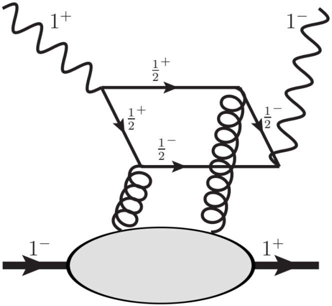
- $\Delta(x, Q^2)$ corresponds to helicity amplitude $A_{+-,-+}$
  - Photon helicity flip of two
  - Unavailable to bound nucleons or pions
  - Purely gluonic observable
- Hadrons: Gluonic Transversity
- Nuclei: Exotic Glue
  - Gluons not associated with an individual nucleon
- Unpolarized e beam on transversely polarized nuclei, spin ≥ 1
  - Primary challenge of measurement is polarized target or source
- Moments calculable in Lattice QCD



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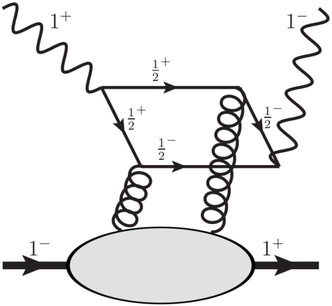

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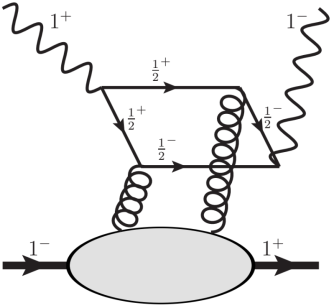

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Lattice QCD Guidance for Δ

- Initial calculations for first moment of Δ on spin-1 ϕ $(s\bar{s})$
  - $m_\pi = 405$ 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
- Calculation with physical d underway

[1] Detmold, Shanahan, P.Rev.D 94, 2016
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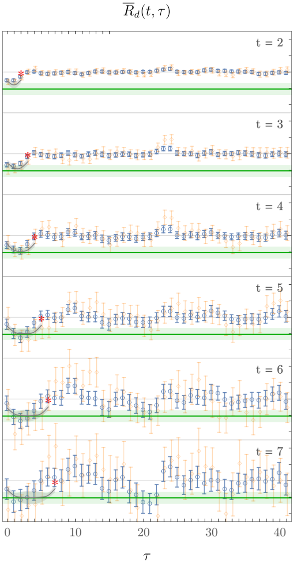

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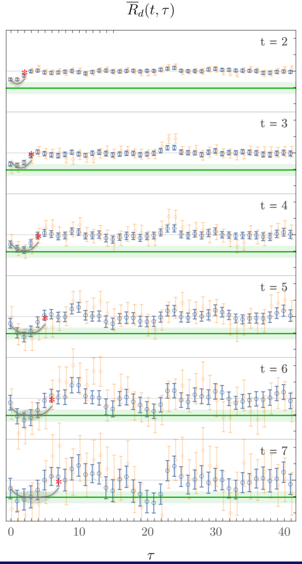

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Measuring $\Delta(x, Q^2)$ via DIS

- 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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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! $(3\cos^2\theta_m - 1) = 0 \quad \Rightarrow \quad \theta_m = 54.7°$

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Difference of Polarized and Unpolarized:

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

- $c_+ - c_0 = 1$

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

- 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≥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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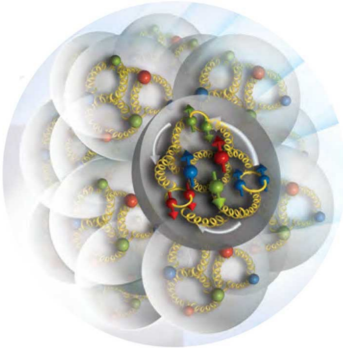

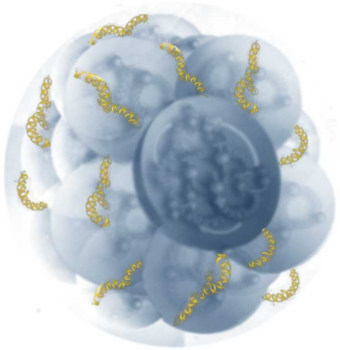

JLab: Fixed, Polarized Target Approach?

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

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: $\mathcal{A} = \frac{1}{A}\frac{N_+ + N_- - 2N_0}{N_+ + N_- + 2N_0}$
   - Set target field at $\theta_m = 54.7°$
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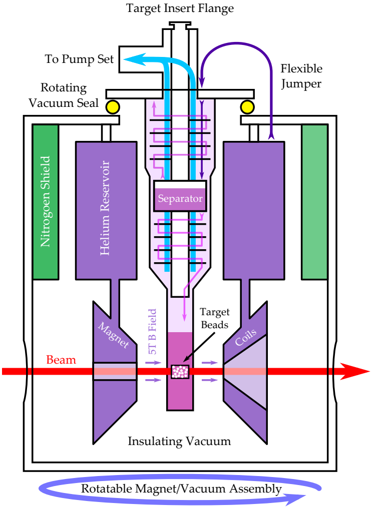
Kinematic Reach with 12 GeV CEBAF in Hall C

- 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/UVa Solid Polarized Target

- Dynamic Nuclear Polarization
  - 5 T field, 1 K ^{4}He evap. fridge
  - Dope material with paramagnetic radicals (NH_3: NH_2 or H)
  - Leverage $e - p$ spin coupling
  - μ-waves drive polarizing transitions
  - e relaxes to flip–flop with new p
- Irradiated Ammonia: 95% p, 40% d
  - Beam current <100 nA
  - P decay: anneals and replacement
- Workhorse DIS technique at SLAC, JLab; 2012's g_p^2 most recently[2]



[2] Pierce, Maxwell, NIM A 738 (2014).

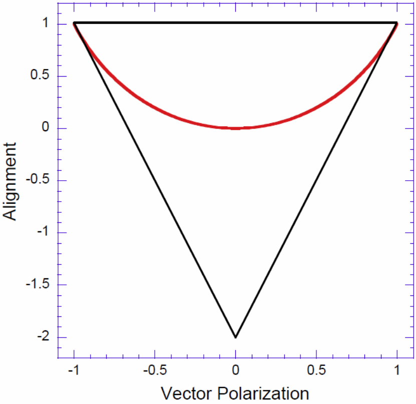
Polarization, Tensor *Alignment* and DNP

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

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

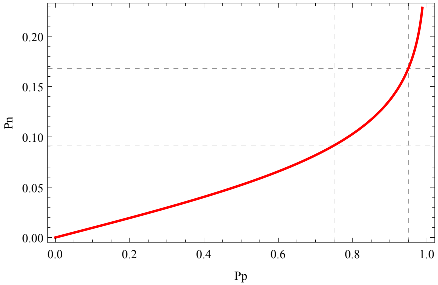


Nitrogen Polarization in Ammonia: Not Easy

- We can also relate polarization of N to p at EST:

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

- 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[3]



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

Nitrogen Polarization in Ammonia: Not Easy

- We can also relate polarization of N to p at EST:

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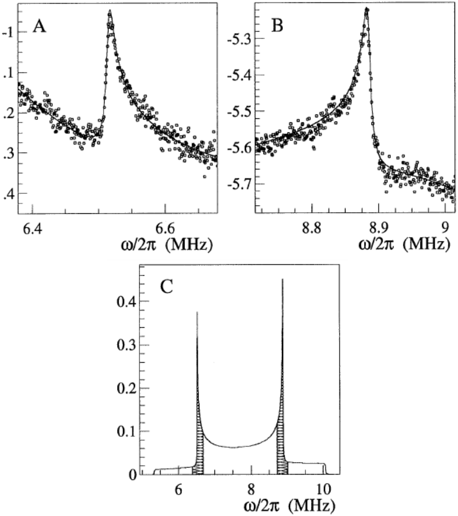
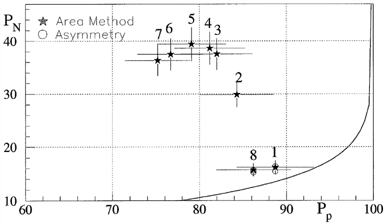
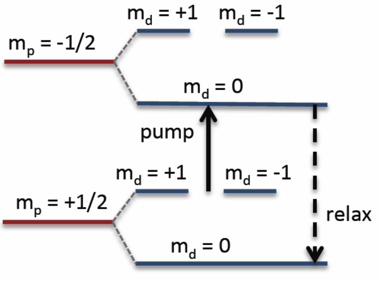


[3] B. Adeva, NIM A 419 (1998).

Techniques to Improve P_N, A_N

- Tricks to help: "RF Hole Burning"[4]
  - 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





[4]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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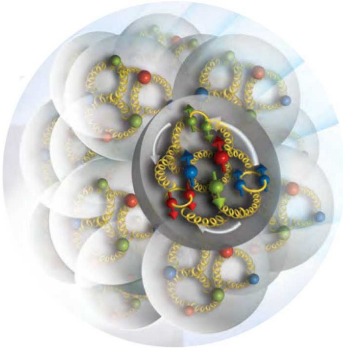
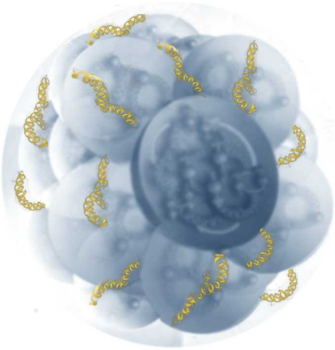
Outline

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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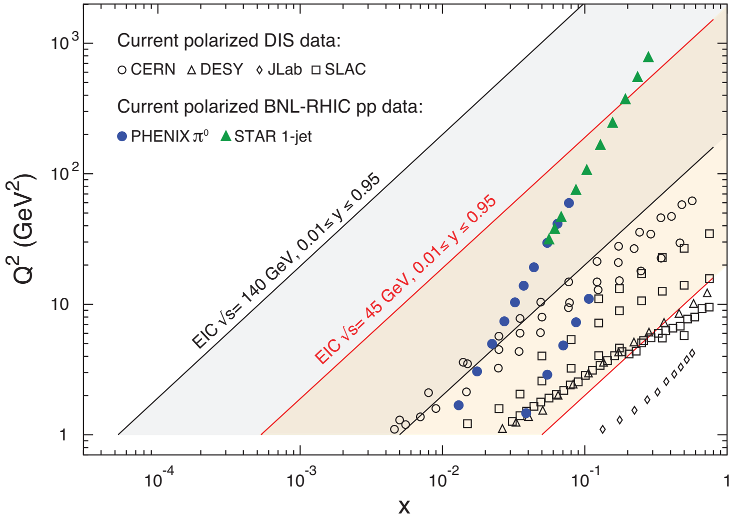
Kinematic Reach at Electron–Ion Collider



EIC white paper

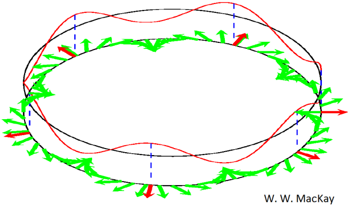
Polarized Ion Beam Possibilities

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
^{8}Li	2	TFM	$\sim 1\%$		
^{10}B	3	Not known			
^{23}Na	$\frac{3}{2}$	OP, ABS	77%	6.5 μA	0.55

Spin Manipulation in Ring

- Depolarizing resonances when spin precession frequency = frequency of perturbing B field[5]
- 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 0.55 could work at RHIC with more snakes
    - Figure–8 makes for easier manipulation at lower G


W. W. MacKay

[5] 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

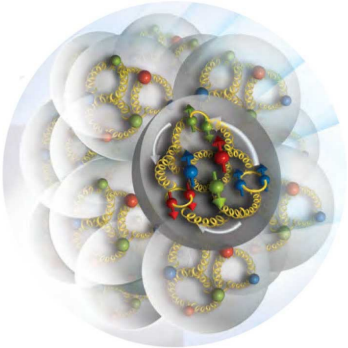
Summary

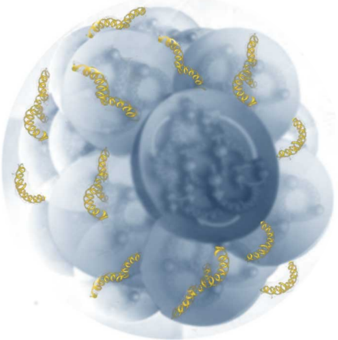
- $\Delta(x, Q^2)$ offers a rare look at gluonic components in the nucleus
  - Significant Lattice QCD result drives interest
  - Need spin ≥ 1, polarized, nuclear target
  - Low x, where glue dominates, region of interest
- Jefferson Lab experiment still in pre-proposal stage
  - $0.05 < x < 0.33$ for exploratory search
  - Polarized ^{14}N target primary difficulty
  - Aim for proposal to JLab PAC45
- EIC capable of thorough search
  - Vast low x exploration
  - Polarized ion sources needed, Li and Na most attractive
  - Spin manipulation of polarized, “heavy” ions crucial
  - Initial investigations towards measurements at eRHIC (R.Milner) and JLEIC (JM) begun

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

Thanks to A. Zelenski, V. Morozov, Y. Furletova





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°
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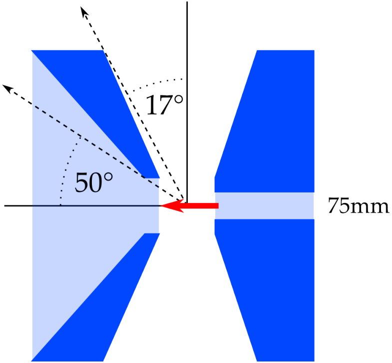
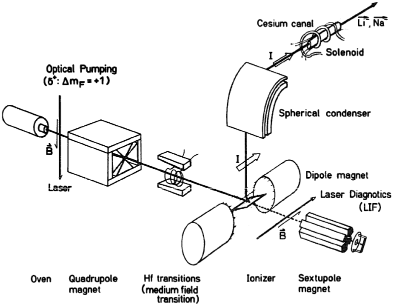


Spin Polarized Alkali Sources

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



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

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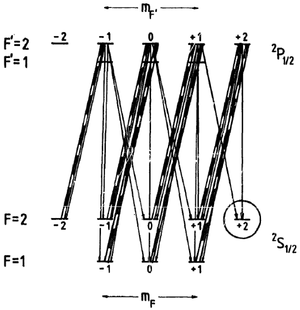

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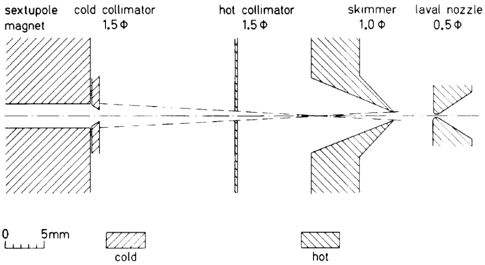
Spin Polarized Alkali Sources

- Heidelberg Atomic Beam Polarized Source (1975)[7]
  - 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



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