Mean-Field Studies of Nuclear Quark Structure

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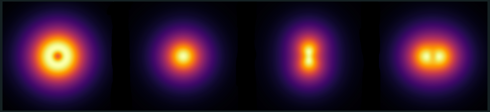


3rd Workshop on Quantitative Challenges in EMC and SRC Research

22-26 March 2021, Meeting host by Jefferson Lab EIC Center and MIT LNS.

Argonne NATIONAL LABORATORY

News

- PAC42 (2014) at Jefferson Lab approved an experiment to measure the "The EMC Effect in Spin Structure Functions" using a ^{7}Li target

  https://www.jlab.org/exp_prog/proposals/14/PR12-14-001.pdf

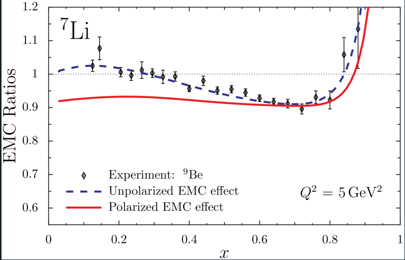
- Proposal went through Jeopardy process in PAC 48 (2020)
  - scientific rating went from B^+ to A^- — almost unheard of — thanks to a lot of work from Will Brooks and Sebastian Kuhn

- Long awaited quasi-elastic electron scattering results from JLab will be presented in a plenary talk by Michael Paolone at the GHP 2021 Meeting (13-16 April)

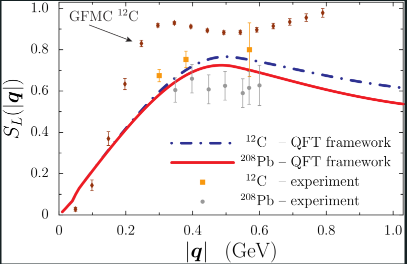
  https://www.jlab.org/indico/event/412/

  - results on ^{12}C and ^{56}Fe will be presented
  - if you are interested please participate in the meeting

[ICC, W. Bentz and A. W. Thomas, PLB 642, 210 (2006)]



[ICC, W. Bentz and A. W. Thomas, PRL 116 032701 (2016)]

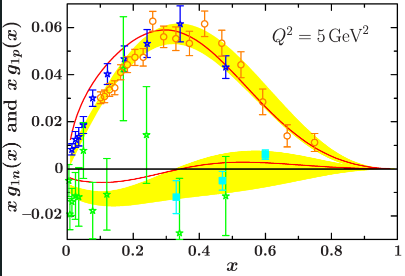


Polarized EMC Effect

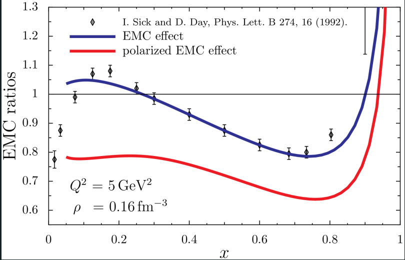
- Spin/Polarized EMC effect experiments are just measurements of the spin structure function(s) of a nucleus – exactly analogous to nucleon DIS
- Polarized EMC effect provides insight into QCD effects in nuclei

$$\Delta R(x) = \frac{g_{1A}(x)}{g_{1A}^{\text{naive}}(x)} = \frac{g_{1A}(x)}{P_p\, g_{1p}(x) + P_n\, g_{1n}(x)}$$

  - P_p & P_n effective polarizations of protons/neutrons in nucleus
- Things to consider when choosing a target
  - spin of nucleus carried by valence nucleons – $1/A$ suppression – so need light nucleus or perhaps tagging
  - $g_{1n}(x)$ is small, so best to have spin dominated by protons
  - candidate nuclei include ^{3}H ($J = \frac{1}{2}$), ^{7}Li ($J = \frac{3}{2}$), ^{11}B ($J = \frac{3}{2}$), . . .
- JLab seems enthusiastic to run polarized ^{7}Li DIS experiment



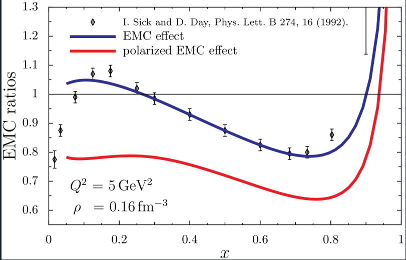
[ICC, W. Bentz and A. W. Thomas, PRL **95**, 052302 (2005)]



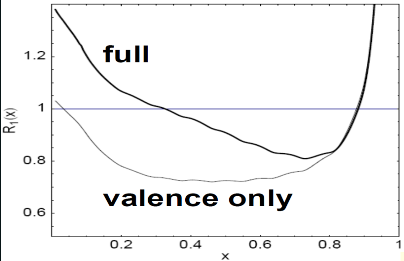
Mean-Field Calculations of Polarized EMC Effect

- Several relativistic mean-field calculations of polarized EMC effect
  - all calculations find polarized EMC same size or larger than EMC effect
- Large polarized EMC effect results because in-medium quarks are more relativistic ($M* < M$)
  - quark lower components are enhanced
  - in-medium we find that quark spin is converted to orbital angular momentum

[ICC, W. Bentz and A. W. Thomas, PRL **95**, 052302 (2005)]



[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]



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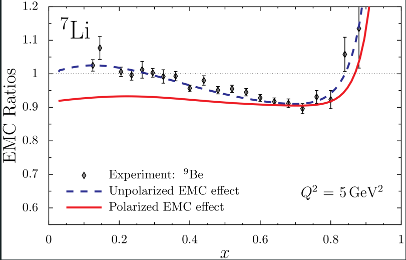
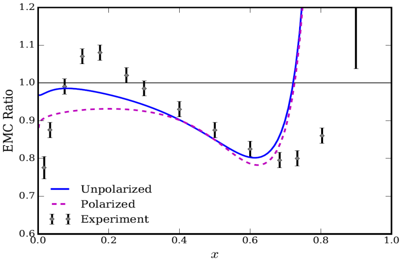


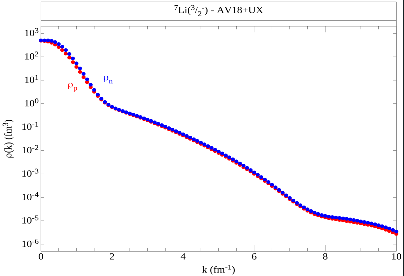
[Tronchin, Matevosyan and Thomas, PLB **783**, 247-252 (2018)]

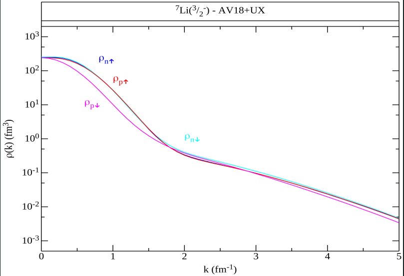


Mean-Field vs SRC Expectations

- To explain EMC effect need medium modification of bound nucleons — or equivalently significant non-nucleonic components in nucleus
  - leading explanation for EMC effect is medium modification from mean-field and/or SRC
- Polarized EMC effect provides a means to possibility distinguish between mean-field and SRC effects
- For SRCs to give large polarized EMC — SRC pairs need to have a significant polarization correlated with spin of nucleus
  - QMC calculations using Argonne v18 potential show very little net polarization for high momentum nucleons
  - integrating distributions shows that only $\sim$2% net polarization from high momentum nucleons
- See also "Reflections on the Origin of the EMC Effect" (A. W. Thomas) for explanation on how SRCs depolarize participants

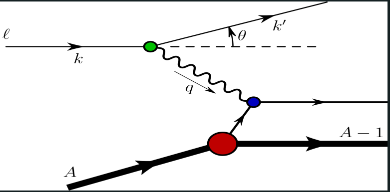
[Bob Wiringa www.phy.anl.gov/theory/research/momenta/]

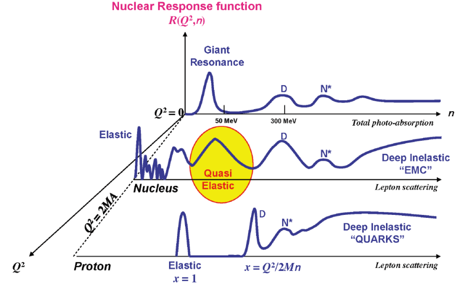




Quasi-elastic scattering

- Quasi-elastic scattering is used to study nucleon properties in a nucleus: $q^2 = \omega^2 - |\boldsymbol{q}|^2$





- The cross-section for this process reads

$$\frac{d^2\sigma}{d\Omega\, d\omega} = \sigma_{\text{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2\,|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

  - response functions are accessed via Rosenbluth separation

- In the DIS regime – $Q^2, \omega \to \infty \quad x = Q^2/(2\,M_N\,\omega) = \text{constant}$ – response functions are proportional to the structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$

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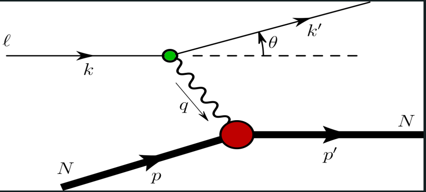

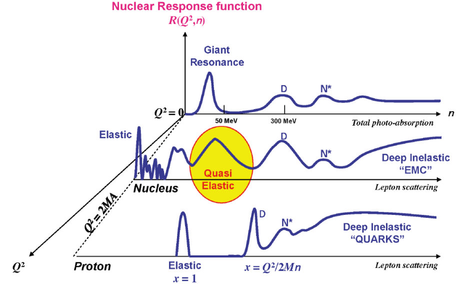

- The cross-section for this process reads

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}}{1+\tau}\left[G_E^2(Q^2) + G_M^2(Q^2)\right]$$

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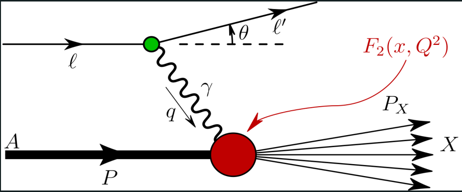
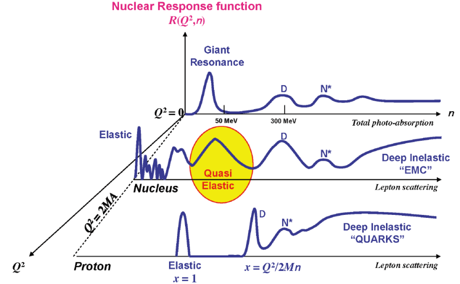




- The cross-section for this process reads

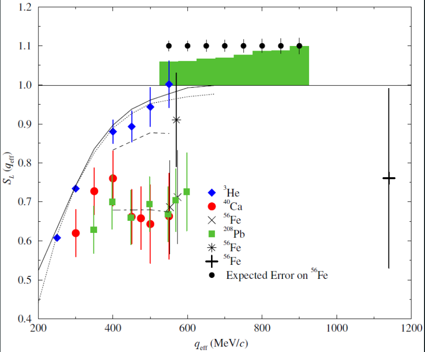
$$\frac{d\sigma}{dx\, dQ^2} = \frac{2\pi\, \alpha_e^2}{x\, Q^4} \left[\left(1 + (1+y)^2\right) F_2(x, Q^2) - y^2 F_L(x, Q^2) \right]$$

  - response functions are accessed via Rosenbluth separation

- In the DIS regime – $Q^2, \omega \to \infty$ $\quad x = Q^2/(2\, M_N\, \omega) = \text{constant}$ – response functions are proportional to the structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$

Coulomb Sum Rule

- The "Coulomb Sum Rule" reads
$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\not{\phi}, |\boldsymbol{q}|)}{\tilde{G}_E^2(Q^2)}, \qquad \tilde{G}_E^2 = Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)$$
- Non-relativistic expectation – as $|\boldsymbol{q}|$ becomes large –
$S_L(|\boldsymbol{q}| \gg p_F) \to 1$ [CSR counts number of charge carriers]
- CSR first measured at MIT Bates in 1980 then Saclay in 1984
  - both experiments observed significant *quenching* of the CSR
  - no new data on the CSR since SLAC data from early 1990s



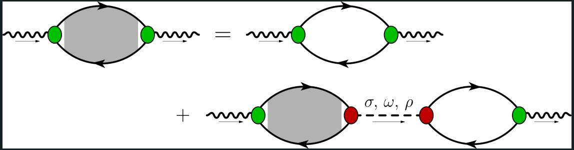
- Two plausible explanations: 1) *nucleon structure is modified in the nuclear medium;* 2) *experiment/analysis is flawed e.g. Coulomb corrections*
- *Quenching* of the CSR has become one of the most contentious observations in nuclear physics
- JLab experiment E05-110 will report ^{12}C and ^{56} Fe results at GHP2021 (13-16 April)
  - will hopefully settle controversy of CSR quenching

Longitudinal Response Function

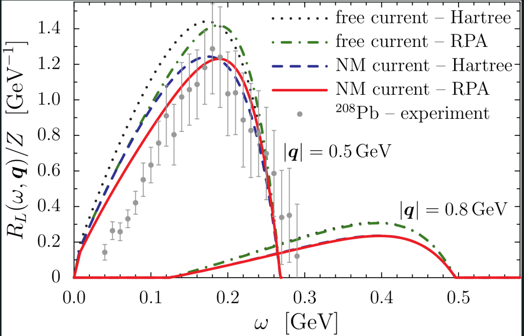
- In nuclear matter response function given by

$$R_L(\omega, \boldsymbol{q}) = -\frac{2\,Z}{\pi\,\rho_B}\,\mathrm{Im}\,\Pi_L\,(\omega, \boldsymbol{q})$$

  - longitudinal polarization – Π_L – is obtained by solving a Dyson equation



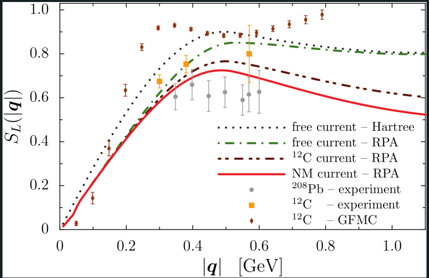
- Response function sensitive to electromagnetic form factors of bound nucleon – consider:
  - 1) electromagnetic current is that if a free nucleon
  - 2) electromagnetic current modified by nuclear medium
- The *in-medium* nucleon current causes a sizeable quenching of the longitudinal response
  - driver of this effect is modification of the proton Dirac form factor
- Nucleon RPA correlations play almost no role for $|\boldsymbol{q}| \gtrsim 0.7$ GeV



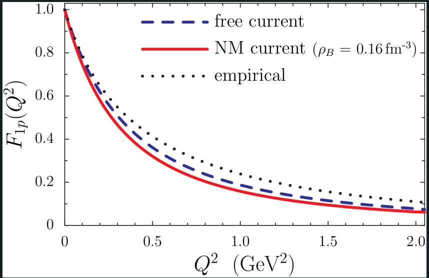
Coulomb Sum Rule

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **116** 032701 (2016)]

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{\tilde{G}_E^2(Q^2)}, \qquad \tilde{G}_E^2 = Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)$$

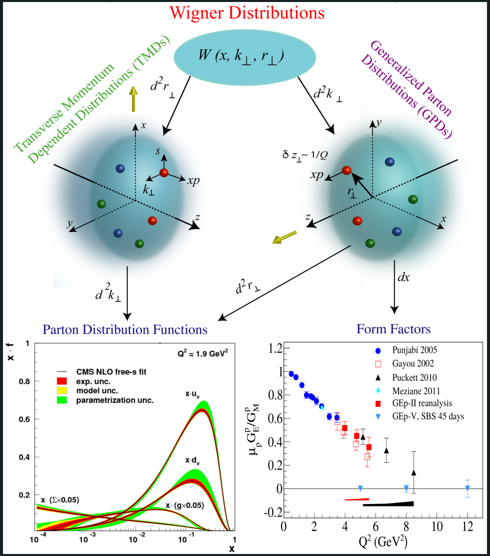


- Recall that the non-relativistic expectation is unity for $|\boldsymbol{q}| \gg p_F$
  - GFMC ^{12}C results appear consistent with this expectation
- For a *free nucleon current* find relativistic corrections of 20% at $|\boldsymbol{q}| \simeq 1\,\text{GeV}$
  - in the non-relativistic limit our CSR result does saturate at unity
- An *in-medium nucleon current* induces a further 20% correction to the CSR
  - good agreement with exisiting ^{208}Pb data
- Quenching of the CSR can be naturally explained by slight modification of bound nucleon EM form factors — natural consequence of QCD models



Nuclear Imaging — Next Steps for Mean-Field Calculations

- During the next 10-20 years Jefferson Lab and the EIC will (hopefully) revolutionize our understanding of QCD and nuclear
  - provide quark and gluon tomography of light nuclei, e.g., quark and gluon GPDs and TMDs of deuteron, ^{3}H, ^{3}He, ^{4}He, ^{7}Li, . . .
  - such progress is likely essential to fully solve the mystery of the EMC effect and to develop a QCD based description of nuclei
- A robust description of nuclear tomography – and forthcoming data – places stringent requirements on model frameworks — ideally:
  - should satisfy Poincaré symmetry to given, e.g., correct support, polynomiality, positivity, correct number of observables, gauge invariance, gluon & flavor separation . . .
- Some relativistic mean-field models of nuclear structure can satisty these requirements

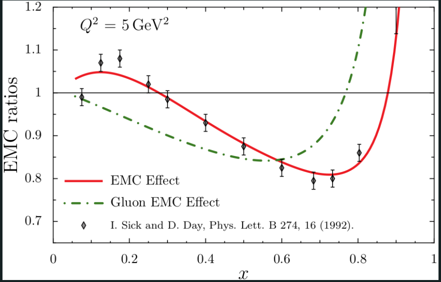


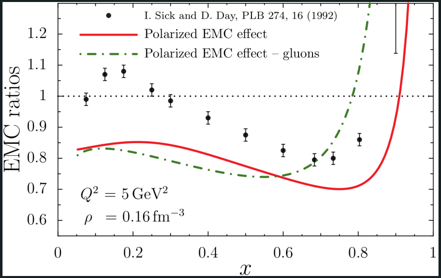
Gluon EMC Effects

- To solve puzzle of EMC effect need new observables, e.g., gluon and spin EMC effects
  - can help distinguish between different explanations of the EMC effect (Everyone's Model is Cool – Jerry Miller)
  - mean-field and SRC make different predictions for spin EMC effect
- The gluon EMC effect can be defined as

$$R_g(x) = \frac{g_A(x)}{Z\, g_p(x) + N\, g_n(x)}$$

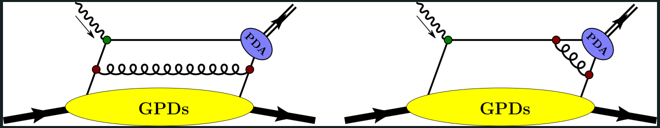
  - analogous definition for gluon spin EMC effect, with, $Z \to P_p$ and $N \to P_n$
- Results opposite obtained in mean-field model that describes the EMC effect and predicts spin EMC effect
  - gluons are generated purely perturbatively
  - provides a baseline for comparison and understanding of future EIC measurements





Generalized Parton Distributions

- GPDs are a generalization of PDFs and form factors, and provide a spatial tomography of hadrons and nuclei
  - measured in processes such as DVCS, DDVCS, DVMP, ...



- For example, the twist-2 spin-independent GPDs of a spin-1/2 target are defined by

$$\int \frac{\mathrm{d}\lambda}{2\pi} e^{2\,i\,x\,\lambda\,P\cdot n} \langle p' \,|\bar{q}(-n\lambda)\, \not{n}\, [-n\lambda, n\lambda] q(n\lambda)|\, p\rangle = \bar{u}(p') \left[\not{n}\, H_q(x,\xi,t) + \frac{i\sigma^{n\Delta}}{2\,M}\, E_q(x,\xi,t) \right] u(p)$$

  - analogous results for helicity and transversity twist-2 GPDs

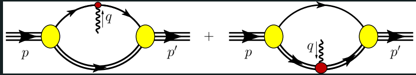
- GPDs have numerous remarkable properties

$$q(x) = H_q(x,0,0), \qquad \int_{-1}^{1} \mathrm{d}x\, [H_q(x,\xi,t), E_q(x,\xi,t)] = [F_1^q(t), F_2^q(t)]\,,$$

$$J_q = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\, [H_q(x,\xi,0) + E_q(x,\xi,0)]\,, \qquad S_q = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\, \tilde{H}_q(x,\xi,0)$$

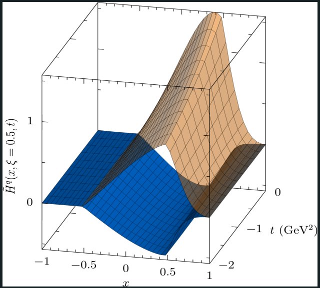
NJL Results for Proton GPDs (including at finite skewness)

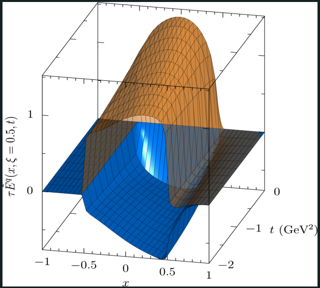
- GPDs are given by the diagrams:

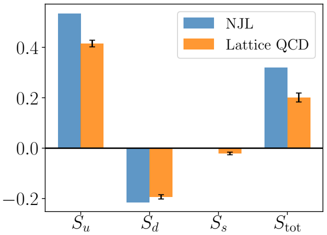


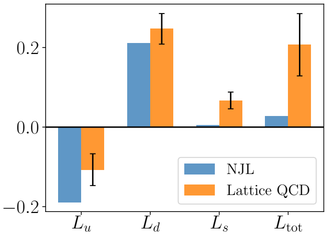
  - quark propagator is solution to gap equation
  - diquark propagators are solutions to Bethe-Salpeter equations
  - quark-diquark vertices from solution to Faddeev equation

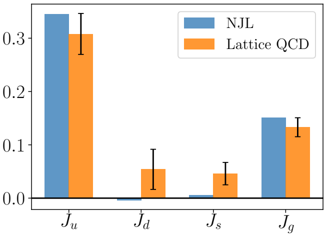
[A. Freese and ICC, Phys. Rev. C **101**, no.3, 035203 (2020); A. Freese and ICC, *to appear* Phys. Rev. C 2021]





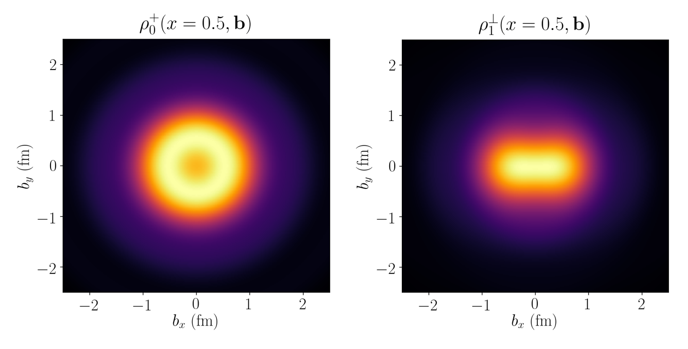


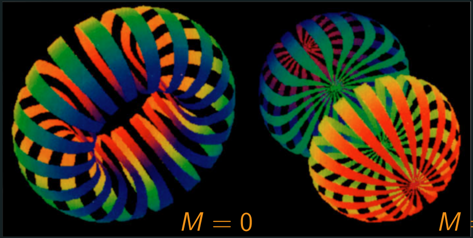




Deuteron GPDs

- The deuteron has a rich GPD structure
- The impact parameter PDFs provide a spatial tomography for various x slices
  - tensor polarized along z-axis – donut shape is clear
  - longitudinally polarized along x-axis – dumbbell shape is clear
- These quantities provide an interesting connection to traditional nuclear physics results for the deuteron
  - nuclear spatial densities have donut and dumbbell shapes
- Does the gluon donut align with the quark donut – does this change with x? Incredible insight into *NN* interaction possible at an EIC





$M = \pm 1$

J. Carlson, R. Schiavalla, Rev. Mod. Phys. **70** 743 (1998)

J. L. Forrest *et al.* Phys. Rev. **C54** 646 (1996)

Results for Deuteron GPDs

- Nuclear GPDs given by convolution between quark/gluon GPDs in nucleon & nucleon GPDs nuclei

$$H_A(x_A, \xi_A, t) = h_A(y_A, \xi_y, t) \otimes H_N(z, \xi_z, t)$$

Gravitational Structure of Nucleons and Nuclear Matter

- The nucleon has 3 gravitational form factors

$$\langle p' \,|\, T^{\mu\nu} \,|\, p\rangle = \bar{u}(p')\left[A(t)\,\frac{P^\mu P^\nu}{M} + D(t)\,\frac{\Delta^\mu\Delta^\nu - \Delta^2 g^{\mu\nu}}{4\,M} + J(t)\,\frac{P^{\{\mu} i\sigma^{\nu\}\alpha}\Delta_\alpha}{2\,M}\right] u(p)$$

  - related to mass and angular momentum distributions $J(t) = \frac{1}{2}\,[A(t) + B(t)]$, and pressure and shear forces

- Gravitational form factors are related to GPDs

$$\sum_{i=q,g}\int_{-1}^{1} \mathrm{d}x\, x\,[H_i(x,\xi,t), E_i(x,\xi,t)] = \left[A(t) + \xi^2 D(t),\ \ B(t) - \xi^2 D(t)\right]$$

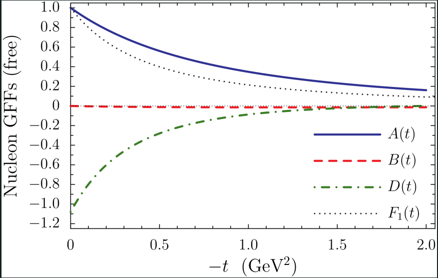
- We find (light front) charge and mass radii of:

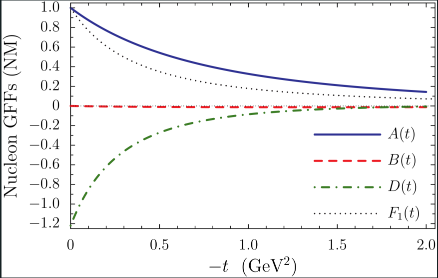
free $\langle r^2\rangle_C = (0.61\,\text{fm})^2$, $\langle r^2\rangle_A = (0.45\,\text{fm})^2$, $D(0) = -1.08$

NM $\langle r^2\rangle_C = (0.66\,\text{fm})^2$, $\langle r^2\rangle_A = (0.46\,\text{fm})^2$, $D(0) = -1.21$

  - mass radius changes much less than the charge radius
  - pressure and shear forces on the nucleon increase by around 10%
  - small mass radius may help explain success of traditional NP

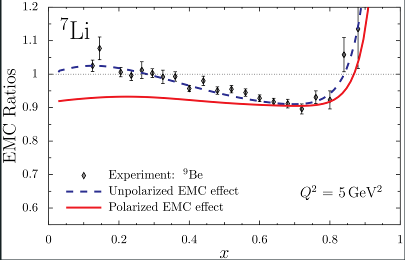
[Adam Freese and ICC, *to appear* (2021)]

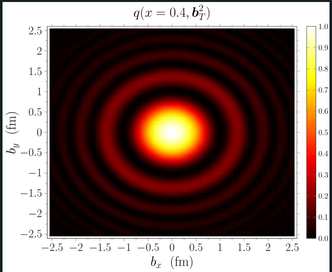


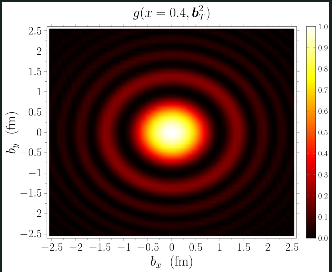


Conclusion and Outlook

- JLab appears motivated to measure polarized EMC effect in ^{7}Li
  - will feature in a new "opportunities" document for JLab
- New Jefferson Lab CSR results will be presented at GHP 2021
  https://www.jlab.org/indico/event/412/
- Tremendous opportunity for the JLab and EIC to transform our understanding of QCD and nuclei via 3D imaging
  - quark & gluon GPDs and TMDs of: p, D, ^{3}H, ^{3}He, ^{4}He, ...
  - quark & gluon PDFs of ^{7}Li, ^{11}B, ^{56}Fe, ...
  - flavor separation, e.g., s-quarks
- Key physics question: How does the NN interaction arise from QCD?
- Can explore this question by imaging nuclei and comparing quarks and gluons for slices in x, $\boldsymbol{k}_T^2$, and $\boldsymbol{b}_T^2$
  - correlations between quarks and gluons in nuclei provide insights into color confinement







Conclusion and Outlook

- JLab appears motivated to measure polarized EMC effect in ^{7}Li
  - will feature in a new "opportunities" document for JLab
- New Jefferson Lab CSR results will be presented at GHP 2021
  https://www.jlab.org/indico/event/412/
- Tremendous opportunity for the JLab and EIC to transform our understanding of QCD and nuclei via 3D imaging
  - quark & gluon GPDs and TMDs of: p, D, ^{3}H, ^{3}He, ^{4}He, ...
  - quark & gluon PDFs of ^{7}Li, ^{11}B, ^{56}Fe, ...
  - flavor separation, e.g., s-quarks
- Key physics question: How does the *NN* interaction arise from QCD?
- Can explore this question by imaging nuclei and comparing quarks and gluons for slices in x, $\boldsymbol{k}_T^2$, and $\boldsymbol{b}_T^2$
  - correlations between quarks and gluons in nuclei provide insights into color confinement