Nuclear reaction theory at intermediate energies

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Hall C Meeting

In collaboration with: J. Ryckebusch, M. Sargsian, Ch. Weiss, C. Colle, M. Vanhalst, and many experimental colleagues

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Why Nuclear Reactions?

Study emergent QCD phenomena: properties of hadrons

- Influence of **nuclear interactions**, medium modifications [E12-11-002,E12-14-002]
  - bound neutron in stable nucleus does not decay [E12-11-009]
  - EMC effect: pdf in A is not that of the nucleon [E12-10-008, E12-11-107]
- Hadronization: how does a colored struck q evolve into a colorless hadron?
  - **space-time evolution** through interactions with the nuclear medium
- Scattering properties of unstable hadrons through secondary interactions
  - scattering lengths of strange baryons (CLAS, ALICE)
- Some phenomena are **unique** to nuclei
  - light nuclei with spin $> \frac{1}{2}$
  - gluon transversity in DIS
  - superfast quarks with $x > 1$
- Color transparency (more on this later) [E12-06-107]
- Gluon saturation at low x (EIC)
- ...

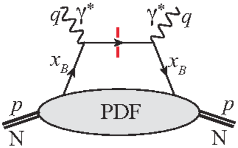
Why Nuclear Reactions?

Learn more about nuclear structure

- What is the nature of the **hard core** in the *NN* interaction
  - deuteron breakup at very high momenta [E12-10-003]
- What are the limits of the nuclear shell model?
  - nature and role of **short-range correlations** [E12-06-105, E12-11-107, E12-17-005]
- **Non-nucleonic** degrees of freedom in nuclei
  - delta isobars, hidden color
- 3D imaging of nuclear bound states in quark and gluon degrees of freedom
  - **coherent** hard exclusive reactions

(Modern) theory is a tale of scales

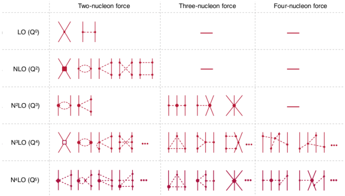
HE scattering: QCD factorization (Collins, Soper, Sterman,...)

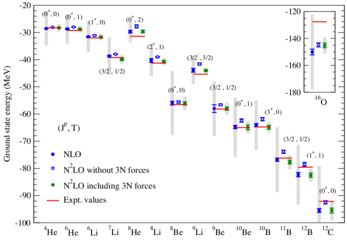


- Expansion in $\frac{\Lambda_{\text{QCD}}}{Q}$
- Leading term factorizes
  $d\sigma = C(\alpha_s, \mu_F) \otimes f(x, Q, \mu_F)$
- Hard coefficients can be calculated perturbatively
- Confined long distance physics enters in **universal** distribution functions → global fits
- Distribution functions obey renormalization group equations (DGLAP), from pQCD
- When is Q large enough? → JLab
- Color transparency is **necessary** condition

(Modern) theory is a tale of scales

Low energy nuclear physics: ab initio many-body frameworks based on precision pheno (AV18, Bonn, ...) or χPT (Weinberg, Leutwyler, Gasser)



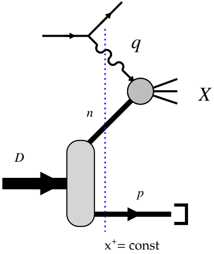


Epelbaum, Kreps, Reinert (2019);LENPIC

- EFT: N, π dof
- Systematic expansion in $\frac{m_\pi}{m_N}$, $\frac{p}{m_N}$
- Short distance physics enters in low-energy constants, fitted
- Current operators can also be treated order by order [ODU/Pisa]
- Renormalized and regularized (cutoff)

(Modern) theory is a tale of scales

So what about intermediate (& high) energy scattering with nuclei?



- **Both** high-energy scattering and low energy nuclear structure is needed/of interest
- Need to work relativistically
- In HE scattering, nuclear structure is probed on the light-front, requires LF nuclear structure input
- Not at a similar level of systematic rigor (yet)
- Nuclear input: relativistic mean field wf, lightfront wf (deuteron), non-relativistic wf, ...
- Scattering input: FF, pdfs, F_{2N}, models on the nucleon, ...
- Different ways of calculating
  - covariant (off-shell effects)
  - lightfront perturbation theory (intermediary particles on-shell)

Kinematics of electron-nucleus scattering

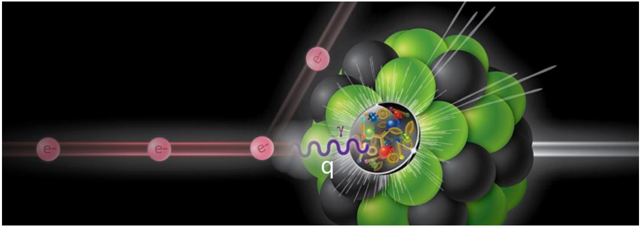


Image: CFNS

- virtual photon fourmomentum q
- $Q^2 = -q^2 \quad \sim$ resolution
- Bjorken x : $0 \leq x = A\frac{Q^2}{2Pq} \leq A$
- $x = A$: elastic scattering
- $x \approx 1$: quasi-elastic scattering
- $x < 1$: resonance production, DIS, hard exclusive processes
- $x > 1 \sim \mathcal{O}[N]$: scattering off N-nucleon correlations (or superfast quarks)

Measurements

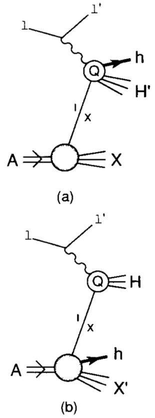
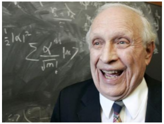
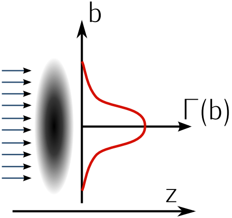


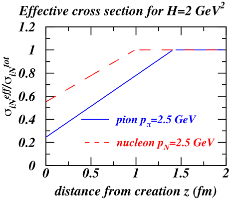
Image: HERA

- Inclusive scattering: SRCs (a_2), F_{2A}, F_{2n}, ...
  - Averages over all nuclear configurations
- Detect additional hadrons in
  - (a) current fragmentation region: select reaction
  - (b) target framentation region: **control** initial nuclear configuration
    - recoil nucleon partner from a SRC
    - nuclear fragments for light nuclei $\rightarrow$ difficult for low momentum in fixed target, but EIC!
- Cuts to ensure a particular residual system (e.g. $A - 1$)
- Light nuclei can be **polarized** (d, ^{3}He)
- Detected particles are subject to **final-state interactions**
  - needs to be accounted for
  - interplays with other reaction effects (medium modifications), how to disentangle?
  - can also be **used** to study hadronization, scattering

FSI in configuration space

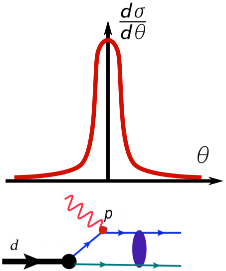




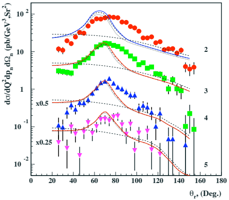


- Glauber theory has origins in optics
- High-energy **diffractive** scattering: small angles
- **Eikonal** method
  $\phi_{\mathrm{scat}}(\boldsymbol{r}) = e^{i\chi(\boldsymbol{r})}\phi_{\mathrm{in}}(\boldsymbol{r}) = (1 - \Gamma(\boldsymbol{b}))\,\phi_{\mathrm{in}}(\boldsymbol{r})$
- Parameters taken from data (NN) or educated guesses
- Frozen approximation : Medium to heavy nuclei (but also ^{4}He)
- Color transparency: effective cross section in the FSI is reduced during formation time

FSI in momentum space



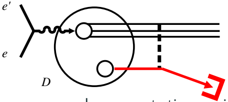
quasi-elastic breakup



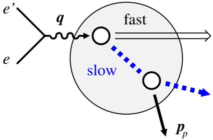
- Eikonal picture: rescatterings are forward peaked
- Effective Feynman diagrammatic rules, takes recoil of medium into account
- Light nuclei!
- FSI peak at deuteron around 70°
- Reduction cross section for spectator momenta ~ 100 MeV
  $\rightarrow$ interference IA-FSI
- Enhancement cross section for spectator momenta > 300 MeV
  $\rightarrow$ FSI^2 term

[Sargsian PRC82]

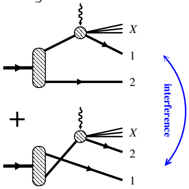
FSI in DIS: physical pictures



subasymptotic regime:
low Q^2, high x



DIS regime, intermediate x



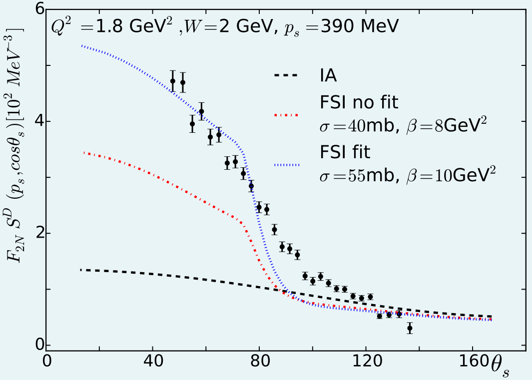
shadowing, low x

- rescattering of resonance-like structure with spectator nucleon in eikonal approximation [Deeps,BONuS].

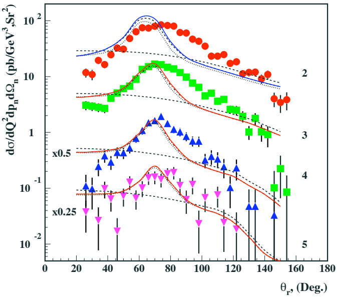
  `WC,M. Sargsian arXiv:1704.06117`
- FSI between slow hadrons from the DIS products and spectator nucleon, fast hadrons hadronize after leaving the nucleus.
  - Data show slow hadrons in the target fragmentation region are mainly nucleons.
  - Input needed from nucleon target fragmentation data $\rightarrow$ possible at EIC

    `M. Strikman, Ch. Weiss PRC'18`
- Shadowing in inclusive DIS $x \ll 10^{-1}$
  - Diffractive DIS on single nucleon (leading twist, HERA)
  - Interference of DIS on nucleon 1 and 2
  - Calculable in terms of nucleon diffractive structure functions `[Gribov 70s, Frankfurt,Guzey,Strikman '02+]`

FSI: DIS subasymptotic vs QE



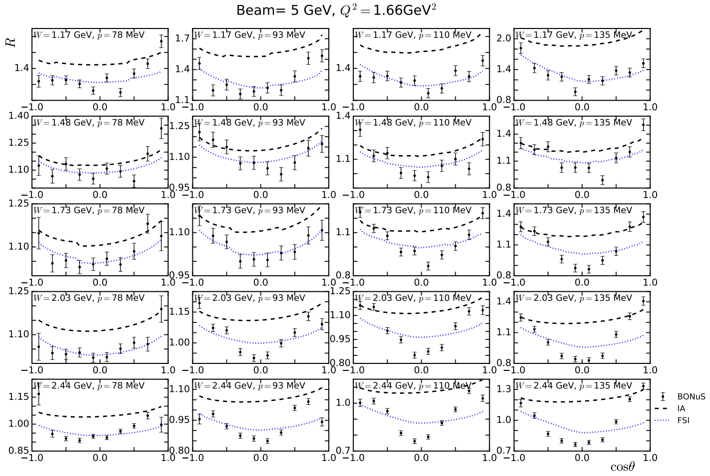
D(e,e’p_s)X WC, M. Sargsian PRC84



D(e,e’p_s)n
M. Sargsian PRC82 014612 (’10)

- Plane-wave calculation shows little dependence on spectator angle
- FSI effects grow in forward direction, different from quasi-elastic case
- Needs more data to **constrain**!

Get rid of FSI, measure backwards (?)

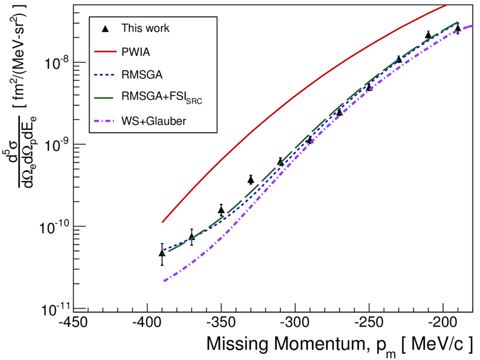


data: BONuS **S. Tkachenko et al., Phys.Rev. C89 (2014) 045206**

- In backward region FSI not necessarily small (compared to forward region) in these kinematics!

In an ideal world... $A(e, e'p)$

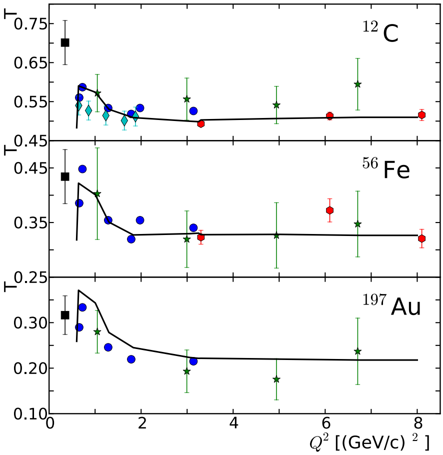
- $d^5\sigma \approx K\sigma_{ep}S(p_m)$
- Cross section vs relativistic **unfactorized** calculation



- Proton knockout from valence $p_{3/2}$ shell
- FSI: Relativistic Multiple Scattering Glauber Approximation
- Nice agreement between RSMGA calculations and data up to very high missing momenta $\rightarrow$ **No** free parameters!

P. Monaghan et al. (JLab Hall A), JPG41 105109 ('14)

CT in proton knockout? A(e,e'p)

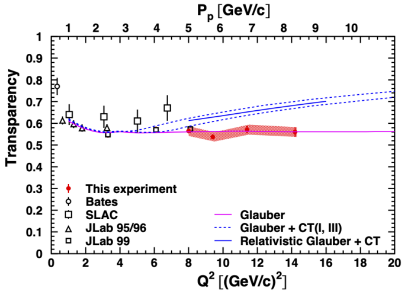


W.C., J. Ryckebusch, arXiv:1301.1904 ('13)

- RMSGA: excellent agreement with A(e,e'p) world data (JLab, SLAC, MIT Bates)
- No signs of CT yet

Baryons take three quarks close together to form colorless object, what about **mesons**?

CT in proton knockout? A(e,e'p)



JLab Hall C, 2011.00703

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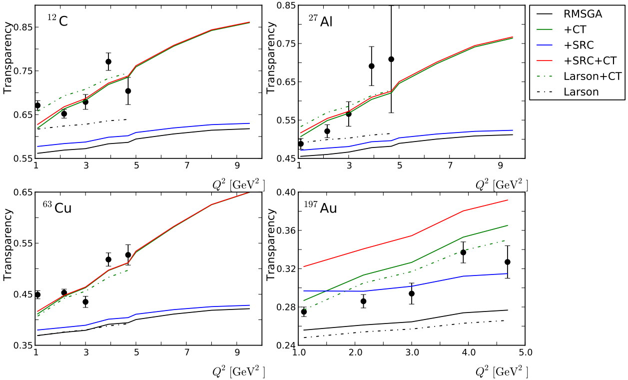
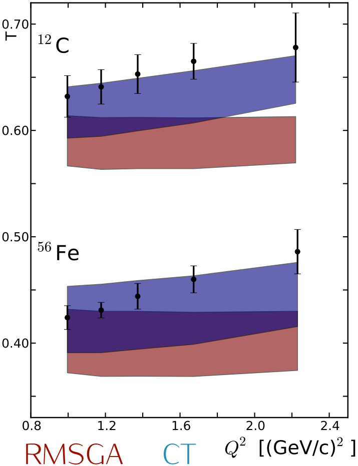
Pion transparencies: A(e,e'π)



First signs of CT onset at intermediate energies observed for pions in electro– and photoproduction

data: B. Clasie et al. (JLab Hall C), PRL99 242502 ('07)
W.C., M.C. Martinez, J.R., B. Van Overmeire, PRC74 062201(R) ('06)
W.C., M.C. M., J.R., PRC77 034602 ('07)

ρ transparencies A(e,e'ρ)



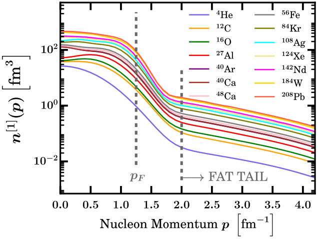
RMSGA CT

data: L. El Fassi et al. (JLab CLAS), PLB712 326 ('12)
W.C,J.R., arXiv:1301.1904 ('13)

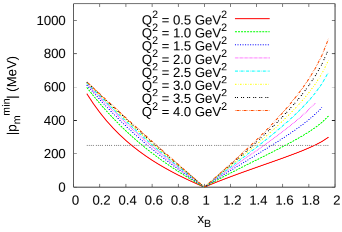
- Calculations account for ρ-meson decay and SRC in the FSI, band reflects theoretical uncertainty
- No scattering data for ρ-N, here $\sigma_{\rho\mathrm{N}}$ =20 mb (similar to pion)
- Again clear signs for the onset of CT, slope of calculations even underestimates data

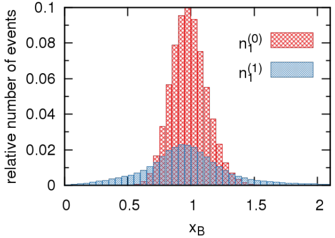
Nuclear SRCs: what to keep in mind

- High-momentum, high-density fluctuations in a nucleus, dominated by 2N SRCs
- Nucleons in 2N SRC have **high** relative momentum, above k_{Fermi}; **low** CM momentum, mean-field like → back-to-back
- Local phenomenon → one expects **universal behavior** to some degree across the nuclear chart



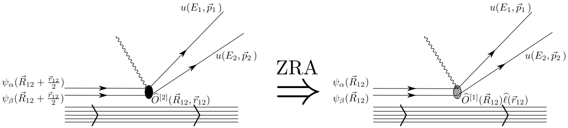
Electron scattering: kinematics to probe SRC





- Scattering at Bjorken x > 1.4 and high Q^2
- Kinematics yield initial nucleon momenta of $p_{miss} > 300$ MeV
- $1 < x_B \leq 2$: single nucleon contribution $k < k_F$ dies off, sensitive to **high initial momenta** associated with $2N$ configurations
- Initial beam, scattered beam and detected "fast" nucleon all have momenta in the few GeV region

Exclusive $A(e,e'NN)$ reactions

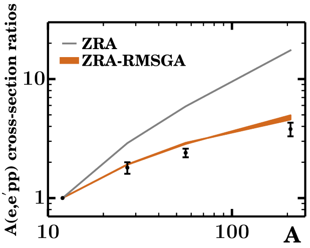


For **close-proximity pairs** $\vec{r}_{12} \approx 0$ (Zero-Range Approximation, ZRA) the $(e,e'NN)$ cross section **factorizes** as [J. Ryckebusch, PLB383 1-8 ('96),C.Colle et al., PRC89 024603 ('14)]

$$\frac{d^8\sigma(e,e'NN)}{d^2\Omega_{k_{e'}}d^3\vec{P}_{12}d^3\vec{k}_{12}} = K_{eNN}\,\sigma_{e2N}(\vec{k}_{12})F^D(\vec{P}_{12})$$

- $\sigma_{e2N}(\vec{k}_{12})$ encodes the photon coupling to a correlated nucleon pair with **relative** momentum $\vec{k}_{12}$
  - includes FSI between the pair
- $F^D(\vec{P}_{12})$ is the two body **center of mass** momentum distribution of SRC pairs
  - normalization is related to number of short-range correlated pairs in nucleus
  - contains effect of FSI of outgoing nucleons with $A-2$

Mass dependence of pp cross section ratio



C.Colle et al. PRC92 024604 ('15)

- $\frac{\sigma[A(e,e'pN)]}{\sigma[^{12}C(e,e'pN)]} \approx \frac{\int d^3\vec{P}_{12} F^D_A(\vec{P}_{12})}{\int d^3\vec{P}_{12} F^D_{^{12}C}(\vec{P}_{12})}$
- Data from data mining initiative for the Jefferson Lab CLAS collaboration (4π detector, **huge phase space**)
- Calculations performed for ^{12}C,^{27}Al,^{56}Fe and ^{208}Pb.
- Cross section ratios scale much softer than $Z(Z-1)$
- Final-state interactions soften the mass dependence further
- Charge-exchange effects in final-state interactions also taken into account

LCA: a simple model to include correlations

- Expectation values between **correlated states** Ψ can be turned into expectation values between **uncorrelated states** Φ

$$\langle \Psi \mid \widehat{\Omega} \mid \Psi \rangle = \frac{1}{\mathcal{N}} \langle \Phi \mid \widehat{\Omega}^{\text{eff}} \mid \Phi \rangle$$

- "Conservation Law of Misery": multi(A)-body operators

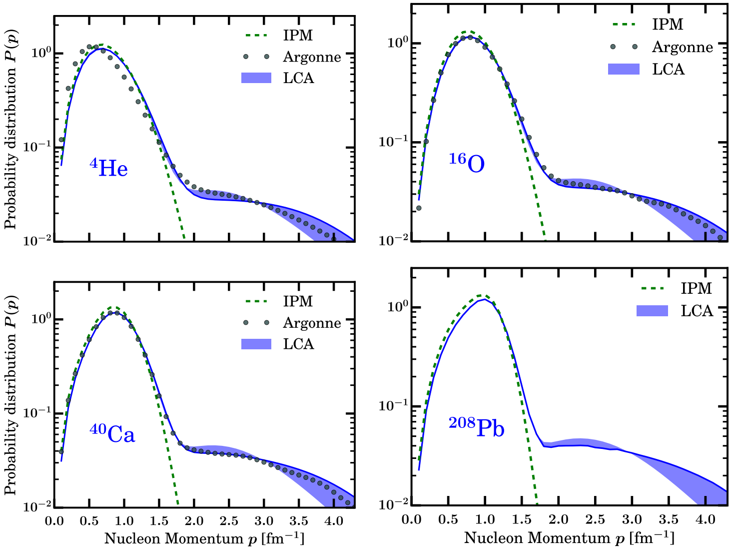
$$\widehat{\Omega}^{\text{eff}} = \widehat{\mathcal{G}}^{\dagger} \, \widehat{\Omega} \, \widehat{\mathcal{G}} = \left(\prod_{i<j=1}^{A} \left[1 - \hat{l}(i,j) \right] \right)^{\dagger} \widehat{\Omega} \left(\prod_{k<l=1}^{A} \left[1 - \hat{l}(k,l) \right] \right)$$

- Low-order correlation operator approximation (LCA): cluster expansion truncated at lowest order [M. Vanhalst, W.C., J. Ryckebusch, '14]
- LCA: N-body operators receive SRC-induced $(N+1)$-body corrections

Dominant contribution to SRC-sensitive matrix elements stems from **relative $n = 0, l = 0$ pairs** in the IPM wf [strength at $r \to 0$]

LCA: Probability distribution $P(p) \sim p^2 n^{[1]}(p)$

Includes central,tensor, spin-isospin correlations



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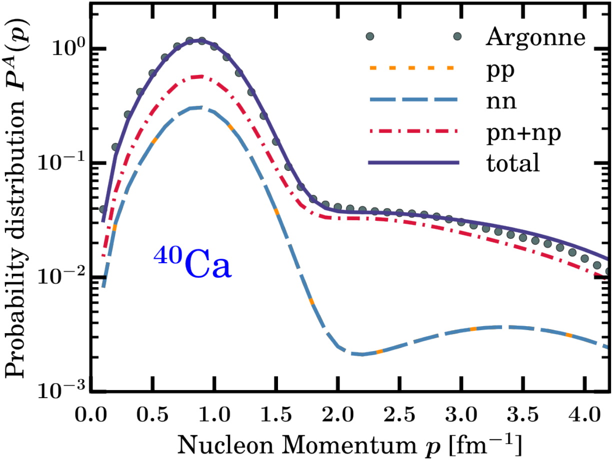
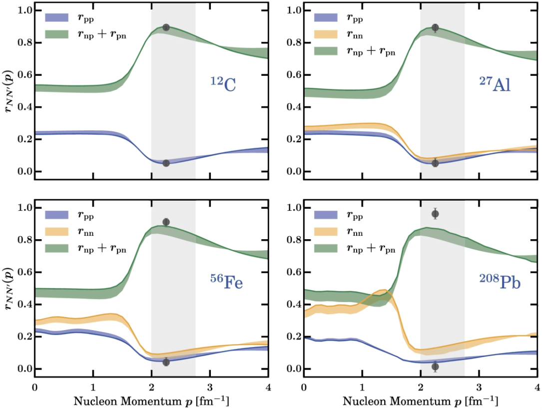


Nuclear momentum distribution: pair composition

$$n^{[1]}(p) \equiv \underbrace{n^{[1]}_{\mathrm{pp}}(p) + n^{[1]}_{\mathrm{pn}}(p)}_{n^{[1]}_{\mathrm{p}}(p)\ \text{(proton part)}} + \underbrace{n^{[1]}_{\mathrm{nn}}(p) + n^{[1]}_{\mathrm{np}}(p)}_{n^{[1]}_{\mathrm{n}}(p)\ \text{(neutron part)}}$$

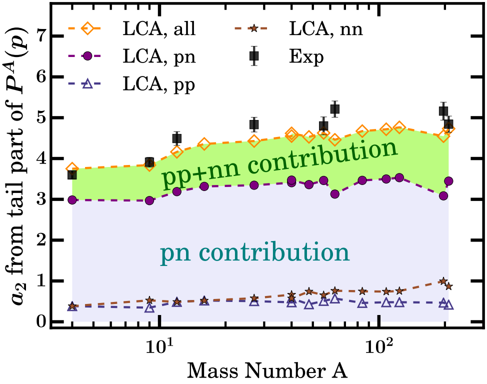


- SRC pair fractions [momentum dependent!]
  $r_{\mathrm{pp}}(p) = \frac{n^{[1]}_{\mathrm{pp}}(p)}{n^{[1]}(p)}$
- Points extracted from DATA [model dependence]: O. Hen *et al.* [CLAS], Science346(2014)

$a_2(A/^2\mathrm{H})$ from $A(e,e')$ at $x_B \gtrsim 1.5$ and LCA

Aggregated quantitative effect of SRC in A relative to d

$$a_2(A) = \frac{\int_{p>2\ \mathrm{fm}^{-1}} dp P^A(p)}{\int_{p>2\ \mathrm{fm}^{-1}} dp P^d(p)}\ ; a_2^{exp}(A) = \frac{2}{A}\frac{\sigma^A(e,e')}{\sigma^d(e,e')} \quad (1.5 \lesssim x \lesssim 1.9)$$

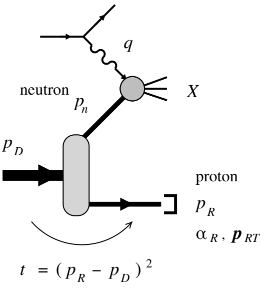


- $A \lesssim 27$: soft A dependence
- $A \gtrsim 27$: SATURATION
- Ca isotopes: $a_2\left(^{40}\mathrm{Ca}\right) \approx a_2\left(^{48}\mathrm{Ca}\right)$ [D. Nguyen, Hall A PRC'20]

DATA: N. Fomin *et al.*, PRL108(2012) ; B. Schmookler *et al.*, Nature566(2019)
J. Ryckebusch, W.C. et al., PLB '19

Neutron structure with tagging

- Proton tagging offers a way of controlling the nuclear configuration

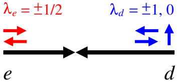


- Advantages for the deuteron
  - active nucleon identified
  - recoil momentum selects nuclear configuration (medium modifications)
  - limited possibilities for nuclear FSI, calculable
    `Strikman, Weiss PRC '18`
- Allows to extract **free** neutron structure with on-shell extrapolation $p_s \to 0$
  - Small deuteron binding energy results in small extrapolation length
  - Eliminates nuclear binding and FSI effects
    `[Sargsian,Strikman PLB '05]`

- Suited for colliders: no target material ($p_p \to 0$), forward detection, polarization.
  fixed target CLAS BONuS limited to recoil momenta $\sim$ 70 MeV

Polarized structure function: longitudinal asymmetry

- Goal is extraction of neutron spin structure function g_{1n}



- On-shell extrapolation of double spin asymmetry
  - Nominator
    $d\sigma_{||} \equiv \frac{1}{4}\left[\mathrm{d}\sigma(+\frac{1}{2},+1) - \mathrm{d}\sigma(-\frac{1}{2},+1) - \mathrm{d}\sigma(+\frac{1}{2},-1) + \mathrm{d}\sigma(-\frac{1}{2},-1)\right]$
  - Denominator

$$d\sigma_2 \equiv \frac{1}{4}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1)\right]$$

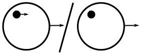
- Impulse approximation yields in the Bjorken limit $\left[\alpha_p = \frac{2p_p^+}{p_D^+}\right]$

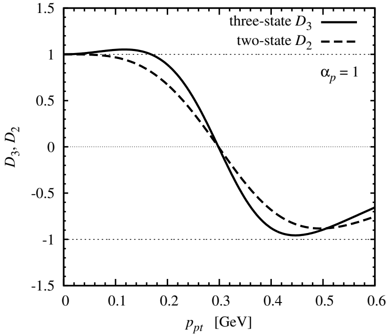
$$A_{||} \approx \mathcal{D}(\alpha_p, |p_{pT}|)A_{||n} = \mathcal{D}(\alpha_p, |p_{pT}|)\frac{D_{||}g_{1n}(\tilde{x}, Q^2)}{2(1+\epsilon R_n)F_{1n}(\tilde{x}, Q^2)}$$

[W.C., Ch. Weiss PLB ’19, PRC ’20]

Nuclear structure factor $\mathcal{D}$

- Quantifies neutron depolarization due to nuclear structure
- Depends on spectator kinematics α_p, p_{pT}
- $\mathcal{D} = \Delta S_d[\text{pure } +1]/S_d[\text{pure } +1]$ has **probabilistic interpretation**





- Bounds: $-1 \leq \mathcal{D}_2 \leq 1$
- Due to lack of OAM $\mathcal{D}_2 \equiv 1$ for $p_T = 0$
- Clear contribution from D-wave at finite recoil momenta
- 2-state asymmetry is also easier experimentally!!

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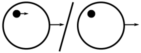

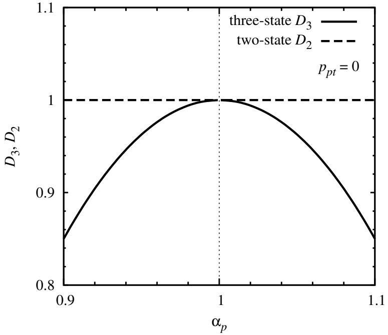

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Conclusions

- Nuclear reactions at intermediate and high energies offer many interesting ways of studying hadronic QCD phenomena and nuclear structure
- Detected hadrons undergo FSI with the nuclear medium
- Many exciting measurements at JLab12 and the future EIC
  - Color transparency results
  - Further exploring the nature of SRCs
  - Spectator tagging with light nuclei
  - ...and a lot more