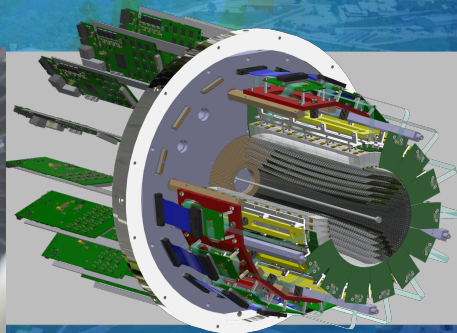
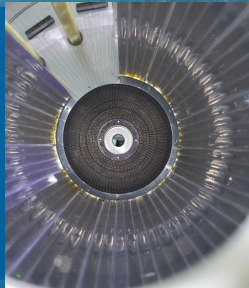


Hard Exclusive Scattering with ALERT

What's the role of QCD in Nuclei?



Whitney Armstrong
Argonne National Laboratory

Towards Improved Hadron Femtography Workshop

July 21, 2026

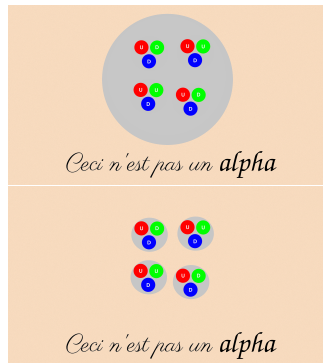


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Overview

- Motivation: QCD and Tomography of light nuclei
- Looking at the ^4He with different goggles
- Overview ALERT Experiments — CLAS12 Run Group L
- New tomography opportunities with ALERT: Coherent J/ψ production off ^4He
- Why the α particle is important
- What causes the EMC Effect and quenching of spectroscopic factors?
- Is α clustering responsible for SRCs and the EMC effect?
- Future Experiments at JLab



QCD and Tomography of light nuclei

Big Questions

- Are quarks and gluons confined within the nucleons in a nucleus?
- If not, are they constrained within alpha clusters?
- If not, what is their role in the structure of light nuclei?
- How does the charge and mass radii differ for nuclei?

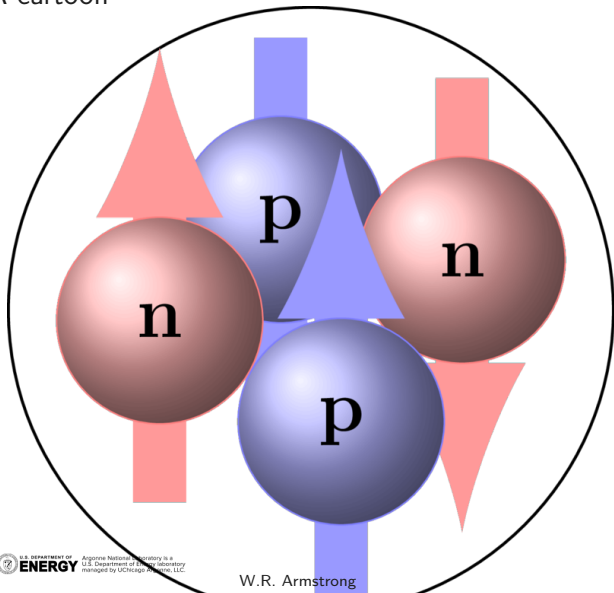
EMC Effect: Nearly as old as QCD itself.

- Two **very different** pictures of the nucleus exist: the low-energy hadronic description and the partonic picture
- The EMC effect is in the valence region, ie, where the hadronic structure make contact with their partonic description
- Still, for more than 40 years the origin of the EMC Effect has been debated.
- Modern explanations center around these questions: *Is modification caused by mean-fields which modify all nucleons all of the time or by SRCs which modify some nucleons some of the time?*

I will argue that the SRCs are a result of α clustering and α clustering appears deeply related to the origin of the EMC effect.

The Partonic Structure of the α particle

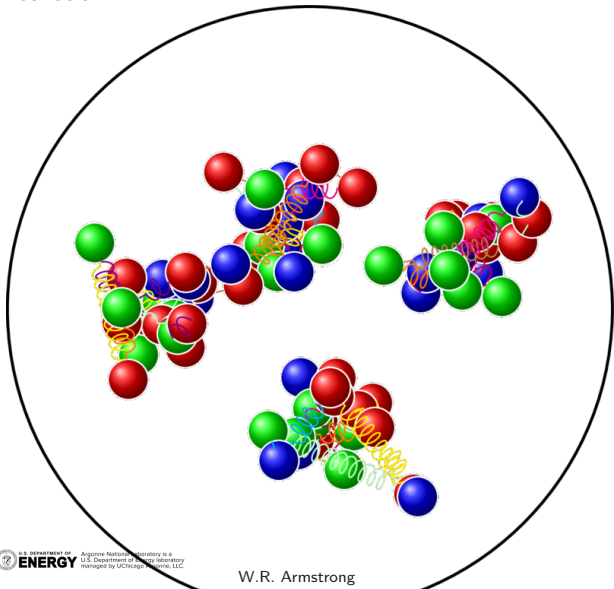
A cartoon



- Two goggles to view the nucleus

The Partonic Structure of the α particle

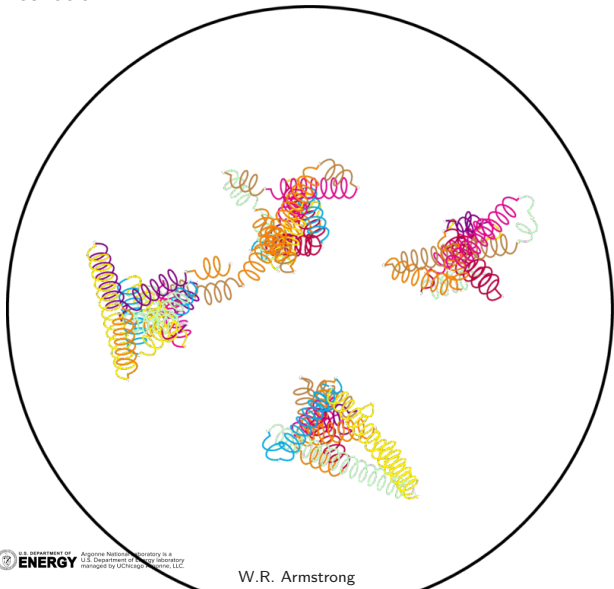
A cartoon



- Two goggles to view the nucleus
- Coherent DVCS to probe the charge profile

The Partonic Structure of the α particle

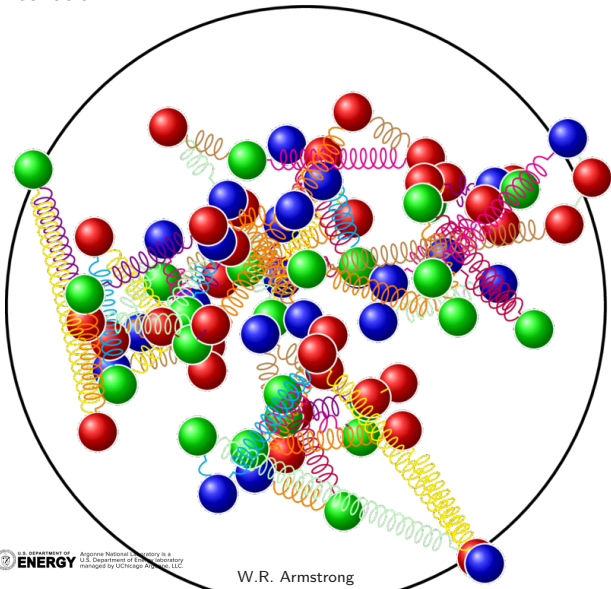
A cartoon



- Two goggles to view the nucleus
- Coherent DVCS to probe the charge profile
- Coherent ϕ or J/ψ production to probe the gluon profile

The Partonic Structure of the α particle

A cartoon



- Two goggles to view the nucleus
- Coherent DVCS to probe the charge profile
- Coherent ϕ or J/ψ production to probe the gluon profile
- How does the gluonic form factor compare to the charge?

Nuclear Physics and the ~~Nucleon~~ α Particle

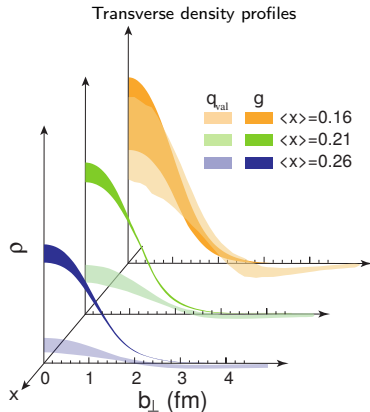
From the **first** textbook on Nuclear Physics

"The general evidence on nuclei strongly supports the view that **the α particle is of primary importance as a unit of the structure of nuclei** in general and particularly of the heavier elements. It seems very possible that the greater part of the mass of heavy nuclei is due to α particles which have an independent existence in the nuclear structure."

— Rutherford, Chadwick, and Ellis (1930)

Note: this is roughly 2 years before the discovery of the neutron.

ALERT Nuclear GPD projected results

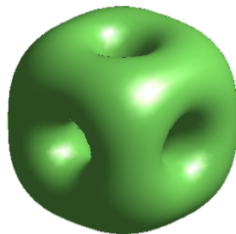
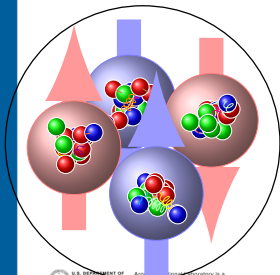


- Extract **quark and gluon distributions** of alpha particle
- Significant impact on EIC physics

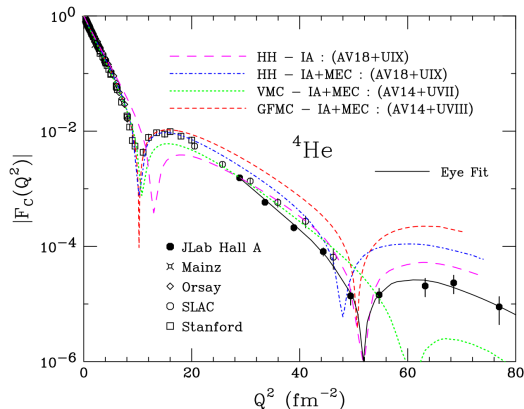
Nuclear Physics and the α Particle

Some things we know.

- Spin-0
 - Only charge form factor
 - two leading twist GPDs
- Tightly bound system → **smaller radius than ^3H and ^3He .**
- Diffractive minimum in charge form factor
 - composite system of nucleons
 - form factor relates to 2D transverse charge distribution



Skyrme Model



(Camsonne, et al., PRL.112. 132503)

The ALERT Experiments

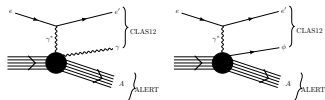
A comprehensive program to study nuclear effects

Coherent Processes on ^4He

DVCS and DVMP

- $^4\text{He}(e, e' \ ^4\text{He} \ \gamma)$
- $^4\text{He}(e, e' \ ^4\text{He} \ \phi)$

Explores the partonic structure of ^4He



Coherent J/ψ production on ^4He

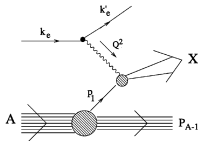
C2 conditionally approved by PAC 53.
Coherent J/ψ measurement could merge into a run group with this proposal.

Tagged EMC Effect

DIS with spectator tagging

- $^4\text{He}(e, e' + ^3\text{H}) X$
- $^4\text{He}(e, e' + ^3\text{He}) X$
- $^2\text{H}(e, e' + p) X$

Test FSI and rescaling models



ALERT SRC

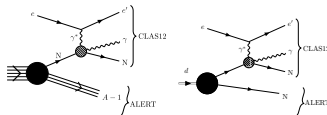
- SRC pair Factorization
Mapping of transition (mean field $\rightarrow$ SRC)

Incoherent processes on $^4\text{He}/^2\text{H}$

Tagged DVCS

- $^4\text{He}(e, e' \gamma p + ^3\text{H})$
- $^4\text{He}(e, e' \gamma + ^3\text{He}) n$
- $^2\text{H}(e, e' \gamma + p) n$

Identify medium modified nucleons



And many more channels for free

Measurement of Coherent J/ψ off ^4He using CLAS12 and ALERT

C12-25-004: PAC54 Conditionally approved C2 100 days

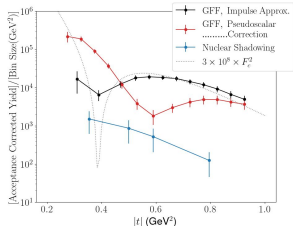
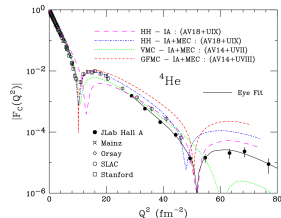
- Elastic scattering and DVCS **probes the quark** transverse spatial distributions
- $F_c(t)$ has a minimum around $|t| \simeq 0.4$ – a reference point for comparison.

Model-independent measurement to study gluons relative to charge

- Exclusive vector meson production **probes the gluons** inside hadrons via gluon exchange
- Heavy charm quark mass $\rightarrow$ gluon exchange dominates the interaction
- Coherent process probes gluonic form factor $\frac{d\sigma}{dt} \propto |G_{^4\text{He}}(t)|^2$
- Focus kinematics near first minimum in $|F_c(t)|$ momentum transfer.

Immediate insight into the role of QCD in Nuclei

- Will determine if a diffraction minimum exists in $|G_{^4\text{He}}(t)|^2$ for $|t| = 0.3$ to 0.9 GeV^2
- If it exists, we will precisely determine its location



Work here from Sangbaek Lee

Direct comparison of **gluonic** and **charge** form factors begins to shed light on the fundamental question:
How are gluons distributed in ^4He relative to the quark charges?



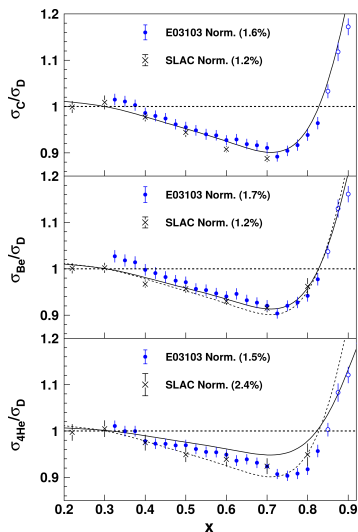
Beyond ^4He



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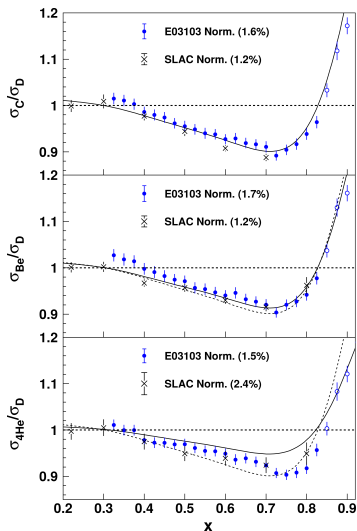


EMC Effect in Light Nuclei



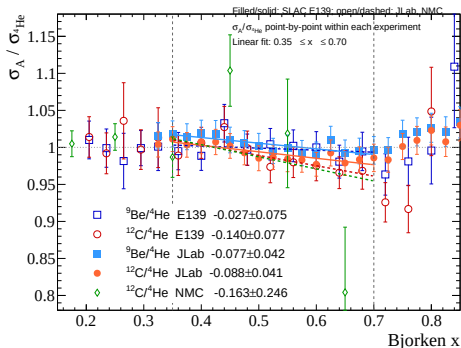
J. Seely et al. Phys.Rev.Lett. 103 (2009) 202301

EMC Effect in Light Nuclei



J. Seely et al. Phys.Rev.Lett. 103 (2009) 202301

Looking at ratio with ${}^4\text{He}$ in denominator



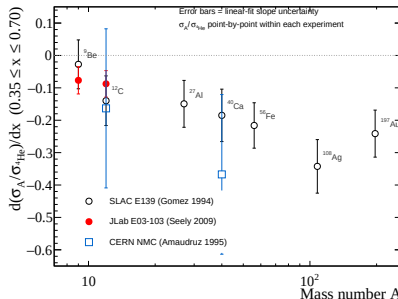
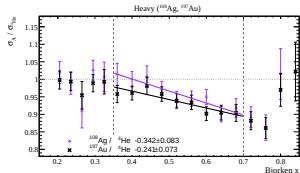
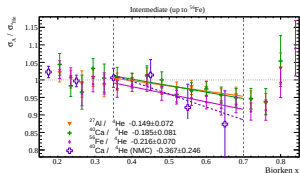
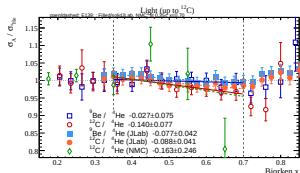
Data from NMC, SLAC and JLab

- ${}^9\text{Be}/{}^4\text{He}$ and ${}^{12}\text{C}/{}^4\text{He}$ ratios consistent with 1.
- Need more precise measurements of ratios to ${}^4\text{He}$.
- Also need more light nuclei: ${}^{16}\text{O}$, ${}^{20}\text{Ne}$, etc.

What about heavier nuclei...?

EMC Effect in Nuclei

Looking at ratio with ^4He in denominator!



Data from NMC, SLAC and JLab

- $^{27}\text{Al} / ^4\text{He}$ and $^{40}\text{Ca} / ^4\text{He}$ very similar.
- Big Step for $^{56}\text{Fe} / ^4\text{He}$... why?
- Note, ^{56}Ni is doubly magic, and ^{18}O has an extremely large alpha-clustering strength [Johnson:2009kj]

→

What does this mean?

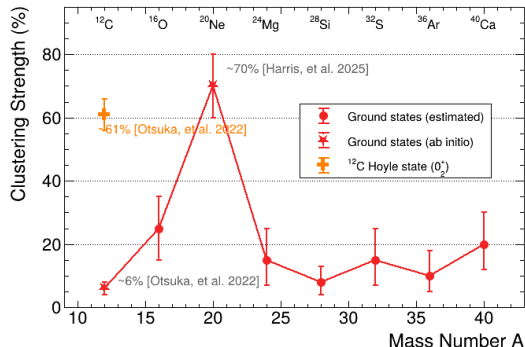
Heavier nuclei results dominated by SLAC E139

Structure of Light Nuclei

Clustering

Clustering Strength

- Ground state of ^{12}C only weakly clustering
- Hoyle state near maximum of clustering string
- ^{20}Ne has the largest clustering strength and can appear as a $^{16}\text{O} + \alpha$.



Structure of Light Nuclei

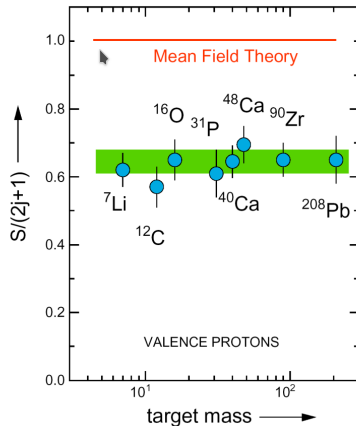
Shell Model

Quenching of the Single-Particle Spectroscopic Strengths

$$S_{nlj} = \sum_{m, M_A} |\langle \Psi_{A+1, J_f M_f} | a_{nljm}^\dagger | \Psi_{A, J_i M_i} \rangle|^2$$

- The Spectroscopic factors are test or measure of the Nuclear Shell Model.
- For most nuclei lies around $S = 0.65$
- SRC important ingredient but only responsible for 10-15% at most, yielding $S \approx 0.9$
→ It's not SRCs
- Long range correlations and other correlations responsible for missing suppression of single-particle strength.

See review: [Aumann, et al., Prog.Part.Nucl.Phys. 118 \(2021\) 103847](#)

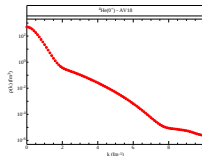


Quenching of Spectroscopic factors remains a puzzle for over 20 years.

The NN Potential

Doesn't this predict SRCs?

- Nucleon momentum distributions from best NN potential models in light nuclei show high momentum tail
- Same tools also show significant clustering effects!



Clustering from NN potential

- Green's function Monte Carlo (GFMC) using Argonne v18
- Taking each MC sample and rotating principal axis to z and averaging clearly produces 2 alpha clusters.

WIRINGA, PIEPER, CARLSON, AND PANDHARIPANDE

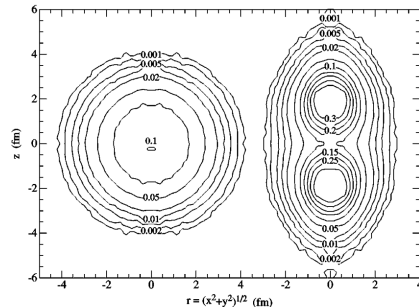


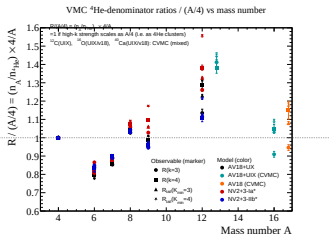
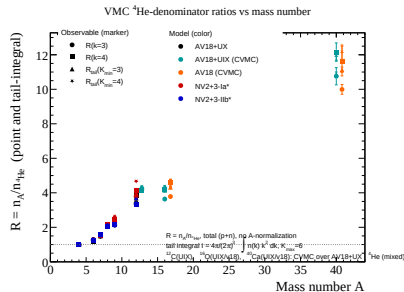
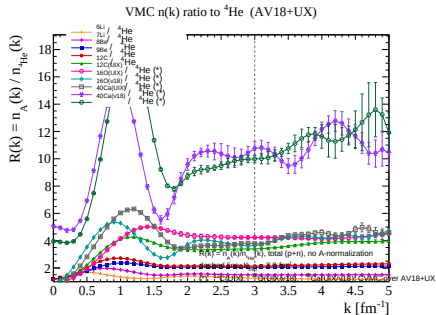
FIG. 15. Contours of constant density, plotted in cylindrical coordinates, for $^8\text{Be}(0^+)$. The left side is in the "laboratory" frame while the right side is in the intrinsic frame.

[Wiringa:2000gb]

Nucleon High-Momentum Tail Counts Clusters

Is clustering the phenomena responsible for SRCs and the EMC Effect?

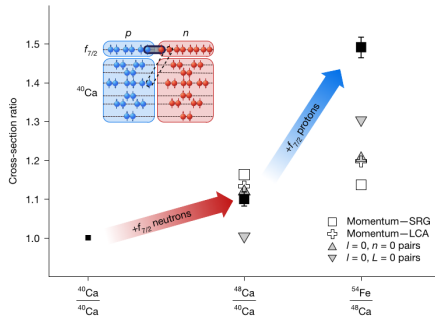
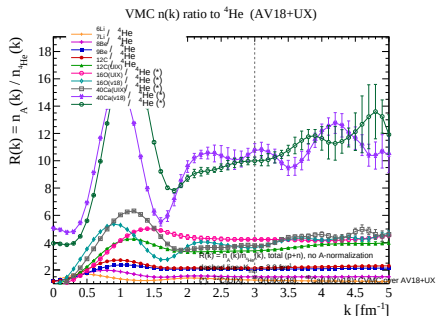
- Take the high momentum tail of the nucleon distributions
- Evaluate the ratio of light nuclei to ${}^4\text{He}$ at 3 fm^{-1} and 4 fm^{-1} or integrate over some range.



Nucleon High-Momentum Tail Counts Clusters

Is clustering the phenomena responsible for SRCs and the EMC Effect?

- Take the high momentum tail of the nucleon distributions
- Evaluate the ratio of light nuclei to ^4He at 3 fm^{-1} and 4 fm^{-1} or integrate over some range.



Nature, Vol 654, 18 June 2026

- "Nuclear shell structure governs short-range nucleon pairing"
- Rather than Neatly explains recent result from $(e,e'p)$ measurements

Other light nuclei $A > 4$

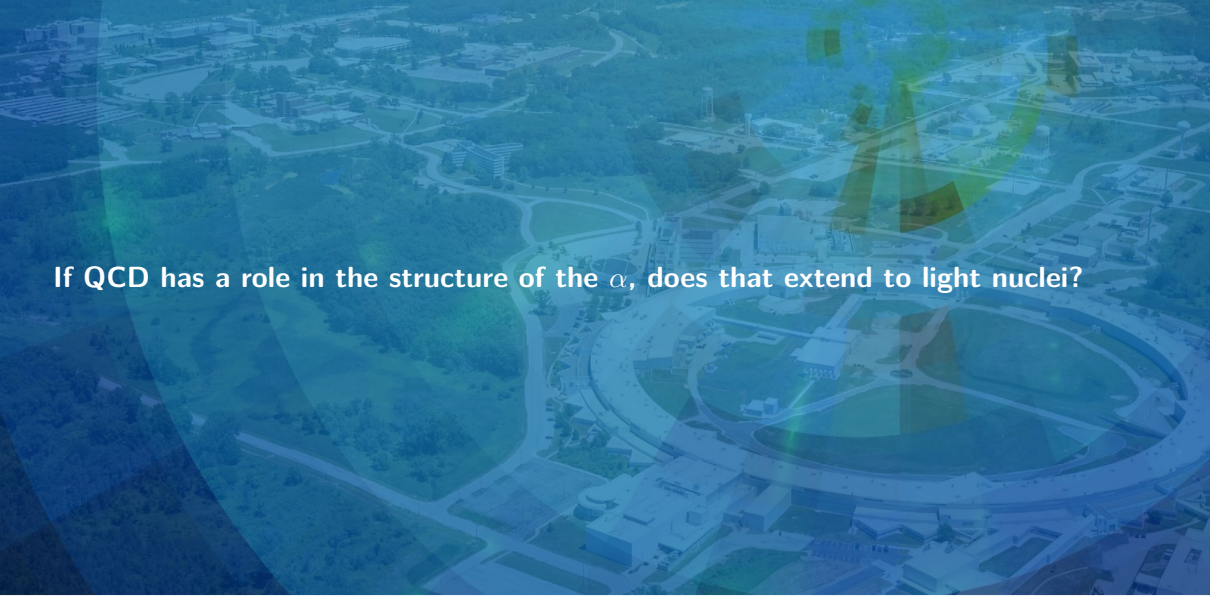
What is the role of QCD in these nuclei?

- Quenching of the Single-Particle Spectroscopic Strengths not explained by SRCs alone!
→ SRC important ingredient but only responsible for 10-15% at most
→ More than 20 year puzzle
- Origin of EMC Effect remains open question even after 40 years!
→ Its not caused by SRCs too.
- Is α clustering the real phenomena responsible for SRCs and the EMC effect ?

The importance of ${}^4\text{He}$

What is the role of QCD in the structure of ${}^4\text{He}$?

- EMC Effect and other nuclear effects
→ ${}^4\text{He}$ the **first iso-scaler** EMC ratio
→ Nearly the **full EMC-effect strength already present**
- First closed shell and ingredient in α cluster models
- Unique **QCD** hexa-diquark hidden color configuration (West, Brodsky) → Jumping off point for other nuclei (${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{20}\text{Ne}$,...)
- Critical ingredient in α clustering models → dual existence of algebraic models, clustering models and shell model



If QCD has a role in the structure of the α , does that extend to light nuclei?

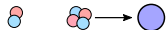


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" α EMC Effect"

Is there a nuclear modification of the α ?



^2H

^4He



^{12}C



^{16}O



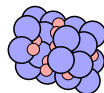
^{20}Ne



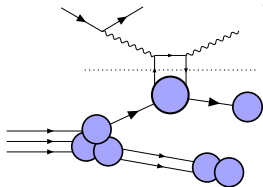
^{32}S



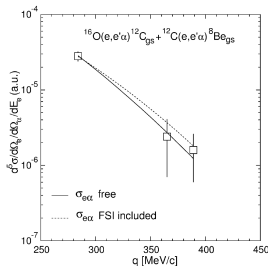
^{40}Ar



^{80}Kr



Parton level probes via
DVCS and DVMP



De Meyer, et.al., PLB 513 (2001) 258-264

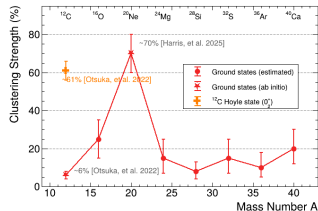
PWIA works pretty well for alpha knockout

- ALERT will measure **quark and gluon distribution** (at fixed x)
- Does the distributions of quarks and gluons in the α 's change in nuclei?
- What is the isospin dependence of this effect?
- How does ^{40}Ar compare to ^{40}Ca

Knockout of α s from light nuclei via Hard Exclusive Processes

New LOI intended for PAC55

- Critical targets: ^{12}C , ^{16}O , ^{20}Ne , Others: argon, krypton
- **Quasi-Elastic** scattering of α
 - *establish a baseline for knockout* testing if clustering strengths are observed
 - test FSI models (need help developing this), optical model might be useful here
 - Observable: ratio of cross sections with ^4He .
- DVCS on bound α
 - **Quark level probe** of bound system
 - Observable: ratio of BSA with ^4He .
- Coherent vector meson production on bound α
 - **Probes the gluon distribution** of bound system
 - Observable: ratio of cross sections with ^4He and/or shift in diffractive minimum (if it exists in the gluonic form factor of Helium)
- Does the clustering strength follow the theory predictions? Is there an enhancement for quarks/gluons relative to QE knockout.
- Similar knockout of deuteron too



Only ALERT is capable of doing such measurements.

New ideas and suggestions welcome.

LOI12-26-005: Alpha Knockout from Nuclei in Hard Exclusive Processes with ALERT

This could be an impactful experiment, exploring the existence of an α EMC effect in α conjugate nuclei, with straightforward experimental execution afforded by ALERT's proven capabilities and the proponent's well-chosen reaction channels of quasi-free, coherent DVCS, and vector meson production. The PAC encourages the proponents to develop a full proposal



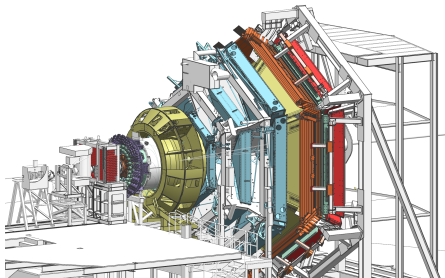
Experimental Setup



Argonne National Laboratory is a
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managed by UChicago Argonne, LLC.

Setup at JLab in Hall B: CLAS12 + ALERT

- Use CLAS12 to detect scattered electron, e' , and forward scattered hadrons.
- A low energy recoil tracker (ALERT) will detect the spectator recoil or coherently scattered nucleus



ALERT requirements

- Identify light ions: H, ^2H , ^3H , ^3He , and ^4He
 - Detect the **lowest momentum** possible (close to beamline)
 - Handle **high rates** (for CLAS12)
 - Survive high radiation environment
→ **high luminosity**
-
- ALERT replaced the CLAS12 silicon vertex tracker (SVT).

ALERT Detector

Hyperbolic Drift Chamber (HDC) and Time-of-Flight (TOF) Hodoscope

AHDC

- 2mm wire spacing
- $\pm 4^\circ$ stereo angle (hyperbolic shape)
- Constructed at Orsay (IJCLab)
- DREAM FE Readout

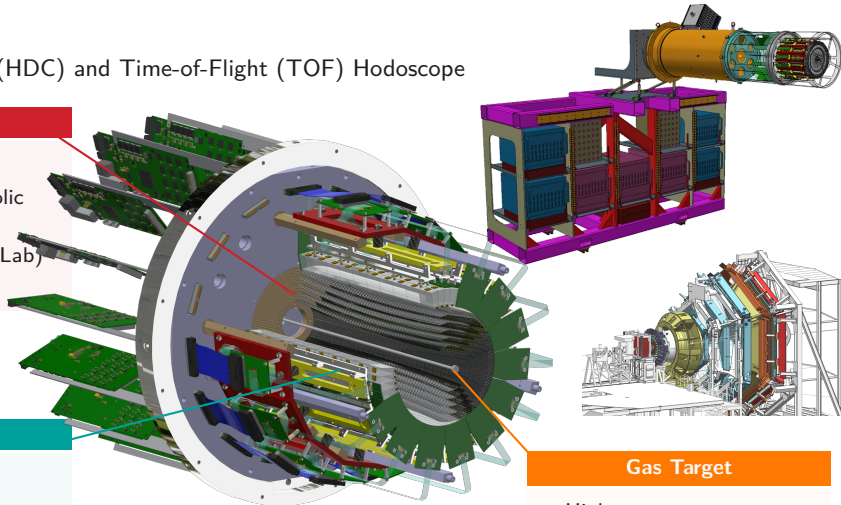
ATOF

- Time-of-Flight PID
- Small barrel of scintillators readout by SiPMs
- Constructed at Argonne

Experiment ran April - August 2025.

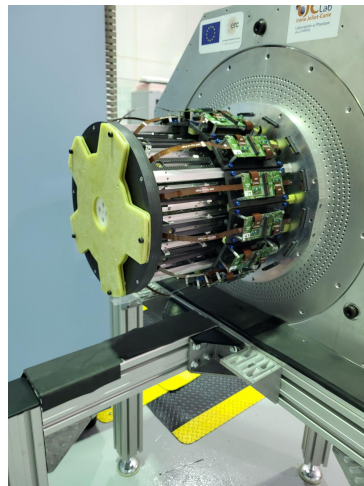
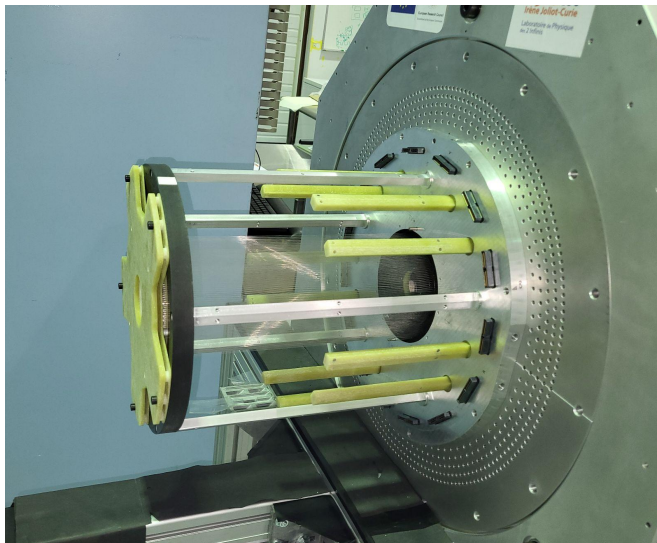
Gas Target

- High pressure straw target gases:
 ^1H , ^2H , and ^4He
- Managed by JLab's Hall-B detector support group

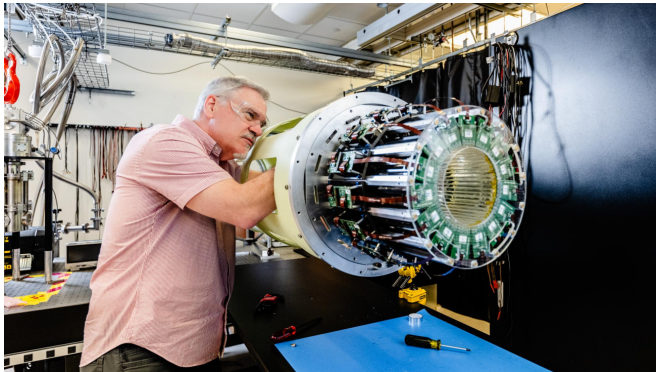


ALERT Detector

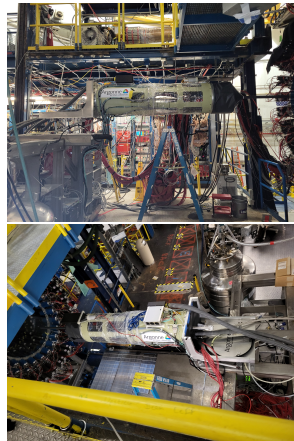
ALERT Drift Chamber and ATOF Modules

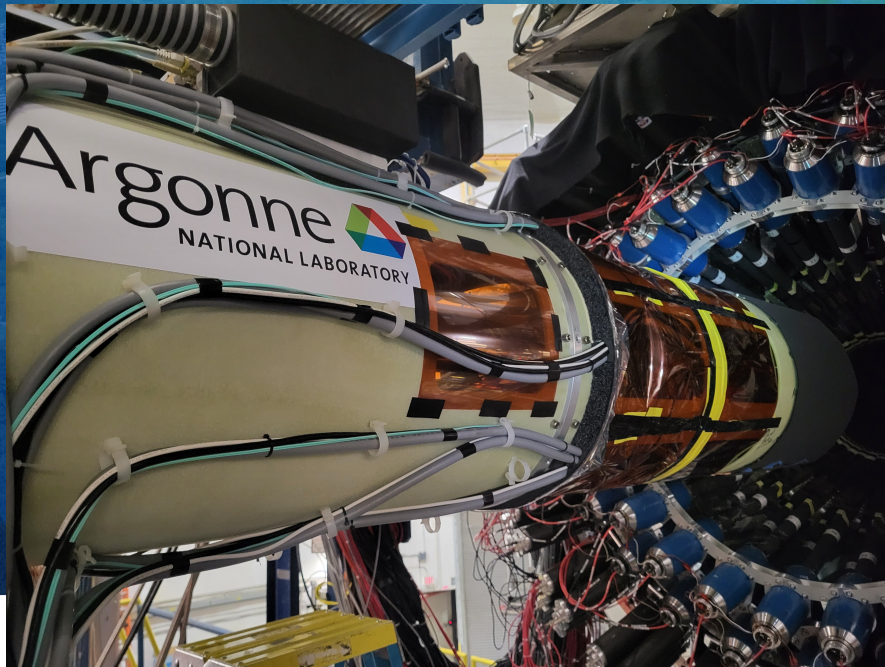


ALERT Detector



Mechanical design of ATOF and ALERT support by Tom O'Connor





ALERT Experimental Run

- Ran Hall B from April 2025 until August 2025
- Relatively smooth run: only 1 broken wire in AHDC and 1/2 ATOF module failure early on pulled wire and swapped with spare module at same time





A New Direction for JLab Experiments



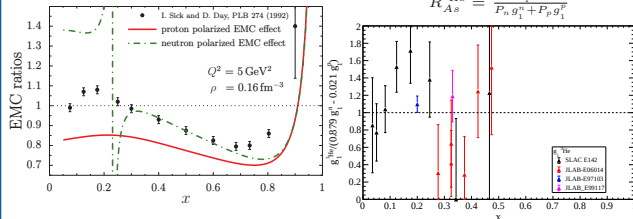
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Polarized EMC Effect in the Neutron

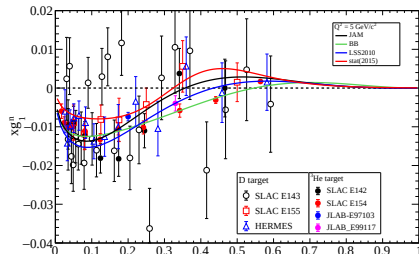
PAC54: Letter of Intent 12-26-002

- The EMC effect is in full effect already for $A=4$ (see previous slides)
→ Sizeable polarized EMC effect (pEMC) is predicted for the proton [Cloet:2006bq]
- $\bar{n}$ from ^2H **should be best** option for extracting g_1^n with minimal nuclear effects
→ is experimentally challenging due to large dilution and low polarization, $g_1^d \simeq g_1^p$
- ^3He dominates recent DIS data from polarized neutron target – better polarization from target technology advances
- First neutron pEMC ratio is $^3\text{He}/n^*$ – no predictions, mean field model does not apply for $A=3$
- First proton pEMC ratio requires polarized Tritium – also no predictions
- Upcoming Clas12 Experiment will use lithium target



Polarized EMC effect with ^3He needs better ^2H data

- Tag spectator proton: $\vec{e} + \vec{D} \rightarrow e' + p + X$
- Improve g_1^n to better constrain zero-crossing region
- $g_1^{^3\text{He}}$ sensitive to non-nucleonic degrees of freedom [Bissey:2001cw]
- Low moments more sensitive to Δ contributions to WF [Ethier:2013hna]



- JLab 12 GeV program will produce more precise polarized ^3He data.
- EIC will have spectator tagging with $\vec{D}$, however, new technology enables opportunities at JLab for active $\vec{D}$ targets.
- Support active target R&D leveraging technology advancements and existing facilities to enhance US nuclear science over next 5-10 years

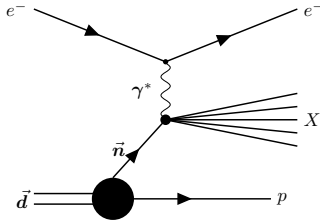
Physics with an Active Polarized Neutron Target

PAC54: Letter of Intent 12-26-002

$\vec{D}$ target with spectator proton tagging

- Scattered electron / proton coincidence **eliminates target dilution**
- ND₃ target **figure-of-merit improves by factor a of 50-100!**

$$f.o.m. \propto P_T^2 f^2$$



LOI12-26-002: Physics with an Active Polarized Neutron Target: The Neutron Polarized EMC Effect

The proposed active polarized neutron target could enable innovative studies of nucleon spin structure, including the polarized EMC effect. However, its feasibility depends on the successful development of the target system. The PAC encourages the proponents to reduce the remaining technical uncertainties before submitting a full proposal

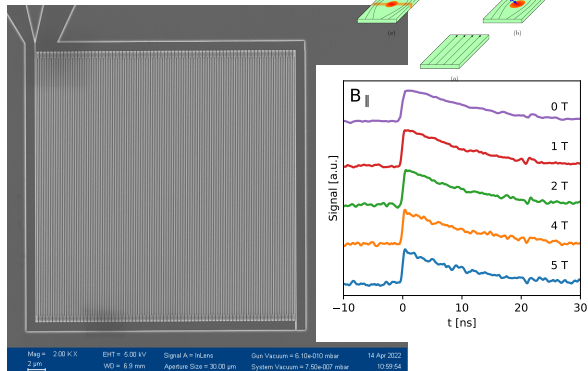
Possible physics with new target

- Polarized DIS with long and transverse targets
→ higher twists in bound vs quasi-free
- Polarized SIDIS — Sivers on the neutron
- Elastic FF ratio via polarization method
- Coherent polarized deuteron tagging recoiling ^2H (maybe)
- And more!

Superconducting Nanowire Active Polarized Target

Superconducting nanowire detectors

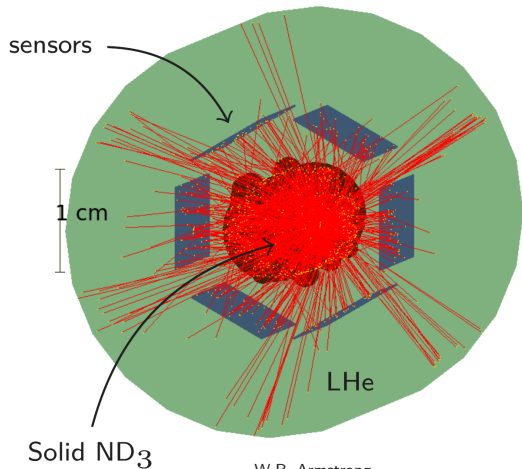
- Quantum sensor operates at $T < 5\text{K}$
- 10 nm NbN thin film, $T_c \simeq 14\text{K}$ [ionBeamNbN]
- Meandering geometry 100nm wide wire
- Current biased at roughly $20\text{ }\mu\text{A}$
- Nearly zero dark count rate
- SNSPD pixels $10 \times 10\text{ }\mu\text{m}$ to $100 \times 100\text{ }\mu\text{m}$
- Detect photons at high rate in strong magnetic field $> 5\text{ T}$ [Polakovic:2019wrh]
- Microelectronics R&D underway to develop high-channel count cryogenic readout ASIC for SNSPDs [braga:2022]



Superconducting Nanowire Active Polarized Target

Target Concept

- Polarized material (ND_3) surrounded by SNSPDs in LHe
- 5 T magnetic field traps recoil in target material
- Recoiling proton generates photons in polarized material and scint. in LHe

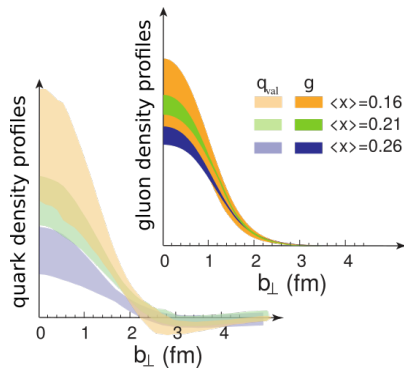


- Cryogenic photon detector solves problem of efficient photon detection in $< 1\text{K}$ cryostat
- R&D needed to shape polarized target material (ND_3) and design integrated superconducting nanowire sensor
- LHe is a great scintillator — detect unique recoil proton signal
- Other nuclei such as ^6Li could also be explored and would complement polarized light ions at the EIC
- Working on simulation for coherent deuteron tagging too.

Summary

- α clusters are key ingredient in nuclear structure — “standard candle” for QCD and nuclei
- α clustering likely key phenomena in explaining EMC effect and SRCs.
- Quark and gluon structure of ^4He can be accessed in hard exclusive processes
- Transverse spatial charge and gluonic matter distributions will be extracted as a function of x .
- ALERT provides key detection capability to produce clean datasets for coherent and incoherent DVCS/DVMP on ^4He and ^2H .
- Calibrations are maturing and we will soon be ready to look at physics for Run Group L.
- A successful run opens door to enhanced physics reach with coherent J/ψ production
- New ideas to use ALERT with nuclear targets to understand role of clustering in the partonic structure
- New detector technology (SNSPDs) can enhance existing polarized target technology for high impact tomography at JLab

before the EIC



Thank you to organizers for invitation to this workshop.

Special thanks to Ian Cloët, Bob Wiringa and Don Geesaman for entertaining these ideas and providing useful discussion, feedback and suggestions.

Thank you!

backup

Neutron DVCS: A sensitive probe for medium modifications

$$A_{LU,n}^{\sin\phi} \propto \text{Im} \left(F_1^n \mathcal{H}^n - \frac{t}{4M^2} F_2^n \mathcal{E}^n + \frac{x_B}{2} (F_1^n + F_2^n) \tilde{\mathcal{H}}^n \right)$$

Term by term breakdown:

- ① Suppressed by neutron Dirac FF
- ② Connected to Ji's sum rule and quark OAM through GPD
- ③ Related to Polarized EMC effect and Modified Form Factors

The Connection to Spin Structure Functions and Modified Form Factors:

The third term above is

$$\text{Im} \left((F_1 + F_2) \tilde{\mathcal{H}} \right) = G_M(t) \text{Im}(\tilde{\mathcal{H}}(\xi, \xi, t))$$

Forward Limit (at leading order):

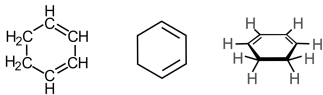
$$\begin{aligned} \text{Im}(\tilde{\mathcal{H}}(x, \xi, t)) &\rightarrow \tilde{H}(x, 0, 0) = g_1(x) \\ G_M(t) &\rightarrow \mu \end{aligned}$$

Ultrafast Pump-probe Spectroscopy

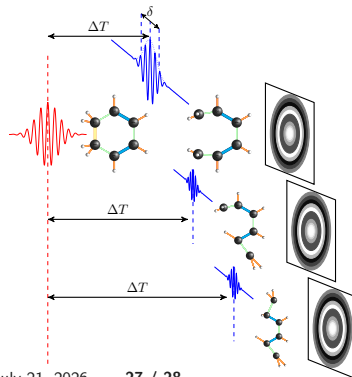
Analogy for tagged DVCS process

Molecular Dynamics

- Breakdown of Born-Oppenheimer approximation : Motion of atomic nuclei now matters
- The $\psi \neq \psi_e \times \psi_{\text{Nucleus}}$
- 1,3-cyclohexadiene molecular dynamics
- myoglobin "Protein Quakes"

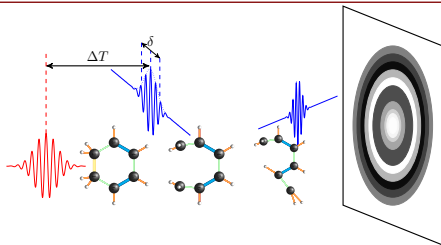


- Modeling the molecular dynamics and simulating diffractive patterns
- The initial state is modeled (i.e., when molecular bond broken)
- The final state is well known (since it is stable $\Delta T \rightarrow \infty$)



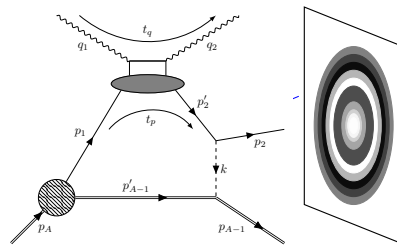
Ultrafast x ray pump-probe

- Breakdown of Born-Oppenheimer Approximation
- Initial state is modeled
- Final state after long time is known
- Studying the response for different parameters (Δt , λ , etc...) allows the **model of dynamics** to be better understood.
- Requires **high intensity** to resolve diffractive pattern



Incoherent Tagged DVCS

- Breakdown of PWIA
- Initial state is modeled
- Final state is fully measured (γ , p , $A-1$)
- Studying the response for different parameters (P_s , θ_s , ϕ_s , x , Q^2 , t , $\phi...$) allows model of the **nuclear dynamics** to be refined
- Requires **high luminosity** to resolve multidimensional FSI pattern

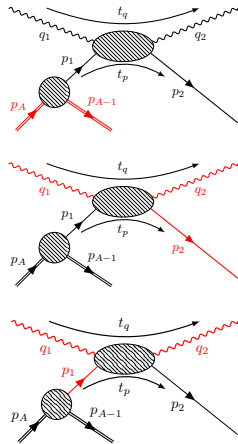


Fully Exclusive Incoherent DVCS

- Proton DVCS on ${}^4\text{He} \rightarrow$ easiest to measure full final state with ALERT
 ${}^4\text{He}(e, e'\gamma + {}^3\text{He}p)$
- Use this channel to study FSIs $\rightarrow$ apply to neutron channels.
- ${}^4\text{He}(e, e'\gamma + {}^3\text{He})n$
- ${}^2\text{H}(e, e'\gamma + p)n$

Looking to future

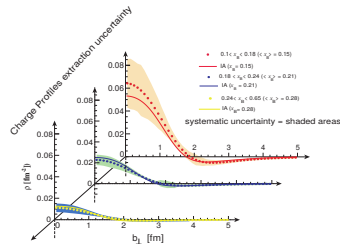
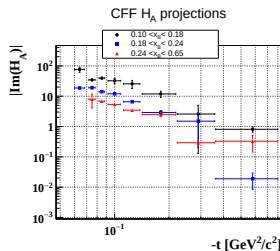
- Theory development moving closer to fully exclusive tagged incoherent DVCS on ${}^4\text{He}$.
- Need help working out best way to leverage kinematic redundancy to study FSIs.



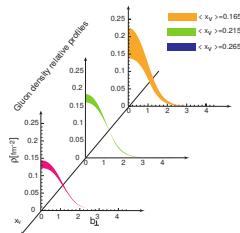
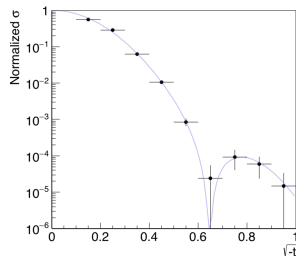
4He Transverse Quark and Gluon Densities

Coherent scattering on ^4He

DVCS
Charge profile

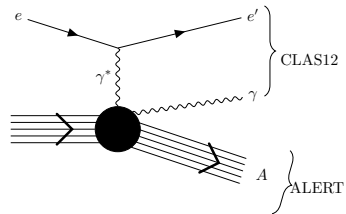


ϕ Production
Gluon profile



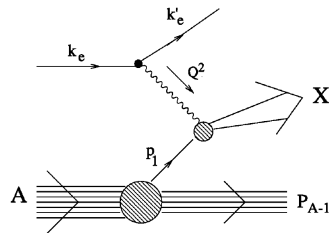
Experiment Measurements

- Coherent DVCS and DVMP: 4 dimensional data (x, Q^2, t, ϕ)
→ **Requires polarized beam** for BSA on ^4He target



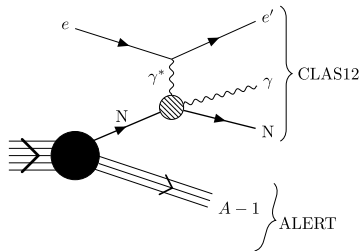
Experiment Measurements

- Coherent DVCS and DVMP: 4 dimensional data (x, Q^2, t, ϕ)
→ **Requires polarized beam** for BSA on ^4He target
- Tagged EMC: 4 dimensional data (x, Q^2, P_s, θ_s)
→ Uses ^2H and ^4He targets



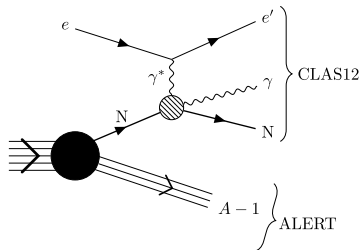
Experiment Measurements

- Coherent DVCS and DVMP: 4 dimensional data (x, Q^2, t, ϕ)
→ **Requires polarized beam** for BSA on ^4He target
- Tagged EMC: 4 dimensional data (x, Q^2, P_s, θ_s)
→ Uses ^2H and ^4He targets
- Incoherent DVCS: 6 dimensional data $(x, Q^2, t, \phi, P_s, \theta_s)$
→ **Requires polarized beam** for BSAs on ^2H and ^4He targets



Experiment Measurements

- Coherent DVCS and DVMP: 4 dimensional data (x, Q^2, t, ϕ)
→ **Requires polarized beam** for BSA on ^4He target
- Tagged EMC: 4 dimensional data (x, Q^2, P_s, θ_s)
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- Incoherent DVCS: 6 dimensional data $(x, Q^2, t, \phi, P_s, \theta_s)$
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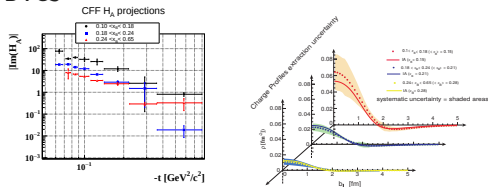


High beam polarization critically important for ALERT physics!

^4He Transverse Quark and Gluon Densities

Coherent scattering on ^4He

DVCS

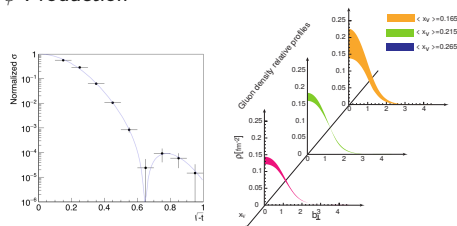


Quark and gluon radii apparent!

At $x > 0.2$ is the diffractive minimum at the same t value?

Is it washed out at low- x by the sea?

ϕ Production



$$|\langle H_g \rangle|(t) \propto \sqrt{\frac{d\sigma_L}{dt}(t - t_{min})} / \frac{d\sigma_L}{dt}(0)$$

$$\frac{d\sigma_L}{dt}(^4\text{He}) \propto |\langle H_g \rangle|^2$$

$$\frac{d\sigma_L}{dt} = \frac{1}{(\epsilon + 1/R)\Gamma(Q^2, x_B, E)} \frac{d^3\sigma}{dQ^2 dx_B dt}$$

$$W(\cos \theta_H) = \frac{3}{4} [(1 - r_{00}^{04}) + (3r_{00}^{04} - 1) \cos^2 \theta_H]$$

$$r_{00}^{04} = \frac{\epsilon R}{1 + \epsilon R}$$

Hadron Tomography

The basic strategies using electron beams

- Deep-Inelastic Scattering (DIS)
→ **1D** - Longitudinal parton momentum distribution
- Elastic Scattering
→ **2D** - Transverse charge distribution integrated over all x
- Deeply Virtual Compton Scattering (DVCS)
→ **3D** - Transverse **quark** distribution at fixed x
- Deeply Virtual Meson Production (DVMP)
→ **3D** - Transverse **gluon** distribution at fixed x

x = fraction of hadron's LC momentum carried by parton

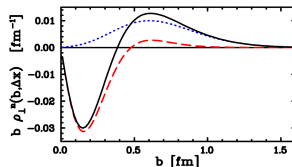
Key insight - G. Miller

FT is 2D (not 3D) yielding transverse charge distributions.

$$\rho_{\perp}(b_{\perp}) = \int \frac{d^2 q}{(2\pi)^2} e^{i\mathbf{q} \cdot \mathbf{b}_{\perp}} F_1(Q^2)$$

As $x \rightarrow 1$:

- proton - all momentum carried by u-quark at center (positive)
- neutron - all momentum carried by d-quark at center (negative)



Miller and Arrington, Phys.Rev. C78 (2008) 032201

neutron $x > 0.23$ is the **dashed**, $x < 0.23$ is **dotted**

Generalized Parton Correlation Function relations



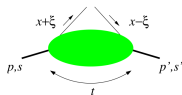
Generalized Parton Distributions

Quick Overview

GPDs are non-perturbative objects describing the probability (correlation) of:

- ① finding a parton with light-cone momentum fraction $(x + \xi)$ in a hadron N and
- ② putting the parton back into the hadron with LC momentum fraction $(x - \xi)$ and
- ③ while transferring some transverse momenta (t) to the hadron.

- $F^{q,g}(x, \xi, t)$ where $F \in (H, \tilde{H}, E, \tilde{E})$
- $-1 < x < 1$
- $0 < \xi < 1$ (time reversal invariance)
- $x_B = Q^2 / (2p \cdot q)$
- $Q^2 = -q^2$
- $\xi = x_B / (2 - x_B)$ in Bjorken limit



$$H_q(x, 0, 0) = q(x) \quad \sum_q e_q \int dx H_q(x, \xi, t) = F_1(t)$$

$$\tilde{H}_q(x, 0, 0) = \Delta q(x) \quad \sum_q e_q \int dx E_q(x, \xi, t) = F_2(t)$$

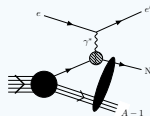
Impact parameter GPDs / Transverse distributions

$$q(x, \mathbf{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} H_q(x, 0, -\Delta_\perp^2) e^{-i\mathbf{b}_\perp \cdot \Delta_\perp}$$

$$\rho_\perp(b_\perp) = \int dx q(x, \mathbf{b}_\perp)$$

$$\xi > |x|$$

(2)→ and finding anti-quark with LC momentum fraction $(x - \xi)$



Behaves like distribution amplitude

Gravitational Form Factors

The **Gravitational Form Factors (GFFs)** parameterize the matrix elements of the **QCD energy momentum tensor**:

$$\langle p' | T_{\mu\nu}^q | p \rangle = \bar{u}(p') \left[A^q(t) \frac{P_\mu P_\nu}{M} + J^q(t) \frac{iP_{\{\mu} \sigma_{\nu\} \rho} \Delta_\rho}{2M} + D^{q,g}(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{4M} + \bar{c}^q(t) M g_{\mu\nu} \right] u(p) \quad (1)$$

- GFFs are $A^q(t)$, $J^q(t)$, $D^q(t)$, and $\bar{c}^q(t)$.
- A similar matrix element holds for gluons with the index replacement $q \rightarrow g$.
- The last GFF is constrained by $\sum_a \bar{c}^a(t) = 0$. In the limit
- $t \rightarrow 0$, $A(0) = 1$ as expected from energy and momentum conservation,
- $J(0) = 1/2$ for the nucleon.

Spin-0 Particles

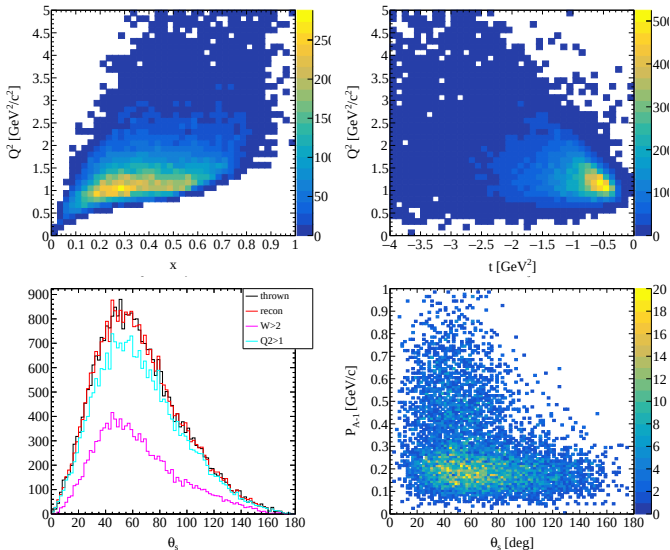
$$\langle p' | T_{\mu\nu}^{q,g} | p \rangle = 2A^{q,g}(t) P_\mu P_\nu + \frac{D^{q,g}(t)}{2} (\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2) + M^2 \bar{c}^{q,g}(t) g_{\mu\nu},$$

- Only two unconstrained GFFs $A(t)$ and $D(t)$.
- Similarly, GFFs are related to moments of the GPDs (Tanaka, 2018)
- $\int_{-1}^1 dx x H_2^q(x, \eta, t) = A^q(t) + \eta^2 D^q(t)$
where H_2^q is the leading twist quark GPD.

Measurements of the GPDs provides information encoded in the energy momentum tensor of QCD.

Tagged DVCS Kinematics

6-dimensional binned asymmetries: x , Q^2 , t , ϕ , p_s , θ_s



DVCS Observables

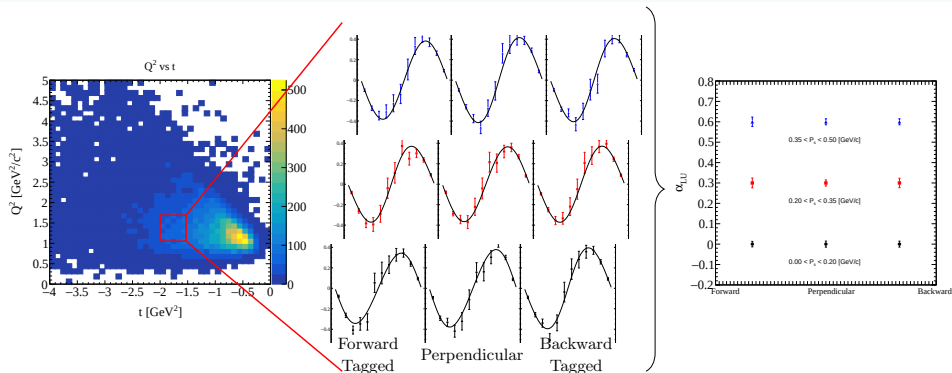
Beam Spin Asymmetries

We will measure the DVCS BSA

$$A_{LU}(\phi) = \frac{d\sigma^{\uparrow}(\phi) - d\sigma^{\downarrow}(\phi)}{d\sigma^{\uparrow}(\phi) + d\sigma^{\downarrow}(\phi)}$$

Extract the $\sin \phi$ harmonic

$$A_{LU}^{\sin \phi} = \frac{1}{\pi} \int_{\pi}^{\pi} d\phi \sin \phi A_{LU}(\phi) = \alpha_{LU}$$



Take bin x, Q^2, t, P_s, θ_s .

Extract harmonic content

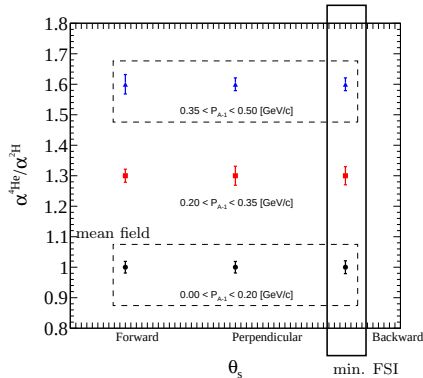
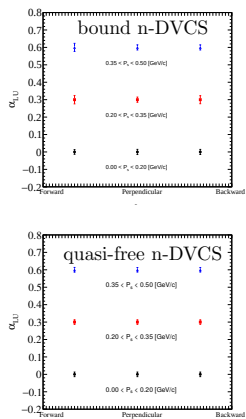
Now a 5 dimensional data set.

Off-forward EMC Effect Ratios

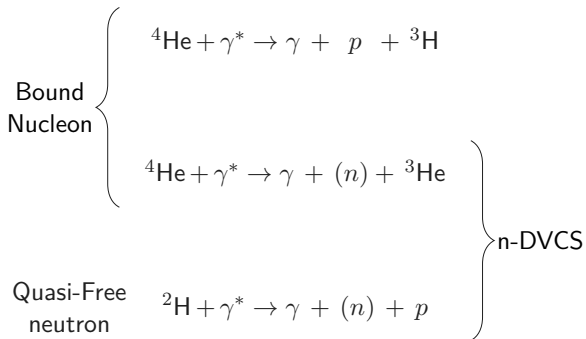
Neutron data from ^2H and ^4He combined to form ratio

$$R_{\alpha}^n = \frac{\alpha_{n^*}^{(^4\text{He})}}{\alpha_n^{(^2\text{H})}}$$

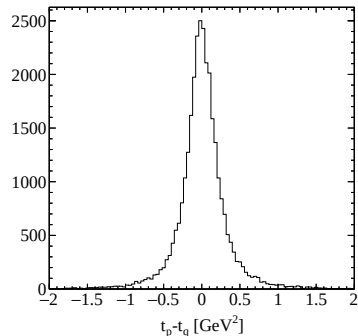
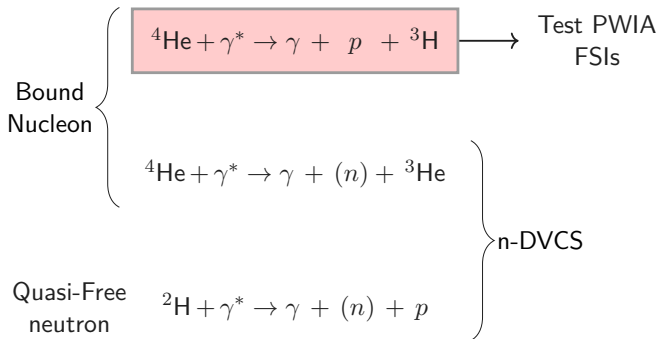
- Ratio is clean experimental quantity
- GPDs do not enter the analysis



Using p-DVCS to cleanly measure n-DVCS

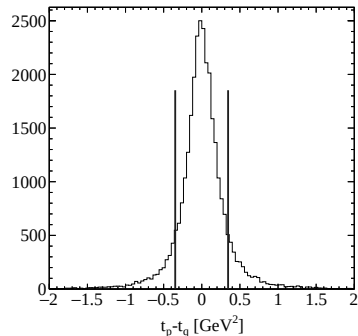
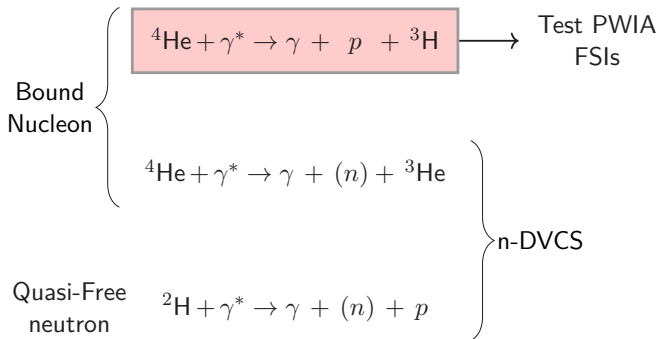


Using p-DVCS to cleanly measure n-DVCS



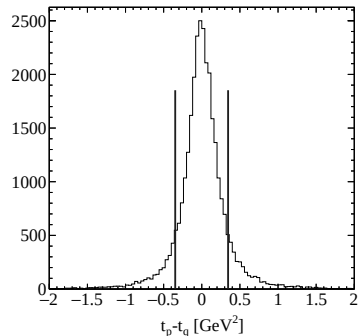
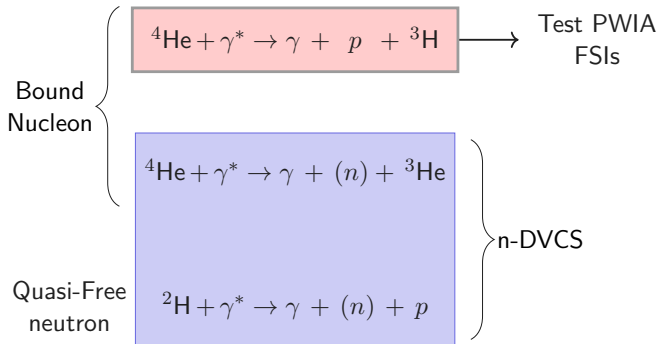
- Use pDVCS to study FSIs and test the PWIA.

Using p-DVCS to cleanly measure n-DVCS



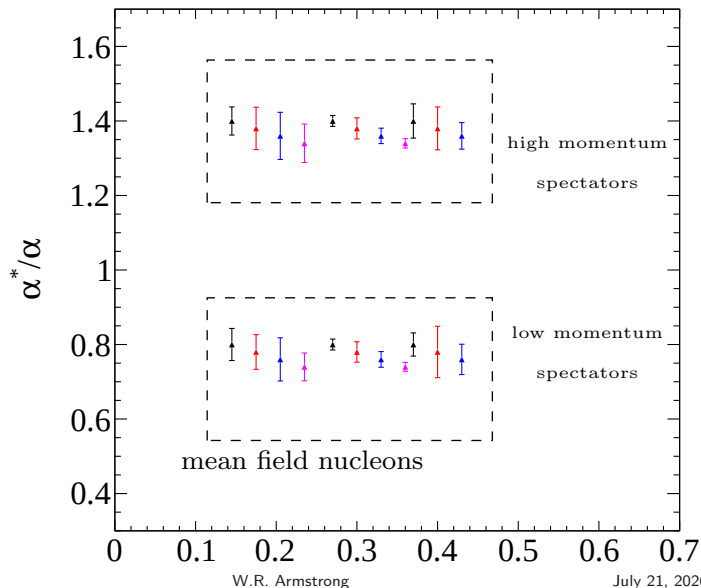
- Use pDVCS to study FSIs and test the PWIA.
- Identify kinematics without FSIs (or where amplitudes interfere to same effect)

Using p-DVCS to cleanly measure n-DVCS



- Use pDVCS to study FSIs and test the PWIA.
- Identify kinematics without FSIs (or where amplitudes interfere to same effect)
- Use charge symmetry $\rightarrow$ n-DVCS similarly free of FSI

Projected Results: Off-forward EMC Ratio



Colors indicate the different t bins which are shifted horizontally for clarity

Separated **mean field** nucleon EMC Effect and **SRC** nucleon EMC Effect

References I