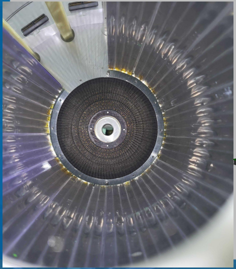
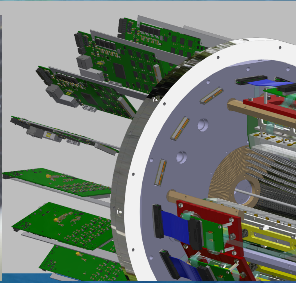
α Knockout via Hard Exclusive Processes with ALERT

LOI





Whitney Armstrong
Argonne National Laboratory

March 13, 2026

Outline

- **Introduction** and invitation to grow the science
- **Motivation**: What is the role **QCD** in light Nuclei?
  $\rightarrow$ The partonic structure of ^{4}He is the key ingredient
  $\rightarrow$ Quick review of ALERT physics program
- **The Structure of Light Nuclei**
  $\rightarrow$ What is going on in low energy NP?
  $\rightarrow$ The challenges of nuclear effects and QCD
  $\rightarrow$ Short range correlations are red herring in understanding the origins of EMC effect.
- **Proposed program** of knockout measurements
  $\rightarrow$ Utilized unique capabilities of ALERT and CLAS12 $\rightarrow$ Builds on Run Group L physics and Coherent J/ψ proposal

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And an invitation to help grow the physics program

- I am working developing a LOI for upcoming PAC and all are welcome to join
- New ideas for measurements to grow the physics program are welcome
- Any feed back is also appreciated!

This is new idea, so please bear with me

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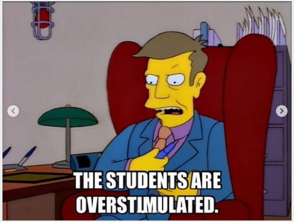

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- Looking for theory input to model FSIs and/or cross sections.
- Need to talk to low energy theorists, and
- Collaborate with QCD phenomenology, specifically modeling GPDs of free/bound ^{4}He

Motivation

What is the role of QCD in the Nucleus?

- **ALERT is comprehensive program** to study the partonic structure of ^{4}He and ^{2}H.
- We ought know something about partonic structure of ^{4}He and ^{2}H before going further.
- Isn't the Shell Model + partonic structure of nucleon "good enough"? ... No.

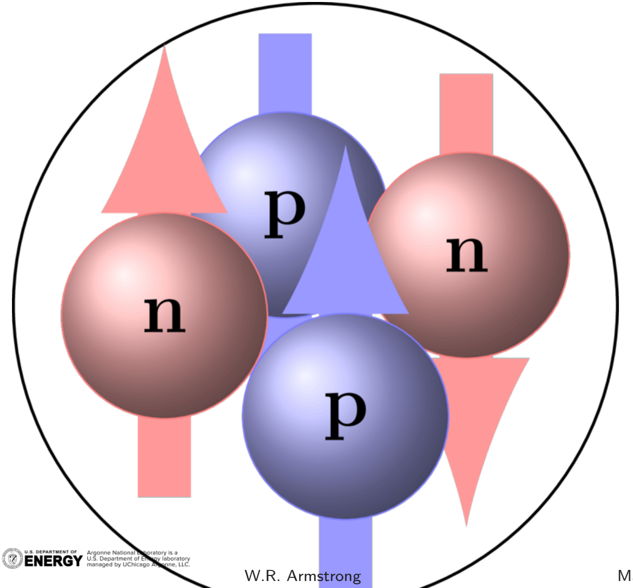
The importance of ^{4}He

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

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

The Partonic Structure of the alpha particle

A cartoon



- Two goggles to view the nucleus

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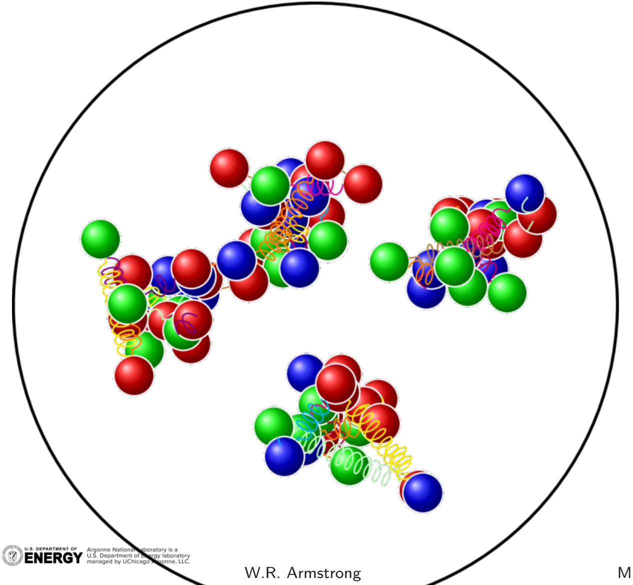

- Two goggles to view the nucleus
- Coherent DVCS to probe the charge profile

The Partonic Structure of the alpha particle

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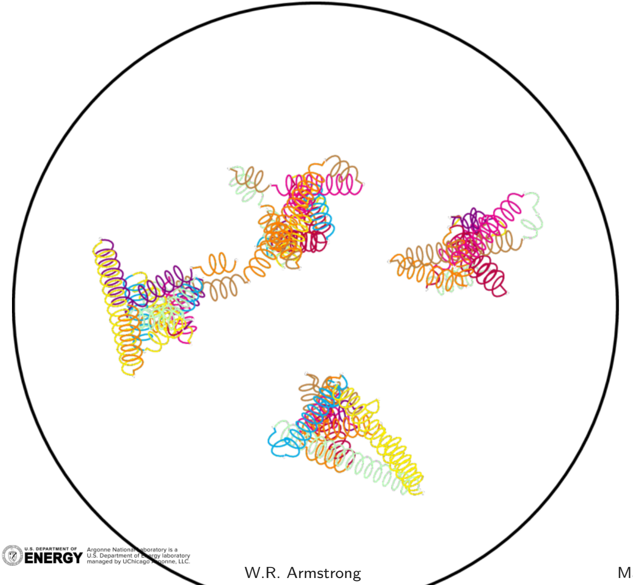

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- Coherent ϕ and J/ψ production to probe the gluon profile

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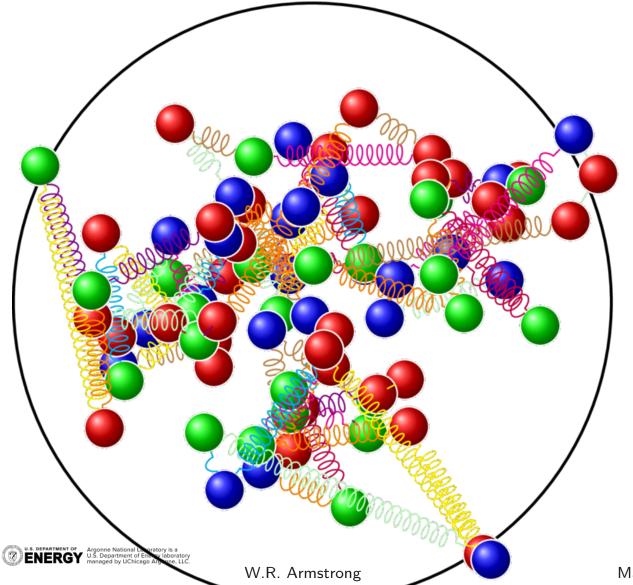


- Two goggles to view the nucleus
- Coherent DVCS to probe the charge profile
- Coherent ϕ and J/ψ production to probe the gluon profile
- How does the gluonic form factor compare to the charge?

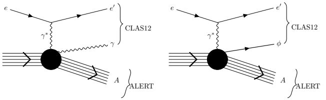
The ALERT Experiments

A comprehensive program to study nuclear effects

Coherent Processes on ^{4}He

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

Explores the partonic structure of ^{4}He



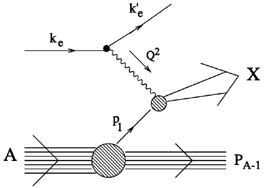
Coherent J/ψ production on ^{4}He

C2 conditionally approved by PAC 53. See talk at previous meeting for details. Coherent J/ψ measurement could merge into a run group with this proposal.

DIS on ^{4}He and ^{2}H : Tagged EMC Effect

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

Test FSI and rescaling models



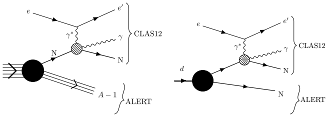
ALERT SRC

- SRC pair Factorization
  Mapping of transition (mean field → SRC)

Incoherent processes on ^{4}He and ^{2}H

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

Identify medium modified nucleons



And many more channels for free

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**."

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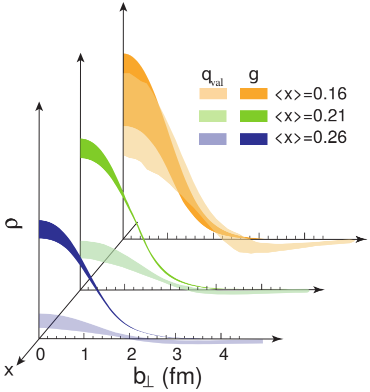
Note: this is roughly 2 years before the discovery of the neutron.

ALERT Nuclear GPD projected results



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

Structure of Light Nuclei

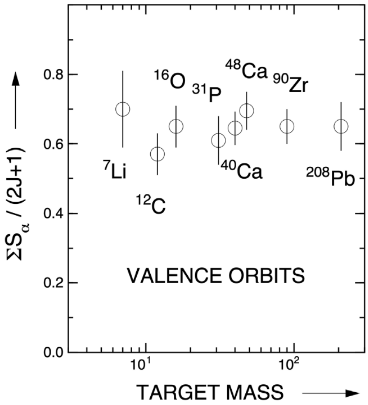
Shell Model

Quenching of the Single-Particle Spectroscopic Strengths

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

- 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 $S \approx 0.9$
  $\rightarrow$ 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



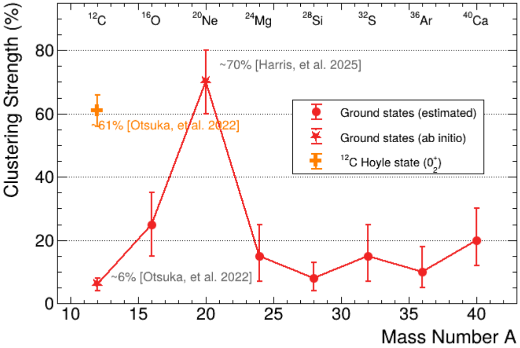
Quenching of Spectroscopic factors remains a puzzle and has been for 20 years.

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 $^{16}\text{O} + \alpha$.



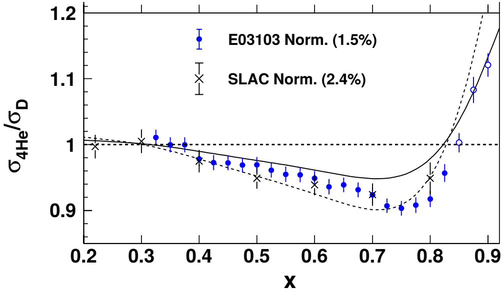
Lower energy NP has had a resurgence of interest in clustering, however, unsurprisingly they only consider **clusters of nucleons**...

Why the α?

Rough hadron sizes

π	0.64
p	0.84087 ± 0.00039
^{2}H	2.130 ± 0.010
^{3}H	1.755 ± 0.087
^{3}He	1.959 ± 0.034
^{4}He	1.676 ± 0.008
^{9}Be	2.519 ± 0.012
^{12}C	2.472 ± 0.015
^{13}C	2.440 ± 0.025

- Smaller charge radius than ^{3}He and ^{3}H
- Directly compare transverse quark and gluon distributions of a free and bound α



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

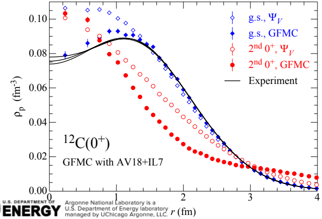
Alpha Clustering Models

- The nuclear shell model provides framework for understanding ground states and many excited states through individual nucleon configurations
  - Coexistence with clustering: alpha clustering are complementary rather than contradictory
  - Some nuclear states are better described by shell model (individual nucleon excitations)
  - Other states show clear alpha-cluster characteristics
- Cluster Shell Model (CSM) Hybrid approach of alpha particles with additional nucleons
  - Help understand transition between mean-field (shell model) and cluster descriptions in light nuclei
- Cluster Model
  - α spectroscopic factors – provides predictions for the probability of finding pre-formed alpha particles
  - Essential for interpreting $(e, e'\alpha)$ and similar measurements
- Antisymmetrized Molecular Dynamics (AMD)
- Fermionic Molecular Dynamics (FMD)
- Resonating Group Method (RGM)
- Generator Coordinate Method (GCM)
- Algebraic Cluster Model – Bijker, Iachello
- Supersolidity Model

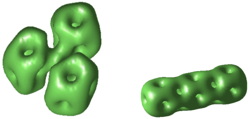
Nuclear Physics ~~at~~ before an EIC

Looking to the near future

- Can we measure the transverse quark and gluon distributions in ^{12}C?
  - Detecting the recoil ^{12}C is very difficult! $\rightarrow$ new detector technology and likely need to collider configuration
  - Probe the Hoyle state at the EIC via EM excitation
    $\rightarrow$ is *partonic structure* of the Hoyle state consistent with increased clustering strength
    $\rightarrow$ need to do at JLab because limited integrated luminosity at EIC.
- Can we measure the **quark and gluon distributions of the** α **particles inside ^{12}C?**
  - Detecting the recoil α is slightly easier and ALERT ideal detector
  - A new kind of nuclear EMC effect – αs are the new nucleons
- We can measure the coherent deuteron with ALERT. What about the coherent knockout of a deuteron in ^{4}He? (Non-nucleonic degrees of freedom, Hidden color)



Carlson, et al., Rev.Mod.Phys. 87 (2015) 1067



Karliner, et.al., J.Phys. G43 (2016) no.5, 055104

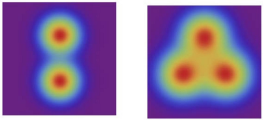
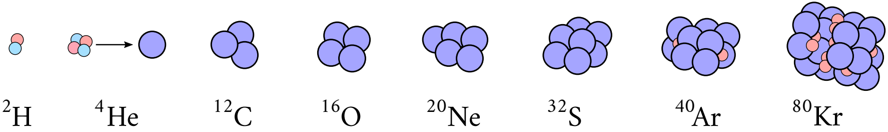


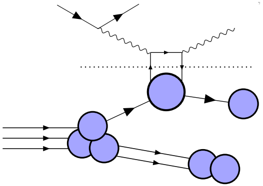
Figure 1 Charge density of ^{8}Be and ^{12}C in ACM.

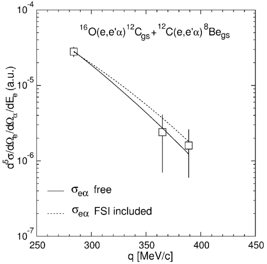
(Della Rocca, Iachello in progress)

"α EMC Effect"

Is the there a nuclear modification of the α?







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

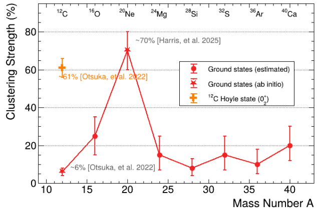
PWIA works pretty well for alpha knockout

- ALERT will measure **quark and gluon distribution** (at fixed x)
- Does the alpha quark and gluon radius change in nuclei?
- What is the isospin dependence of this effect?

Proposed Experimental Program

Knockout of αs via Hard Exclusive Processes

- Critical targets: ^{12}C, ^{16}O, ^{20}Ne, Others: argon, krypton
- Quasi-Elastic scattering of α
  $\rightarrow$ establish a nucleonic baseline for knockout
  $\rightarrow$ test FSI models (need help developing this), optical model might be useful here
  Observable: ratio of cross sections with ^{4}He.
- DVCS on bound α
  $\rightarrow$ **Quark level probe** of bound system
  Observable: ratio of BSA with ^{4}He.
- Coherent vector meson production on bound α
  $\rightarrow$ **Probes the gluon distribution** of bound system
  Observable: ratio of cross sections with ^{4}He 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 can be done



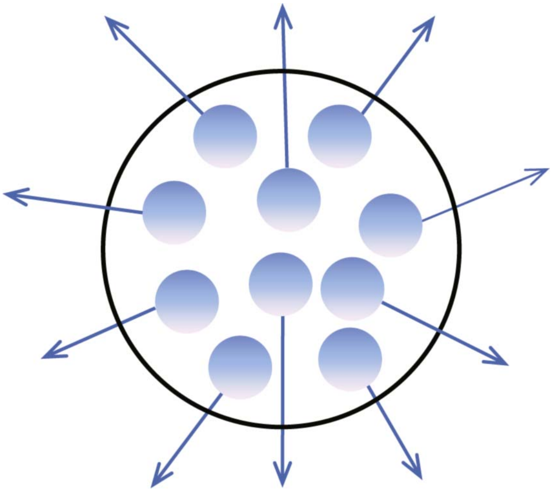
Only ALERT is capable of doing such measurements.

Summary

New LOI for PAC54

- Novel set of observables will shed light on the role of QCD in the structure of light nuclei
- Plenty of opportunity to interact with theorists low energy theory motivating non-trivial long range correlations $\rightarrow$ need to understand FSI and other corrections
- Additions and improvements welcome – please reach out if you are interested

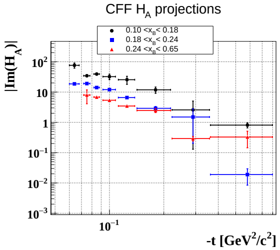
Coulomb explosion



4He Transverse Quark and Gluon Densities

Coherent scattering on ^{4}He

DVCS
Charge profile



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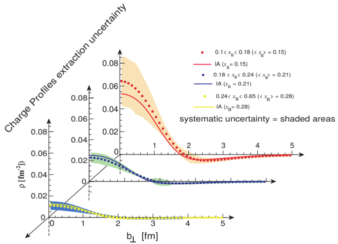
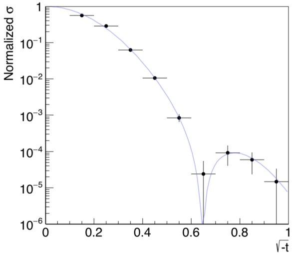


ϕ Production
Gluon profile



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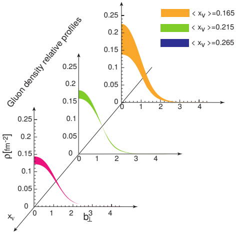

Gravitational Form Factors

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

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

- 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 $q \to g$.
- The last GFF is constrained by $\sum_a \bar{c}^a(t) = 0$. In the limit
- $t \to 0$, $A(0) = 1$ as expected from energy and momentum conservation,
- $J(0) = 1/2$ for the nucleon.

Spin-0 Particles

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

- Only two unconstrained GFFs $A(t)$ and $D(t)$.
- Similarly, GFFs are related to moments of the GPDs (Tanaka,2018)
- $\int_{-1}^{1} dx x H^q_2(x,\eta,t) = A^q(t) + \eta^2 D^q(t)$
  where H^q_2 is the leading twist quark GPD.

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

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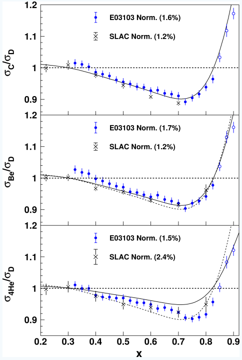
- First closed shell and ingredient in α cluster models
  $\rightarrow$ Jumping off point for other nuclei (^{12}C, ^{16}O, ^{20}Ne,...)
- $A = 4$ and fully closed shell
- Critical ingredient in α clustering models $\rightarrow$ dual existence of algebraic models, clustering models and shell model
- shell needed to generate Pauli forbidden states to generate α condensate

Nuclear Medium Effects

A quick glance

EMC Effect in DIS



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

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Significant even in ^{4}He!
Origin of effect remains unclear

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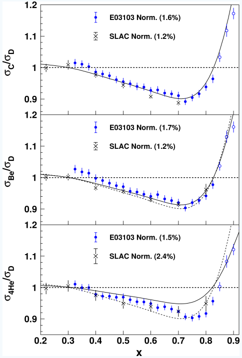

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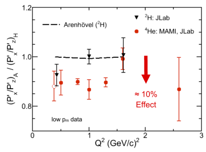
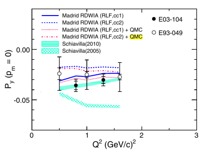
Polarization Transfer

$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E+E')}{2M}\tan\theta/2$$



P_y is a measure of FSI



Quasi-elastic knockout possibly observing medium modified form factors

^{2}H: B. Hu et al., PRC 73, 064004 (2006). ^{4} He: S. Dieterich et al., PLB 500, 47 (2001); S. S., et al., PRL 91, 052301 (2003); M. Paolone, et al., PRL 105, 0722001 (2010); S. Malace et al., PRL 106, 052501 (2011)

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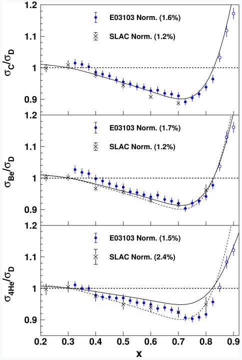

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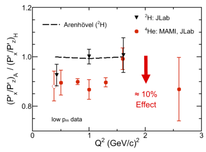

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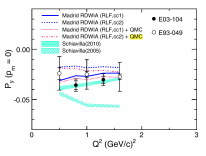

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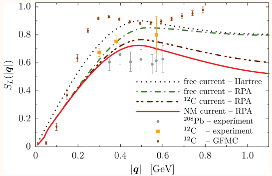
Coulomb Sum Rule

$$S_L(q) = \frac{1}{Z}\int_{\omega_{th}^+}^{\infty} d\omega \frac{R_L(q,\omega)}{|G_E^p|^2(Q^2)}$$



Cloet, et.al., Phys.Rev.Lett. 116 (2016)032701
Lovato, et.al., Phys.Rev.Lett. 111 (2013)092501

Observations of quenching the CSR remain contested.
New theory predictions will be put to the test with soon to be completed JLab experiment.
But nuclear effects persist, in the form of corrections, and possibly cloud conclusions.

The Challenge of Nuclear Effects

And attempts to overcome them

EMC Effect in DIS

Control initial state via **Spectator tagging** – separate mean field and SRC nucleons
FSI introduce model dependence

Partonic interpretation

Polarization Transfer

Induced polarization (P_y) provides feedback to FSI model FSIs

But only a **Nucleonic Observable**:
What is going on with the quarks and gluons?

Coulomb Sum Rule

Observations of quenching complicated by model dependent nuclear corrections

Nucleonic Interpretation

Model dependent corrections and FSIs are significant barrier to **unambiguously identifying any modification at the partonic level**.

Can we connect the **Partonic and Nucleonic** interpretations while systematically controlling final-state interactions and other model dependence?

A Low Energy Recoil Tracker (ALERT)

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?

$$
\begin{aligned}
|\langle H_g\rangle|(t) &\propto \sqrt{\frac{d\sigma_L}{dt}(t - t_{min}) \Big/ \frac{d\sigma_L}{dt}(0)} \\
\frac{d\sigma_L}{dt}(^4\mathrm{He}) &\propto |\langle H_g\rangle|^2 \\
\frac{d\sigma_L}{dt} &= \frac{1}{(\epsilon + 1/R)\Gamma(Q^2, x_B, E)} \frac{d^3\sigma}{dQ^2 dx_B dt} \\
W(\cos\theta_H) &= \frac{3}{4}\left[(1 - r^{04}_{00}) + (3r^{04}_{00} - 1)\cos^2\theta_H\right] \\
r^{04}_{00} &= \frac{\epsilon R}{1 + \epsilon R}
\end{aligned}
$$