Deeply Virtual Compton Scattering Measurement off Bound Protons in $^4$He

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- Physics Motivations
- Recent Results.
- Future Measurements.

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Most of what we know today about hadrons’ structure has come from the electromagnetic probes which give access to measure structure functions that quantify the properties of partons in hadrons.

- **Form Factors (FFs)**
  - Provide the charge and magnetization distributions inside a hadron.
  - Accessible via Elastic Scattering (ES).

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{exp}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Moti}} \frac{E'}{E} \left( \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2(\theta_c/2) \right)
\]

- **Parton Distribution Functions (PDFs)**
  - Provide partons longitudinal momentum distributions
  - Measurable via Deep Inelastic Scattering (DIS).

  - For nucleons, the unpolarized DIS cross section is parametrized by two PDFs: \( F_1,2(x) \), with

\[
F_1(x) = \frac{1}{2} \sum_a e_{q,a}^2 f_q(x) \quad \text{and} \quad F_2(x) = x \sum_a e_{q,a}^2 f_q(x)
\]

All seems well and working, until ...
EMC Effect

EMC effect: the modification of the PDF $F_2$ as a function of the longitudinal momentum fraction $x$ [0.3, 0.75] carried by the parton.

- Precise measurements at CERN, SLAC and JLab
  → Links with the nuclear properties, i.e. mass & density

- The origin of the EMC effect is still not fully understood, but possible explanations:
  → Modifications of the nucleons themselves
  → Effect of non-nucleonic degrees of freedom, e.g. pions exchange
  → Modifications from multi-nucleon effects (binding, N-N correlations, etc...)

Clear explanations may arise from measuring the nuclear modifications via measuring the Generalized Parton Distributions.
Generalized Parton Distributions

- Contain information on:
  → Correlation between quarks and anti-quarks
  → Correlation between longitudinal momentum and transverse spatial position of partons

- Can be accessed via hard exclusive processes such as deeply virtual Compton scattering (DVCS):

\[ \xi \simeq x_B / (2 - x_B) \quad x_B = Q^2 / 2 p.q \]
\[ t = (p - p')^2 = (q - q')^2 \]

* At leading order in \(1/Q^2\) (twist-2) and in the coupling constant of QCD (\(\alpha_s\)).

- Experimentally, the measured photon-electroproduction cross section \((ep \rightarrow ep\gamma)\) is:

\[ d\sigma \propto |\tau_{BH}|^2 + (\tau_{DVCS}^* \tau_{BH} + \tau_{BH}^* \tau_{DVCS}) + |\tau_{DVCS}|^2 \]

- The DVCS signal is enhanced by the interference with BH.
Two DVCS channels are accessible with nuclear targets:

◊ **Coherent DVCS:** $e^- A \rightarrow e^- A \gamma$
  → Study the partonic structure of the nucleus.
  → One chiral-even GPD ($H_A(x, \xi, t)$) is needed to parametrize the structure of the spinless nuclei ($^4$He, $^{12}$C, $^{16}$O, ...).

◊ **Incoherent DVCS:** $e^- A \rightarrow e^- N \gamma \ X$
  → The nucleus breaks and the DVCS takes place on a nucleon.
  → Study the partonic structure of the bound nucleons (4 chiral-even GPDs are needed to parametrize their structure).
DVCS Observables

The four-fold cross section for the process $e^- N \rightarrow e^- N \gamma$:

$$\frac{d\sigma}{dx_B dy d|\Delta^2| d\phi} = \frac{\alpha^3 x_B y}{16 \pi^2 Q^2 \sqrt{1 + e^2}} \frac{|T_{BH}|^2 + |T_{DVCS}|^2 + I}{e^6}$$

The BH term $|T_{BH}|^2$, squared DVCS amplitude $|T_{DVCS}|^2$, and interference term $I$ read:

$$|T_{BH}|^2 = \frac{e^6}{x_B y^2 (1 + e^2) \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n \phi) + s_1^{BH} \sin(\phi) \right\},$$

$$|T_{DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{DVCS} + \sum_{n=1}^{2} [c_n^{DVCS} \cos(n \phi) + s_n^{DVCS} \sin(n \phi)] \right\},$$

$$I = \frac{\pm e^6}{x_B y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^I + \sum_{n=1}^{3} [c_n^I \cos(n \phi) + s_n^I \sin(n \phi)] \right\}.$$

Beam-spin asymmetry ($A_{LU}(\phi)$) : (+/- beam helicity)

$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B} \frac{N^+ - N^-}{N^+ + N^-}$$

$$A_{LU}^{\sin \phi} \propto \text{Im}(F_1 H - \frac{t}{4M^2} F_2 E + \frac{x_B}{2} (F_1 + F_2) \tilde{H})$$
Proton Tomography via DVCS

• Local fit of all the JLab data
  – Jlab Hall A (σ, Δσ)
  – CLAS (σ, Δσ, ITSA, DSA)

• Enough coverage to explore the \( t \) and \( x^B \) (→ξ) dependence
  of \( H_{lm} \).

• Obtaining the tomography of the proton
  – Represented is the mean square charge radius of the proton for slices of \( x \).

• The nucleon size is shrinking with \( x \).

Theoretical Predictions of the EMC in $^4$He

On-shell calculations:

(1) Impulse approximation

$$GPD^{^4He}(x, \xi, t) = \sum (\text{free p and n GPDs})^* F_{^4He}(t)$$

(2) Medium modifications:

$$H_q/p^* (x, \xi, t, Q^2) = \frac{F_{p^*}^q (t)}{F_{p^*}^q (t)} H_q (x, \xi, t, Q^2),$$

$$H^A (x, \xi, t) = \sum \int \frac{d^2 p_1 dY}{(2\pi)^3} \frac{1}{A - Y} A^A (p_1^2, p^2)$$

$$\times \sqrt{\frac{Y - \xi}{Y} \left[ H_{\text{off}}^N \left( \frac{x}{Y}, \frac{-\xi}{Y}, p_1^2, t \right) - \frac{1}{4(1 - \xi/Y)} E_{\text{off}}^N \left( \frac{x}{Y}, \frac{-\xi}{Y}, p_1^2, t \right) \right]}$$

Nucleus = bound nucleons + nuclear binding effects


Off-shell calculations:

$$e(^4He, e' \gamma pX)$$

[S. Liuti, K. Taneja, PRC 72 (2005) 034902]
CLAS - E08-024 Experimental Setup

\[ e^- \, ^4\text{He} \rightarrow e^- \,(^4\text{He}/pX) \, \gamma \]

- **CLAS:**
  - Superconducting Torus magnet.
  - 6 independent sectors:
    - DCs track charged particles.
    - CCs separate e\(^-\)/\(\pi^-\).
    - TOF Counters identify hadrons.
    - ECs detect γ, e\(^-\) and n [8\(^\circ\), 45\(^\circ\)].

- **IC:** Improves γ detection acceptance [4\(^\circ\), 14\(^\circ\)].

- **RTPC:** Detects low energy nuclear recoils.

- **Solenoid:**
  - Shields the detectors from Møller electrons.
  - Enables tracking in the RTPC.

- **Target:** \(^4\text{He} \) gas @ 6 atm, 293 K

Beam polarization (\(P_B\)) = 83%
Incoherent DVCS Selection & Asymmetries

1. We select events which have:
   ◊ Events with:
     - Only one good electron in CLAS
     - At least one high-energy photon ($E_\gamma > 2$ GeV)
     - Only one proton in CLAS.
   ◊ $Q^2 > 1$ GeV$^2$ and $W > 2$ GeV/c$^2$
   ◊ Exclusivity cuts (3 sigmas).

2. $\pi^0$ background subtraction (contaminations ~ 8 - 11%)

3. Beam-spin asymmetry:
   \[
   A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B} \frac{N^+ - N^-}{N^+ + N^-}
   \]
   \[
   A_{LU} \propto \alpha(\phi)\{F_1H + \xi(F_1 + F_2)\tilde{H} + \kappa F_2E\}
   \]
   - 2D bins due to limited statistics
   - Fits in the form: $\frac{\alpha \sin(\phi)}{1 + \beta \cos(\phi)}$

[S. Liuti and K. Taneja. PRC 72 (2005) 032201]
We comparing our measured incoherent asymmetries to the asymmetries measured in CLAS DVCS experiment on free proton

→ Incoherent/proton is suppressed compared to both the PWIA and the nuclear spectral function calculations.

[S. Liuti and K. Taneja. PRC 72 (2005) 032201]
[V. Guezy et al., PRC 78 (2008) 025211]
CLAS12-ALERT Program

- **CLAS–E08-024 experiment:**
  - 2D binning due to limited statistics
  - Limited phase-space.

- **CLAS12 experimental apparatus:**
  - High luminosity & large acceptance.
  - Measurements of deeply virtual exclusive, semi-inclusive, and inclusive processes.

- **We proposed to measure with CLAS12:**
  - Partonic Structure of Light Nuclei.
  - Tagged EMC Measurements on Light Nuclei.
  - Spectator-Tagged DVCS Off Light Nuclei.
  - Other Physics Opportunities.

- The momentum threshold of the CLAS12 inner tracker is **too high** to be used for our measurements.

- **Proposed experimental setup:**
  - CLAS12 forward detectors.
  - A Low Energy Recoil Tracker (ALERT) in place of CLAS12 Central detector (SVT & MVT).

- **CLAS12-ALERT** setup will allow **higher statistics and wider kinematical coverage.**
Partonic Structure of Light Nuclei (PR12-17-012)

- Map the fundamental structure of nuclei within the GPD framework
- Compare the quark and gluon 3D structure of the Helium nucleus

\[ \text{e}^{4}\text{He} \rightarrow \text{e}^{'4}\text{He} \gamma: \]
- Fully model independent extraction of \( H_A \) CFF from fitting the BSA.
- Fourier transform of \( \text{Im}(H_A) \) at \( \xi=0 \) gives probability density of quarks as function of \( x \) and impact parameter.
\[
\rho(x,0,b) = \int_{0}^{\infty} J_0(b\sqrt{t}) H_A(x,0,t) \frac{\sqrt{t}}{2\pi} d\sqrt{t}
\]

\( \text{e}^{4}\text{He} \rightarrow \text{e}^{'4}\text{He} \phi: \)
- Detect recoil \( ^4\text{He} \), e, and \( K^+ \) (missing \( K^- \))
- The longitudinal cross-section will be extracted from the angular distribution of the kaon decay in the phi helicity frame.
- Gluon density extraction:
\[
\rho_g(x,0,b) \rightarrow \int_{0}^{\infty} J_0(b\sqrt{t}) \frac{\sqrt{d\sigma_L}}{2\pi} d\sqrt{t}
\]

Requested PAC days: 20 days at \( 3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) + 10 days at \( 6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) + (5 Com.)
DIS, with tagged spectator, provides access to new variables and explore links between EMC effect and intranuclear dynamics.

- **Tagged DIS provides test for:**
  - FSI models over wide momentum and angle ranges.
  - EMC effect models: \( x/Q^2 \) scaling.
  - \( d/u \) ratio changes in nuclear medium.

- **Comparing D to \(^4\)He is particularly interesting:**
  - It conserves the nucleus isospin symmetry.
  - \(^4\)He is a light nucleus with a sizable EMC effect.
  - The two rescaling effects are cleanly separated by the comparison between the two nuclei.
  - They complement each other in spectator momentum coverage.

- **40 (+5) PAC days**
  - 20 on \(^4\)He (3x10\(^{34}\) cm\(^{-2}\)s\(^{-1}\)).
  - 20 on D 3x10\(^{34}\) cm\(^{-2}\)s\(^{-1}\)).

\[ R(P_{A-1}) = \frac{\sigma(D(e,e'p)X)}{\sigma(^4\text{He}(e,e'\alpha)\alpha)X} \]

\[ \theta_{A-1} = 180^\circ \]
Spectator-Tagged DVCS On Light Nuclei (PR12-17-012B)

- Probe connection between partonic and nucleonic interpretations via DVCS
- Partonic interpretation and in-medium hadron tomography of nucleons
- Study of Off-Forward EMC effect in incoherent DVCS

- **Bound-p DVCS:**
  - Fully detected ep\(^3\)H final state, provides unique opportunity to study FSI, test PWIA, identify kinematics with small/large FSI.

- **Bound neutron in \(^4\)He/quasi-free in \(^2\)H:**
  - e\(^3\)He(n) / ep(n) final states (p detection down to ~70 MeV, \(^3\)He to ~120 MeV).
  - Six-dimensional binning (\(Q^2, x_B, t, \varphi, p_s, \theta_s\)).

- **No additional PAC days**
Other Physics Opportunities (PR12-17-012C)

The three main proposals of the ALERT run group is only a fraction of the physics that can be achieved by successfully analyzing the ALERT run group data.

- **π⁰ production off ^4He**
  - Coherent and incoherent production.
  - Measure BSA, leading to chiral-odd CFFs.
  - Also as a DVCS background.

- **Coherent DVCS off D**
  - Access to new GPDs, H₃, with relationships to deuteron charge form factors.

- **Coherent DVMP off D**
  - π⁰, φ, ω and ρ mesons.

- **Semi-inclusive reaction p(e,e'p)X**
  - Study the π⁰ cloud of the proton.

- **D(e, e'ppₛ)X**
  - Study the π⁻ cloud of the neutron.

- **More Physics:**
  - Helium GPDs beyond the DVCS at leading order and leading twist.
  - Tagged nuclear form factors measurements.
  - The role of Δs in short-range correlations.
  - The role of the final state interaction in hadronization and medium modified fragmentation functions.
  - The medium modification of the transverse momentum dependent parton distributions.
  - ... and more
Several decades of elastic and DIS experiments on hadrons have provided one-dimensional views of hadrons’ structure.

We are now exploring the 3D structure of nucleons within the GPD framework
→ Fifteen years of successful experiments at JLab.
→ Accumulated a wide array of proton data.
→ The first tomography was extracted.

The first exclusive measurement of DVCS off $^4$He:
→ The bound proton has shown a different trend in the asymmetries compared to the free one indicating the medium modifications of the GPDs and opening up new opportunities to study the EMC effect.
→ We extracted EMC ratios and compared them to theoretical predictions.

CLAS12-ALERT will provide wider kinematical coverage and better statistics that will:
→ Allow performing $^4$He tomography in terms of quarks and gluons.
→ Allow comparing the gluon radius to the charge radius.
→ Use tagging methods to study EMC effect via DIS measurements.
→ Use Tagged-DVCS techniques to study in-medium nucleon interpretations.
→ Reinforce EIC physics program by proving their usefulness in the valence region.
Coherent $A_{LU}$ and CFFs

→ Same $A_{LU}$ sign as HERMES.
→ Asymmetries are in agreement with the available models.
→ The first ever experimental extraction of the real and the imaginary parts of the $^4\text{He}$ CFF. Compatible with the calculations.
→ More precise extraction of $\text{Im}(H_A)$.


[S. Liuti and K. Taneja. PRC 72 (2005) 032201]
[HERMES: A. Airapetian, et al., PRC 81, 035202 (2010)]
1. We select events which have:

◊ Events with:
  - Only one good electron in CLAS
  - At least one high-energy photon \((E_{\gamma} > 2 \text{ GeV})\)
  - Only one proton in CLAS.

◊ \(Q^2 > 1 \text{ GeV}^2\)
◊ Exclusivity cuts (3 sigmas).

- In Black, incoherent events before all exclusivity cuts.
- In shaded gray, incoherent DVCS events which pass all the other exclusivity cuts except the one on the quantity itself.

2. \(\pi^0\) background subtraction based on data and simulation (contaminations \(\sim 8 - 11\%\))
Incoherent Beam-Spin Asymmetry Fitting

\[ A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B} \frac{N^+ - N^-}{N^+ + N^-} \]

\[ A_{LU} \propto \alpha(\phi)\{F_1H + \xi(F_1 + F_2)\tilde{H} + \kappa F_2E\} \]

- 2D bins due to limited statistics
- Systematic uncertainties (~10%) dominated by exclusivity cuts (~6%) and large phi bining (~7%)
- Fits in the form: \[ \frac{\alpha \sin(\phi)}{1 + \beta \cos(\phi)} \]

- **bins in t’**: smeared due to radiative effects
- **bins in t**: smeared due to Fermi motion
Fermi Motion Effect on the Incoherent Channel

- Typically $t = t'$
- $t$ suffers from Fermi motion
- $t'$ suffers from radiative effects

Evaluate the size radiative effects from free proton DVCS data (E1-DVCS1&2)

 Corrections for radiative effects
Fermi Motion Effect on the Incoherent Channel

- Induced systematic uncertainties based on free proton data

- EG6 incoherent DVCS $A_{LU}$ @ $\varphi = 90^\circ$
Free Proton $A_{LU}$ Fitting

(Q$^2 = 1.16, x_B = 0.13$)

(Q$^2 = 1.36, x_B = 0.17$)

(Q$^2 = 1.56, x_B = 0.16$)

(Q$^2 = 1.70, x_B = 0.25$)

(Q$^2 = 1.95, x_B = 0.25$)

(Q$^2 = 2.20, x_B = 0.25$)

(Q$^2 = 2.01, x_B = 0.34$)

(Q$^2 = 2.33, x_B = 0.35$)

(Q$^2 = 2.59, x_B = 0.35$)
**ALERT Detector**

- **Cylindrical target:**
  - 30 cm long
  - 6 mm outer radius.
  - Target at 3 atm pressure.
  - 25μm target wall (Kapton).

- **A clear space filled with helium** to reduce secondary scattering from the high rate Moller electrons ($R_{\text{out}} = 30$ mm).

- **Hyperbolic drift chamber** ($32 \text{ mm} < R < 85 \text{ mm}$):
  - Will detect the trajectory of the low energy nuclear recoils.
  - 8 circular layers of 2mm hexagonal cells.
  - 10° stereo-angle to give z-resolution.
  - Total of 2600 wires, < 600 kg tension.
  - Maximum drift time ~ 250 ns, will be included in the trigger.

- **Two rings of plastic scintillators** (Total thickness of 20 mm, SIPMs directly attached):
  - TOF (< 150 ps resolution) and deposited energy measurements.

  
  → **Separate protons, deuterium, tritium, alpha, $^3$He**