Study of Few-Nucleon Systems with the CLAS

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Outline

• Introduction.

• Studies of Short-Range Correlations in Nuclei.

• Studies of Three-Body Mechanisms in Photodisintegration.

• Studies of Onset of Scaling of Invariant Cross Sections of Exclusive Processes.

• Summary.
Thomas Jefferson
National Accelerator Facility

- Electron-beam accelerator
- Polarized c.w. electron beam
- Beam energies up to $E_0 = 6$ GeV
- Three experimental Halls A, B, and C
The CEBAF Large Acceptance Spectrometer

CLAS

Performance

- $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- $\Delta p/p \sim 0.5-1 \%$
- $\sim 4\pi$ acceptance
- Best suited for multiparticle final states
- Bremsstrahlung Photon Tagger ($\Delta E_\gamma/E_\gamma \sim 10^{-3}$)
Physics with the CLAS

Nuclei
Physics with the CLAS

Nuclei

Transition from meson-nucleon to quark-gluon df
Physics with the CLAS

Nuclei

Transition from meson-nucleon to quark-gluon df

Scaling of $d\sigma/dt$
Physics with the CLAS

Nuclei

Transition from meson-nucleon to quark-gluon df

Scaling of $d\sigma/dt$

Color Transparency
Physics with the CLAS

Nuclei

Three-Body Mechanisms

Transition from meson-nucleon to quark-gluon df

Scaling of $d\sigma/dt$

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Nuclei

- Short-Range Correlations
- Three-Body Mechanisms
- Transition from meson-nucleon to quark-gluon df
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- Color Transparency
Physics with the CLAS

Nuclei

Nuclear GPDs

Short-Range Correlations

Three-Body Mechanisms

Transition from meson-nucleon to quark-gluon df

Scaling of $d\sigma/dt$

Color Transparency
Physics with the CLAS

- **Nuclei**
  - Short-Range Correlations
  - Three-Body Mechanisms
  - Transition from meson-nucleon to quark-gluon df
  - Scaling of $d\sigma/dt$
  - Color Transparency

- **Medium Modifications of Hadrons**

- **Nuclear GPDs**
Physics with the CLAS

- Medium Modifications of Hadrons
- Quark Propagation
- Nuclear GPDs
- Transition from meson-nucleon to quark-gluon df
- Scaling of $d\sigma/dt$
- Short-Range Correlations
- Three-Body Mechanisms
- Color Transparency
Physics with the CLAS

- Quark Propagation
- Nuclear GPDs
- Medium Modifications of Hadrons
- YN interaction
- Short-Range Correlations
- Three-Body Mechanisms
- Transition from meson-nucleon to quark-gluon df
- Scaling of $d\sigma/dt$
- Color Transparency
The Dual Universe of Nuclear Physics

Our understanding of the strong interaction depends on the scale...

When does the transition between the two descriptions happen? How to describe it?

\[ \lambda = \frac{h}{p} \]

\[ p = 1 \text{ GeV/c probes 1.2 fm} \]
Theoretical Description of Nuclear Dynamics

• Low Energies: Effective Field Theory (nucleons or nucleons and pions)
• High Energies: pQCD
• Medium Energies: traditional nuclear models, quark models, pQCD extensions through factorization (relevant degrees of freedom?).
  • Some Open Questions
    • short-range correlations (SRC)
    • three-body mechanisms
    • color transparency
    • hidden color
Nuclear Structure at Short Distances

Short-Range Correlations

- high nucleon momentum ($p > p_f$) balanced by only one other nucleon
- give rise to high-momentum part of nuclear wf
- nucleon momentum distributions similar for light and heavy nuclei
- scaling of $A(e,e')$ cross section at high momenta

$$R(Q^2, x_B) = \frac{\sigma_{A1}(Q^2, x_B) / A_1}{\sigma_{A2}(Q^2, x_B) / A_2}$$

Nuclear Structure at Short Distances: SRC

- quantified NN and NNN SRC probabilities
- more than 90% of all nucleons with $k \geq 300$ MeV/c belong to NN SRC
- NN SRC build of $6q, \Delta N$, $\Delta \Delta < 10 - 20\%$ of the NN SRC
- NNN SRC present in nuclei with significant probability

Nuclear Structure at Short Distances: SRC

\(^3\text{He}(e,e'pp)n\)

High-momentum components of the nuclear wf

• measured two-nucleon momentum distributions of correlated pn and pp pairs
• reduced FSI: leading nucleon \(p_T<0.3\) GeV/c
• pair momentum along \(q\) is very small
• little \(Q^2\) or isospin dependence

measured spectator correlated NN pairs


• pp to pn cross section ratio increases quickly to 0.4 - 0.5
• indicative of tensor correlations in pn pairs

Diagram:
- Golak one-body
- Golak bound-state
Three-Body Mechanisms in Reactions on Light Nuclei at Medium Energies

- Traditional Nuclear models: Diagrammatic approach, with one-, two-, and three-body mechanisms, is used to calculate the scattering amplitude.
Predictions for Two-Body Photodisintegration of $^3\text{He}$

- Difficult to treat theoretically.
- Three-body mechanisms predicted to dominate at large $t$ for all photon energies.
- Two-body mechanisms sufficient to describe data at low $t$.
- Are three-body mechanisms dominant at large $t$ for $E_\gamma$ above 1 GeV?

Two-Body Photodisintegration of $^3$He

- An order of magnitude forward-backward asymmetry.
- Slope of differential cross section nearly independent of $E_\gamma$.
- Relative contribution of three-body mechanisms is larger at 600-800 MeV than at higher photon energies.

$E_\gamma : 0.4 - 1.4 \text{ GeV}$

$\theta^*_p : 40^\circ - 140^\circ$
Three-Body Photodisintegration of $^3$He: Beam-Helicity Asymmetry $A(\phi)$

$$A(\phi) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

- Neutron non-spectator events: $p_n > 200$ MeV/c
- Helicity asymmetry peaks between 0.6 and 1.0 GeV.
- Signature for three-body mechanisms?

Two-Body Photodisintegration of $^4$He

Comparison with predictions

- Kinematic coverage:
  $E_\gamma : 0.35 - 1.5$ GeV
  $\theta^*_p : 40^\circ - 130^\circ$

- Two orders of magnitude forward-backward asymmetry.

- Relative contribution of three-body mechanisms is large at all photon energies for $\theta^*_p > 60^\circ$.

Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom

Tool: Exclusive nuclear reactions with real photons

- large momentum transfer $t$ selects small-size configurations.

Signatures:

- **scaling** of invariant cross sections (Constituent Counting Rules).
- **factorization** (Reduced Nuclear Amplitudes).
- **color transparency**.
Quark Dynamics: Constituent Counting Rules (pQCD, AdS/CFT)

- At high $t$, high $s$, and high $u$, the invariant cross section of an exclusive process $A + B \rightarrow C + D$ has the following asymptotic behavior:
  \[
  \frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t / s)
  \]
  where $n$ is the total number of the initial and final elementary fields.

- Examples:
  \[
  \begin{align*}
  \gamma d & \rightarrow \pi^0 d, \quad n - 2 = 13 \\
  \gamma d & \rightarrow pn, \quad n - 2 = 11 \\
  \gamma p & \rightarrow \pi^0 p, \quad n - 2 = 7 \\
  \gamma p & \rightarrow K^+ \Lambda, \quad n - 2 = 7
  \end{align*}
  \]

- Reflect underlying scale free interactions (Brodsky, DeTeramond): scale independence of $\alpha_s$.

Quark Dynamics: Constituent Counting Rules (pQCD, AdS/CFT)

- At high t, high s, and high u, the invariant cross section of an exclusive process receives a correction of an asymptotic behavior:

$$\alpha_s(Q^2) = \frac{1}{n} - \frac{1}{s} + \frac{2}{3} + \frac{2}{3s} + \gamma_E + \text{log}_{s,\Lambda}(Q^2/n^2)$$

where n is the total number of elementary fields.

- Examples: 
  - $\alpha_s/\pi$ measured from JLab CLAS
  - $\alpha_s/\pi$ from OPAL

- Reflect underlying scale free interactions (Brodsky, DeTeramond): scale independence of $\alpha_s$.

Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleon

- Many exclusive processes on nucleon targets show scaling already at moderate momentum transfer
Oscillating scaling: scale invariance broken by resonance excitations in $\gamma N \to \pi N$
What about exclusive processes on nuclear targets?

**Deuteron Photodisintegration**

\[
\frac{d\sigma}{dt} = \frac{1}{s^{11}} f(t/s)
\]

- Fits of \(d\sigma/dt\) data at \(p_T>1.1\) GeV/c with \(A_{11}^{-1}\)
- All but two fits have \(\chi^2 \leq 1.34\)

Photodisintegration of a pp pair

What about exclusive processes on nuclear targets?

\[ p_n < 0.25 \text{ GeV/c} \]

- Cross section scales approximately as \( s^{-11} \)
- \( \gamma \text{ pp} \rightarrow \text{p + p} \) is symmetric about 90°
- Scaled deuteron photodisintegration (\( \times 1/4 \)):
  - \( \bigcirc \) forward angles
  - \( \bigtriangleup \) backward angles


Steffen Strauch, private communication, 2010
Photodisintegration of a pp pair

What about exclusive processes on nuclear targets?

- Hall-A new data extend to higher energies.
- Hall-A and Hall-B data in very good agreement.
- Cross section scales as $s^{-11}$ for $E_\gamma > 2$ GeV. Deuteron photodisintegration scales already at $E_\gamma > 1$ GeV.
- Large structure between 1 and 2 GeV. Not observed in deuteron photodisintegration.

Figure from R. Gilman, talk given at High-Energy Nuclear Physics and QCD, FIU, Miami, FL, 2010
Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleus

What about exclusive processes on nuclear targets?

Coherent Pion Photoproduction off the Deuteron

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)$$

CCR Predict $n-2=-13$
Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleus

What about exclusive processes on nuclear targets?

Coherent Pion Photoproduction off the Deuteron

\[ \frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s) \]

CCR Predict \( n-2 = -13 \)

- CLAS data generally consistent with scaling for \( \cos \theta_\pi < -0.25 \). This is consistent with previous results.
What about exclusive processes on nuclear targets?

\[ \gamma d \rightarrow \pi^0 d \]

\[ \frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s) \]

CCR Predict \( n-2 = -13 \)

Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleus

What about exclusive processes on nuclear targets?

\[
\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)
\]

\text{CCR Predict } n-2=-13

- Oscillating scaling: scale invariance broken by non-perturbative rescattering subprocesses in $\gamma d \rightarrow \pi^0 d$.

Two-Body Photodisintegration of $^3$He

Scaling of invariant cross sections

\[
\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)
\]

- CCR Predict $n-2=-17$
- Indication that above $\sim 0.7$ GeV data consistent with scale invariance for all CM angles
- $p_{\perp,d} > 0.65$ GeV/c and large range of $|t|$

I. Pomerantz et al., private communication (2010)
Conclusions

• Indication for Short-Range Tensor Correlations in $e^3He \rightarrow e'ppn$

• Two-Body Mechanisms in Photodisintegration of $^3He$ and $^4He$
  - measured differential cross sections for $E_\gamma = 0.4 - 1.4$ GeV and $\theta^*_p = 40^\circ - 140^\circ$.
  - established optimum kinematic range to probe three-body dynamics in photoreactions on $^3He$ and $^4He$

• Transition from meson-nucleon to quark-gluon $\text{df}$
  - $\gamma \text{ pp(n)}_s \rightarrow \text{pp(n)}_s$
    • at 90 deg, CCR scaling for $E_\gamma > 2$ GeV.
    • scale invariance is broken below $E_\gamma$ of 2 GeV
  - $\gamma \text{ d} \rightarrow \pi^0\text{d}$
    • oscillating CCR scaling at $\cos \theta^*_\pi < -0.25$
    • oscillations mostly due to re-scattering mechanisms
  - $\gamma \text{ }^3He \rightarrow \text{pd}$
    • data consistent with scale invariance for $E_\gamma > 0.7$ GeV
  - $\gamma \text{ }^4He \rightarrow \text{pt}$
    • no evidence for CCR scaling