Overview of Color Transparency Measurements

CIPANP, May 29\textsuperscript{th}, 2012

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(On behalf of CLAS Collaboration)
Overview of Color Transparency Measurements

Outline

- Introduction
- Overview of previous Color Transparency (CT) measurements
- Newest JLab $\rho^0$ CT results
- Summary and Outlook

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Introduction

Study of hard interactions in nuclei gives information about the time evolution of the produced states, and investigates the properties of the nucleus itself.

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Color Transparency is the proposal that under certain circumstances the strong interactions can be controlled and in some cases reduced in magnitude.

CT Basics: Survival of the smallest

Creation of Small Size Configuration (SSC)

via hard and exclusive reactions.
In QCD the color field of a color neutral object vanishes as the size of the object is reduced.

The interaction cross-section has a dipole form $\sigma \propto b^2$. 

**QCD Color Screening**

$Q^+ = (\bar{q}, u)$

$Q \text{ increases}$

$\sigma \propto b^2$

**QED Charge Screening**

$\pi^0$ emulsion produced in cosmic rays (Perkins 1955)
Creation of Small Size Configuration (SSC) via hard and exclusive reactions.

SSC experiences reduced attenuation before evolving to normal hadron.

The distance over which a SSC expands to its free size is at least as large as the nuclear radius.
The signature of Color Transparency is the increase of the medium “nuclear” Transparency $T_A$ as a function of the momentum transfer.

$$T_A = \frac{\sigma_A}{A\sigma_N}$$

$\sigma_A$ is the nuclear cross section and $\sigma_N$ is the free (nucleon) cross section.
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Experimental Status

Baryon

- A(p, 2p) BNL
- A(e, e’p) SLAC & JLab

Meson

- A(π, di-jet ) FNAL
- A(γ, πp) JLab
- A(e, e’π) JLab
- A(μ, μ’ρ) FNAL
- A(e, e’ρ) DESY & JLab
Quasi-elastic $A(p,2p) : BNL$  
E834 and E850

$$\frac{d\sigma}{dt_{pp}}(\theta = 90^\circ_{c.m.}) = R(s)s^{-10}$$

- Initial rise in transparency at low momentum is consistent with CT predictions.
- Subsequent drop at high momentum was explained by:
  - **Ralston and Pire** as a nuclear filtering of soft amplitudes arising from higher order radiative processes (Landshoff mechanism).
  - **Brodsky and De Teramond** as a threshold of new resonant (charmed quark) states.

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A. Leksanov et al. PRL 2001
Quasi-free $A(e,e'p)$: No evidence for CT

Constant value fit for $Q^2 > 2\, (GeV/c)^2$ has $\chi^2 / df \approx 1$

Conventional Nuclear Physics Calculation by Pandharipande et al. gives good description
(qqq) versus (q,q-bar) systems

- Small size is more probable in 2 quark system such as pions, rho mesons than in protons.
  - B. Blattel et al., PRL 70, 896 (1993)

- Onset of CT expected at lower $Q^2$ in (q,q-bar) system.

- Onset of CT related to onset of factorization required for access to GPDs in deep exclusive (q,q-bar) production.
  - Strikman, Frankfurt, Miller and Sargsian
Coherent $\pi^+$ diffractive dissociation with 500 GeV/c pions on Pt and C.

Fit to $\sigma = \sigma_0 A^\alpha$

$\alpha > 0.76$ from pion-nucleus total cross-section.

Aitala et al., PRL 86 4773 (2001)

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Pion Photo-production $\gamma n \to \pi^- p$ in $^4$He

$\theta_{CM}^{\pi} = 70^\circ$

$\theta_{CM}^{\pi} = 90^\circ$

D. Dutta et al. PRC 2003
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Lamiaa El Fassi et al. PRL 2007

These measurements will be extended to $Q^2$ of about 10 (GeV/c)$^2$ after the JLab 12 GeV upgrade

Pion Electroproduction $A(e,e' \pi^+)$ at JLab

B. Clasie et al. PRL 2007
Exclusive p lepton production: FNAL E665

Adams et al. PRL74, 1525 (1995)

$E_\mu = 470 \text{ GeV}$

$Q^2 (\text{GeV})^2$ vs. $T_{r_A}^{inc}$
What could imitate CT signal?

Coherence length effect (CL) can mimic CT signal

\( Q^2 \) increases \( \Rightarrow T_A \) increases

**Coherence Length**

\[ l_c = \frac{2\nu}{(M^2 + Q^2)} \]

To exclude CL, the \( Q^2 \) dependence of \( T_A \) must be measured at small or fixed \( l_c \).
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Exclusive $p^0$ leptoproduction: HERMES

Airapetian et al. PRL 90 (2003) 052501

$E_{e^+} = 27.5$ GeV

HERMES $^{14}$N Data:

$T_{inc}(l_c,Q^2) = P_0 + P_1 Q^2$

$P_1 = (0.089 \pm 0.046_{\text{stat}} \pm 0.008_{\text{sys}}) (\text{GeV}^{-2})$
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JLab: Exclusive Diffractive $\rho^0$ Electro-production
Winter 2004

Spokespersons:
Brahim Mustapha (ANL)
Kawtar Hafidi (ANL)
Maurik Holtrop (UNH)

Graduate Students:
Lamiaa El Fassi (ANL)
Lorenzo Zana (UNH)

North Linac
South Linac
Injector

Hall C
Hall B
CLAS
Hall A
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- Charged particle angles: 8° - 144°
- Neutral particle angles: 8° - 70°
- Momentum resolution: ~0.5% (charged)
- Angular resolution: ~0.5 mr (charged)
- Identification of $p$, $\pi^+/\pi^-$, $K^+/K^-$, $e^-/e^+$

Beamline

CLAS EVENT DISPLAY

TOF

DC1

DC2

DC3

LAC

EC

CC
Overview of Color Transparency Measurements

EG2 Targets

Beam

Al + empty target

Reference Foil
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Exclusive Diffractive $\rho^0$ production off Nuclei

$$l_c = 2v/(M^2 + Q^2)$$
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Kinematics

\[ \nu = e - e' \]
\[ Q^2 = -(P_{e}^{\mu} - P_{e'}^{\mu})^2 \approx 4 e e' \sin^2(\theta/2) \]
\[ t = (P_{\gamma}^{\mu} - P_{\rho}^{\mu})^2 \]
\[ W^2 = (P_{in}^{\mu} + P_{\gamma}^{\mu})^2 = -Q^2 + M_p^2 + 2M_p \nu \]

- \( W \geq 2 \text{ GeV} \)
  \( \Rightarrow \) avoid resonance region

- \( t \geq -0.4 \text{ GeV}^2 \)
  \( \Rightarrow \) select diffractive process

- \( t < -0.1 \text{ GeV}^2 \)
  \( \Rightarrow \) exclude coherent production

- \( Z_h = E_h/\nu \geq 0.9 \)
  \( \Rightarrow \) select elastic channel
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Iron

After t cut

After w cut

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$M_{\pi^+\pi^-}$ (GeV)

$M_{\pi^+\pi^-}$ (GeV)
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Iron

After t cut

After w and t cuts

After w cut

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Iron

After w, t and z cuts

$M_{\pi^+\pi^-} (GeV)$

After t cut

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Overview of Color Transparency Measurements

Two pions invariant mass

Simple Breit-Wigner:
\[ e + p \rightarrow e + p + \rho^0 \]

Simulated Background’s Shapes:
\[ e + p \rightarrow e + p + \pi^+ + \pi^- \]
\[ e + p \rightarrow e + \Delta^{++} + \pi^- \]
\[ e + p \rightarrow e + \Delta^0 + \pi^+ \]
Overview of Color Transparency

**Coherence Length**

\[ l_c = \frac{2\nu}{M^2 + Q^2} \]

**Hermes**

\[ l_c = \frac{2\nu}{M^2 + Q^2} \]

**Nuclear Transparency**

\[ T^\rho_A = \frac{N^\rho_A}{N^\rho_D \times (\rho_D \times t_D)} / (\rho_A \times t_A) \]

- \( \rho_D \) and \( \rho_A \) are the target densities
- \( t_A \) is a solid target thickness
- \( t_D = 2 \text{ cm} \) is the liquid target length

L. El Fassi et al. PLB 712, 2012
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ρ⁰ CT Results: Iron & Carbon data

L. El Fassi et al. PLB 712, 2012
$\rho^0$ CT Results: Iron & Carbon data

- **FMS**: Glauber model based on multiple diffusion scattering formalism.
  - Frankfurt, Miller & Strikman, PRC 78 (08) & Private communication

- **GKM**: Transport Model (GiBUU)
  - Gallmeister, Kaskulov & Mosel, PRC 83, 015201 (2011)

- **KNS**: Light Cone QCD Formalism
### ρ⁰ CT slopes

<table>
<thead>
<tr>
<th>Target slopes (GeV⁻²)</th>
<th>Carbon</th>
<th>Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMS</td>
<td>0.025</td>
<td>0.032</td>
</tr>
<tr>
<td>GKM</td>
<td>0.06</td>
<td>0.056</td>
</tr>
<tr>
<td>KNS</td>
<td>0.06</td>
<td>0.045</td>
</tr>
<tr>
<td>CLAS Data</td>
<td>0.044±0.015±0.019</td>
<td>0.053±0.008±0.013</td>
</tr>
</tbody>
</table>
Overview of Color Transparency Measurements

C, Fe and Sn

JLab 12 GeV \( p^0 \) electroproduction measurements

Theory: FMS CT Model
Theory: FMS NO CT Model
Exp: Hall B, 11 GeV
Overview of Color Transparency Measurements

C, Fe and Sn
Strong evidence for the onset of Color Transparency using $\rho$ electro-production off nuclei at JLab ($11 \pm 2.3\%$ ($12.5 \pm 4.1\%$) decrease in the absorption of $\rho$ in iron (carbon))

SSC expansion time with FMS model were found to be between 1.1 and 2.4 fm for $\rho$ momenta between 2 and 4.3 GeV

At intermediate energies, CT provides unique probe of the space-time evolution of special configurations of the hadron wave function

Using the upgraded JLab 12 GeV, we plan to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium)
Acknowledgements

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- Maurik Holtrop (UNH)
- William Brooks (JLab/UFTSM)
- Hayk Hakobyan (JLab/Yervan/UFTSM)
- ANL Medium Energy Group
- CLAS Collaboration
Backup Slides
Two pions invariant mass

Iron target

Acceptance corrected invariant mass
Overview of Color Transparency Measurements

Ae^{bt} fit:

\( b(^2\text{H}) = 3.58 \pm 0.5 \text{ GeV}^{-2} \)

\( b(\text{C}) = 3.67 \pm 0.8 \text{ GeV}^{-2} \)

\( b(\text{Fe}) = 3.72 \pm 0.6 \text{ GeV}^{-2} \)

CLAS proton data:

0.22 < \( x_b \) < 0.28, 1.6 < \( Q^2 \) < 1.9 GeV

2.4 < \( W \) < 2.8 GeV \( b = 2.63 \pm 0.44 \text{ GeV}^{-2} \)

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### Systematic error budget

#### Systematic Uncertainty of Nuclear Transparency of Iron

<table>
<thead>
<tr>
<th>Systematic Effect</th>
<th>Kinematical cuts</th>
<th>Acceptance correction</th>
<th>Background subtraction</th>
<th>Radiative corrections</th>
<th>Fermi motion</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q² Bins</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Normalization</td>
<td>0.1</td>
<td>0.8</td>
<td>0.5</td>
<td>0.3</td>
<td>1</td>
<td>1.75</td>
</tr>
<tr>
<td>Point-to-point</td>
<td>1.1 1.3 0.4</td>
<td>1.6 1.7 1.6 1.5</td>
<td>1.3 0.2 1.6 1.5 1.7</td>
<td>1 0.5 1.8 0.1 0.05</td>
<td>0.03 0.08</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Systematic Uncertainty of Nuclear Transparency of Carbon

<table>
<thead>
<tr>
<th>Systematic Effect</th>
<th>Kinematical cuts</th>
<th>Acceptance correction</th>
<th>Background subtraction</th>
<th>Radiative corrections</th>
<th>Fermi motion</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q² Bins</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Normalization</td>
<td>0.49</td>
<td>0.89</td>
<td>1.1</td>
<td>0.47</td>
<td>1</td>
<td>1.75</td>
</tr>
<tr>
<td>Point-to-point</td>
<td>1 1.25 1.18 2.6 1.34 1.31 1.82 0.95</td>
<td>- 0.82 0.37 1.11 1.17 2.3 1.13 1.39 - 1.37</td>
<td>0.1 0.05 0.03 0.08</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Total Systematic Uncertainties of Nuclear Transparency

<table>
<thead>
<tr>
<th>Targets</th>
<th>Iron Case</th>
<th>Carbon Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q² bins</td>
<td>1st bin</td>
<td>1st bin</td>
</tr>
<tr>
<td>Point-to-point</td>
<td>2.5</td>
<td>2.87</td>
</tr>
<tr>
<td>Normalization</td>
<td>2.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Theoretical Prediction of CT
Frankfurt, Miller & Strikman, PRC 78 (2008)

- Model (FMS) based on multiple diffusion scattering formalism

- Effective interaction depends on the propagation length ($l_h$) of (qq-bar) pair

- CT effect depends on the $l_h$ and the PLC formation length $\tau_f$

  - Smaller $l_h$ than $\tau_f$ are designated to the interaction of the expanding PLC
  - Larger $l_h$ than $\tau_f$ are associated to a typical Glauber-like interaction
Model (GKM) based on coupled-channel semi-classical Giessen-Boltzmann-Uehling-Uhlenbeck (GiBUU) transport equation.

Primary electron-nucleon interaction is described by the impulse approximation which assumes interacting with only one nucleon at a time.

Exclusive $\rho^0$ electroproduction is dominated by the hard partonic interaction based on a color string breaking mechanism of DIS.

CT theoretical framework is essentially a Glauber calculation, with the pre-hadronic interactions being described by the pQCD-inspired cross section of Farrar assuming that the formation time ($\tau$) corresponds to the expansion time of a PLC. In this picture, the cross section in FSI, that has a $1/Q^2$–dependent starting value, grows linearly with time $\tau$ till it reaches the full hadron-nucleon cross section.
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Theoretical Prediction of CT
Kopeliovich et al., PRC 65 (2002) 035201

Model based on light-cone (LC) approach

LC dipole phenomenology for elastic production of vector meson (VM) $\gamma^*N \rightarrow VN$

$\mathcal{M}(\gamma^*N \rightarrow VN) = \langle V|\sigma(qq-bar)|\gamma^*\rangle$

$\sigma(qq-bar)$: universal flavor independent dipole cross section for qq-bar interaction with a nucleon fitted to the proton structure function data over a large range of $x_B$ and $Q^2$.

$\Psi_{\gamma^*}$ : LC wave function for qq-bar fluctuation of the virtual photon

$\Psi_v$ : LC wave function for the vector meson

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