SHELL DEPENDENCE ON TRANSPARENCY IN E12-06-107

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Mississippi State University
GHP Meeting (Virtual)
Apr 14, 2021
Color transparency (CT) is a unique prediction of Quantum Chromo Dynamics (QCD) where the final (and/or initial) state interactions of hadrons with the nuclear medium are suppressed for exclusive processes at high momentum transfers squared ($Q^2$).

A clear signal for the onset of CT for baryons would show the transition from the nucleon-meson picture to quark-gluon degrees of freedom → Onset is signature for QCD degrees of freedom in nuclei.

- Introduced by Mueller and Brodsky, 1982. It arises in picture of quark-gluon interactions only.
- Basically, CT takes place in the following 3 steps:
  - Selection of the PLC [Squeezing - QM].
  - Lifetime of the PLC [Freezing - Relativity].
  - Small sized objects have reduced interaction [Color Screening - Strong force / QCD].
Signature for the onset of CT involves a rise in nuclear transparency \((T_A)\), as a function of the momentum transfer \((Q^2)\).

\[
T_A = \frac{\sigma_A}{A \sigma_N} \quad \text{(nuclear cross section)}
\]

\[
\sigma_A/A \rightarrow \text{bound nucleon cross section}
\]

Clear onset of CT would be dramatic rise in \(T_A\) around some \(Q_0^2\).

**Ingredients**

- \(\sigma_{hN}\) (h-N cross-section)
- Glauber multiple scattering approximation
- Correlations & FSI effects
CT PAST EXPERIMENTS

CT Experiments

\[ \begin{aligned}
\text{Baryon} & : \ A(p,2p): \ BNL \\
& : \ A(e,e'p): \ SLAC, \ JLab
\end{aligned} \]

\[ \begin{aligned}
\text{Meson} & : \ A(\pi, \text{di-jet}): \ FNAL \\
& : \ A(\gamma, \pi^- p): \ JLab \\
& : \ A(e, e'\pi^+): \ JLab \\
& : \ A(e, e'\rho^0): \ DESY & JLab
\end{aligned} \]
CT PAST RESULTS – FERMILAB

CT is well established at high energies.

500 GeV $\pi^+ + \text{Pt} \rightarrow 2 \text{ Jets}$

$\sigma_A = \sigma_N A^\alpha$

Experimentally $\alpha = 0.72 - 0.78$ for $\pi, \kappa, p$

$\sigma_A$ is Nuclear cross section

$\sigma_N$ is free nucleon cross section

Coherent diffractive dissociation of pions at Fermilab (E791 Collaboration)

CT PAST RESULTS - BNL A(p,2p)

(p, 2p) experiment at BNL found an enhancement in the transparency.

Decreases at higher momentum.

Result inconsistent with CT only.

Can be explained by including additional mechanisms such as nuclear filtering or charm resonance.

A. Leksanov et al. PRL 87 (2001)
J. L. S. Aclander et al., PRC 70 (2004)
CT PAST RESULTS - $A(e,e'p)$

No evidence for CT

Solid Pts - JLab
Open Pts - Other

$P_p = 5.15 \text{ GeV/c}$
CT PAST RESULTS - MESONS

CT is well established at high energies. Onset of CT has been measured in Mesons but not in Baryons.

PION - $A(e, e'\pi^+)$

RHO - $A(e, e'\rho^0)$

Hall C E01-107 pion electroproduction

CLAS E02-110 rho electroproduction

X. Qian et al. PRC81:055209 (2010)
L. El Fassi et al. PLB 712,326 (2012)
E12-06-107 was the first experiment to run in Hall C in the Jlab 12 GeV era

Ran in Hall C at JLab in Spring 2018

~20 days of data taking

Coincidence trigger

Targets: 10 cm LH$_2$, 6% rl $^{12}$C, $^{27}$Al

Beam current up to 65 μA

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>8.0</td>
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<td>8.505</td>
<td>39.3</td>
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</table>
HYDROGEN NORMALIZATION

E_{miss} < 65 MeV
P_{miss} < 65 MeV/c

Parameterization of the known ep-elastic scattering cross section through a Monte Carlo simulation of the experiment.

MISSING MOMENTUM ($^{12}$C) - $p_{\text{miss}}$

<table>
<thead>
<tr>
<th>Standard Hall C Monte Carlo - SIMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Optics (COSY) and spectrometer apertures</td>
</tr>
<tr>
<td>➢ Radiative corrections, multiple scattering, ionization energy loss, particle decay</td>
</tr>
<tr>
<td>➢ Prescriptions for FSI, coulomb corrections, off shell corrections</td>
</tr>
<tr>
<td>➢ Parametrization of elastic ep scattering cross section + $^{12}$C spectral function</td>
</tr>
</tbody>
</table>

\[
\frac{d^6 \sigma}{dE_e' d\Omega_{e'} dE_p' d\Omega_{p'} E_{p'} |p_{p'}| \sigma_{ep} S(E_m, \vec{p}_m)}
\]

\[Q^2 = 8 \ (GeV/c)^2\]
\[Q^2 = 9.4 \ (GeV/c)^2\]
\[Q^2 = 11.4 \ (GeV/c)^2\]
\[Q^2 = 14.2 \ (GeV/c)^2\]
RADIATIVE CORRECTIONS

PWIA model in Monte Carlo (SIMC) is in agreement with Radiative effects in data

Hydrogen radiative tails: $E_{\text{miss}}$ spectra

Carbon radiative tails: $E_{\text{miss}}$ spectra

5% $^{12}\text{C}$ target, $Q^2 = 8 \text{ GeV}^2$

1.5% $^{12}\text{C}$ target, $Q^2 = 9.4 \text{ GeV}^2$

Courtesy: Holly Szumila-Vance, JLab
LUMINOSITY SCANS ON $^{12}$C TARGET

Single arm runs varying with beam current

(-1.91 +/- 3.95)% / 100 uA

(-1.93 +/- 4.85)% / 100 uA
CUT DEPENDENCE STUDY (+/- 10%)
1H TARGET BOILING CORRECTION

Normalized yields vs current

SHMS Normalized Yield (μC)

-4% +/- 1.02%
per 100 μA

Current [μA]

Correction of 2.6% at 65 μA, highest current in experiment
## Systematic Uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>$Q^2$ dependent uncertainty (%)</th>
<th>Normalization uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrometer acceptance</td>
<td>2.6</td>
<td>1.8</td>
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<tr>
<td>Event selection</td>
<td>1.4</td>
<td>0.5</td>
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<tr>
<td>Tracking efficiency</td>
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<tr>
<td>Radiative corrections</td>
<td>1.0</td>
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<tr>
<td>Live time &amp; Det. efficiency</td>
<td>0.5</td>
<td></td>
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<tr>
<td>Free cross section</td>
<td></td>
<td></td>
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<tr>
<td>Target thickness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam charge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton absorption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>
TRANSPARENCY

No clear sign of increasing transparency

\[ \frac{\sigma_{\text{meas}}}{\sigma_{\text{PWA}}} \]

- \( E_{\text{miss}} < 80 \text{ MeV} \)
- \( P_{\text{miss}} < 300 \text{ MeV/c} \)

Systematic Uncertainty

4 %

COLOR TRANSPARENCY EFFECTS FOR HOLE EXCITATIONS
IN A(e, e'p) REACTIONS

L.L. FRANKFURT, M.I. STRIKMAN and M.B. ZHALOV

Leningrad Nuclear Physics Institute, 188350, Gatchina, USSR

Received 20 February 1990

Abstract: The color transparency effect is estimated for the hole excitation of the levels in high-$Q^2$
A(e, e'p) reactions which can be studied in the high-resolution experiments at CEBAF. We find
that the optimal strategy in a wide $Q^2$ range where the effect is expected to be rather small would
be to study transitions to the s-levels because (i) the effect is significantly enhanced for these
transitions, (ii) the cross section in the absence of the color transparency effect can be reliably
calculated for small nucleon momenta, (iii) the off-shell effects in the discussed kinematics are small.
MISSING ENERGY

$Q^2 = 0.4 \text{ (GeV/c)}^2$, proton $E_m$ plot for $^{12}\text{C}(e,e'p)$ at the MAMI

Spectrometer resolution of $\sim0.1\%$  \textbf{2 - 5.5 MeV resolution}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2$ [GeV/c$^2$]</td>
<td>0.40</td>
</tr>
<tr>
<td>$p_{\text{miss}}$ [MeV/c]</td>
<td>$-130$ to $100$</td>
</tr>
<tr>
<td>$p_e$ [MeV/c]</td>
<td>385</td>
</tr>
<tr>
<td>$\theta_e$ [deg]</td>
<td>82.4</td>
</tr>
<tr>
<td>$p_p$ [MeV/c]</td>
<td>668</td>
</tr>
<tr>
<td>$\theta_p$ [deg]</td>
<td>$-34.7$</td>
</tr>
<tr>
<td># of events after cuts</td>
<td>$1.7 \times 10^6$</td>
</tr>
</tbody>
</table>

$\sim10 \mu\text{A}, 600 \text{ MeV CW polarized e' beam}$

MISSING ENERGY – CONTD.

\[ Q^2 [\text{GeV}^2/c^2] = 0.4 \]
\[ p_{\text{miss}} [\text{MeV}/c] \approx -130 \text{ to } 100 \]
\[ p_e [\text{MeV}/c] = 385 \]
\[ \theta_e [\text{deg}] = 82.4 \]
\[ p_p [\text{MeV}/c] = 668 \]
\[ \theta_p [\text{deg}] = -34.7 \]
\# of events after cuts = 1.7 M

\approx 10 \mu A, 600 \text{ MeV CW polarized } e^- \text{ beam}

\[ Q^2 = 0.4 \text{ (GeV/c)}^2, \text{ proton } E_{\text{in}} \text{ plot for } ^{12}\text{C}(e,e'p) \text{ at the MAMI} \]

Spectrometer resolution of \( \approx 0.1\% \) - 2 - 5.5 MeV resolution

SHELL DEPENDENT TRANSPARENCY RESULT

<table>
<thead>
<tr>
<th>$Q^2$</th>
<th>1p (%)</th>
<th>1s (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>13.36</td>
<td>1.7</td>
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<tr>
<td>9.4</td>
<td>16.46</td>
<td>0.4</td>
</tr>
<tr>
<td>11.4</td>
<td>17.08</td>
<td>1.76</td>
</tr>
<tr>
<td>14.2</td>
<td>7.6</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Uncertainty from $E_m$ variation in s/p shell

4% total uncertainty + uncertainty from $E_m$ variation in s/p shell

4% total uncertainty to be published soon
STATUS OF THE WORK

➢ Done with calibration of the detectors, improved HMS and SHMS efficiencies calculation, improved HMS and SHMS optics now.

➢ Analysis to understand systematic is completed.

➢ Results have been published in PRL last February 2021.

SUMMARY

➢ Measuring the onset of CT is a signature for the onset of QCD degrees of freedom in nuclei.

➢ First experiment to run in the 12 GeV era in Hall C and to take data using both the SHMS and HMS.

➢ Our results DO NOT SHOW the onset of Color transparency in protons up to 14.2 (GeV/c)^2, covering all kinematics of previous BNL results (proton momentum, Q^2).

➢ Future experiments will measure CT effects with different reaction mechanisms and precision.
THANK YOU!