Nuclear Transparency in $A(e,e' \pi/K)X$

Status and Prospects

Tanja Horn

THE

CATHOLIC UNIVERSITY

of AMERICA

Small size configurations at high-t workshop

26 March 2011
Nuclear Transparency

• Color transparency (CT) is a phenomenon predicted by QCD in which hadrons produced at large $Q^2$ can pass through nuclear matter with little or no interaction [A.H. Mueller, Proc. 17th rec. de Moriond, Moriond, p13 (1982), S.J. Brodsky, Proc. 13th intl. Symp. on Multip. Dyn., p963 (1982)]
  – At high $Q^2$, hadron can be created with a small transverse size (PLC)
  – Hadron can propagate through the nucleus before assuming its equilibrium size

• Currently no conclusive evidence of the onset of CT at intermediate energies
  – Proton results negative up to $Q^2 \sim 8 \text{ GeV}^2$

• Advantage of using pions: simple $q \bar{q}$ system
  – Easier to produce a point-like configuration (PLC) of two quarks rather than three
  – Coherence lengths are small ($\sim 1 \text{ fm}$)
Transparency at JLab 6 GeV (E01-107)

- Took data to the highest possible $Q^2$ with 6 GeV electron beam at JLab in 2004
- Main goal: measurement of the nuclear transparency of pions
- Also: full L/T/LT/TT separation in $\pi^+$ production at two values of $Q^2$

| $Q^2$ (GeV$^2$) | $W$ (GeV) | $|t|$ (GeV$^2$) | $E_e$ (GeV) | $\varepsilon$ |
|-----------------|-----------|----------------|-------------|-------------|
| 1.1             | 2.3       | 0.05           | 4.0         | 0.50        |
| 2.15            | 2.2       | 0.16           | 4.0,5.0     | 0.27,0.56   |
| 3.0             | 2.1       | 0.29           | 5.0         | 0.45        |
| 4.0             | 2.2       | 0.44           | 5.0,5.8     | 0.25,0.39   |
| 4.8             | 2.2       | 0.52           | 5.8         | 0.26        |

- LH$_2$, LD$_2$, $^{12}$C, Cu, and Au targets at each kinematic setting
The $A(e,e'\pi^+)$ Reaction

- If $\pi^+$ production from a nucleus is similar to that from a proton we can determine nuclear transparency of pions
- Other mechanisms: NN final state interactions, pion excess, medium modifications, etc.
- Assumption is verified by L/T separations
  - Extracted average results over the acceptance

\[
\sigma_{A(e,e'\pi^+)} = \sigma_{p(e,e'\pi^+)} \otimes S(E,p)
\]

\[S(E,p) = \text{Spectral function for proton}\]
Pion Nuclear Transparency - $Q^2$ Dependence

B. Clasie et al., PRL 99, 242502 (2007)

Inner error bar are statistical uncertainties outer error bar are the quadrature sum of statistical and pt to pt systematic uncertainties.

  - Semiclassical Glauber multiple scattering approximation
  - Dashed: includes CT

  - Relativistic Glauber multiple scattering theory
  - Dash-dot: includes CT+SRC
$\sigma (A) = \sigma_0 \ A^\alpha$

$\therefore \ T = A^{\alpha-1}$

- Fits to $\pi$-N scattering cross sections give $\alpha \sim 0.76$
  - Energy independent

- Energy dependence of $\alpha$, which quantifies the $A$ dependence of nuclear transparency, can be viewed as an indication for CT-like effects

Larson, Miller and Strikman, PRC 74, 018201 (2006)
Cosyn, Ryckebusch et al., PRC 74, 062201R (2006)

B. Clasie et al., PRL 99, 242502 (2007)
`$P_\pi$' Dependence of Transparency

- No conflict between pionCT data and recent Hall-B $e,e'\rho$ data
  - $P_\pi > 2.5$ GeV for all pionCT kinematics while for the Hall B $e,e'\rho$ the highest $\rho$ momentum is < 2.5 GeV

- Solid/Dashed lines are predictions with and without CT
  [A. Larson, G. Miller and M. Strikman, nuc-th/0604022]

Inner error bar are statistical uncertainties
outer error bar are the quadrature sum of statistical and pt. to pt. systematic uncertainties.
Kaon Transparency at 6 GeV JLab

• Kaon transparency from electroproduction has never been measured!
• Kaons contain strange quarks and thus have a very long mean free path, which makes kaons a unique probe of the nuclear force
• Kaon transparency from electroproduction may help verify the anomalous strangeness transparency seen in K-nuclei scattering [S.M. Eliseev, NPA 680, 258c (2001)]

Experimental data from 6 GeV JLab also contain significant sample of kaons!

<table>
<thead>
<tr>
<th>Q² (GeV²)</th>
<th>-t (GeV²)</th>
<th>E_e (GeV)</th>
<th>p_K⁺ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.05</td>
<td>4.0</td>
<td>2.793</td>
</tr>
<tr>
<td>2.1</td>
<td>0.16</td>
<td>5.0</td>
<td>3.187</td>
</tr>
<tr>
<td>3.0</td>
<td>0.29</td>
<td>5.0</td>
<td>3.418</td>
</tr>
</tbody>
</table>
Kaon Transparency Analysis Procedure

Data and simulation for $^{12}$C nucleus at $Q^2=2.1$ GeV$^2$

- Build a model for $p(e,e'K^+)X$ using hydrogen data that is based on earlier kaon production data
- Monte Carlo simulation includes various corrections, e.g., experimental, reaction mechanism (Coulomb distortion), etc.
- The new parameterization of the kaon production cross section is used as an input for the quasi-free model for all target nuclei

Simulation describes shapes reasonably well for all target nuclei and kinematic settings
Kaon Nuclear Transparency - $Q^2$ Dependence

Nuruzzaman et al., arXiv:1103.4120 (2011)

- Kaon transparency and its $Q^2$ dependence for three heavy target nuclei
- Recent JLab data are in agreement with earlier JLab low $Q^2$ data
  - For recent data ratio of proton number from light nuclei to $^2H$ was taken

No energy dependence within uncertainty of the transparency

Earlier data on quasi-free kaon production from light nuclei

Transparency extracted as

\[ T = \frac{\sigma_A^{\text{Exp}}}{\sigma_D^{\text{Exp}}} \times \frac{\sigma_A^{\text{Model}}}{\sigma_D^{\text{Model}}} \]

Compare to deuterium to reduce impact of non-isoscalar effects
Effective Cross Sections

Nuruzzaman et al., arXiv:1103.4120 (2011)

- Investigate relative trends for p/π⁺/K⁺ by extracting effective cross sections
  - Obtained by fitting the measured transparency to an empirical geometrical model

- Energy dependence of effective p/π⁺/K⁺ cross sections is consistent with the one of the free cross sections, but absolute magnitudes are different
  - Kaon effective cross section significantly smaller than free cross section compared to size of the effect for p/π⁺ -- would require more sophisticated models to study
• Energy dependence of $\alpha$, which quantifies the $A$ dependence of nuclear transparency, can be viewed as an indication for CT-like effects

$$\sigma (A) = \sigma_0 \ A^\alpha \quad \therefore \quad T = \left( \frac{A}{2} \right)^{\alpha-1}$$

• Parameter $\alpha$ for $p$, $\pi^+$, $K^+$ from electron scattering is larger compared to high-energy hadron-nucleus collisions
  
  – For kaons, $\alpha$ is significantly larger contrary to traditional nuclear physics expectation.
Goals of the 12 GeV Jlab experiment (E12-06-107)

- Search for CT with $p/\pi^+K^+$ in a region of $Q^2=5-9.5$ GeV$^2$
- For $\pi^+/K^+$, where reaction mechanism not well understood map out both $Q^2$ and $A$ dependence
Hard-Soft Factorization

• To access physics contained in GPDs, one is limited to the kinematic regime where hard-soft factorization applies
  – No single criterion for the applicability, but tests of necessary conditions can provide evidence that the $Q^2$ scaling regime has been reached

• Factorization is not rigorously possible without the onset of CT [Burkhardt et al., Phys.Rev.D74:034015,2006]

• One of the most stringent tests of factorization is the $Q^2$ dependence of the $\pi/K$ electroproduction cross section
  – $\sigma_L$ scales to leading order as $Q^{-6}$

• Factorization theorems for meson electroproduction have been proven rigorously only for longitudinal photons [Collins et al, Phys. Rev. D56, 2982 (1997)]
The $Q^2$ scaling prediction is consistent with the JLab $\sigma_L$ data

- Limited $Q^2$ coverage and large uncertainties make it difficult to draw a conclusion

The two additional predictions that $\sigma_L >> \sigma_T$ and $\sigma_T \sim Q^{-8}$ are not consistent with the data

Testing the applicability of factorization requires larger kinematic coverage and improved precision
Kaons: $Q^{-n}$ scaling of $\sigma_L/\sigma_T$ in the resonance region

- $Q^{-n}$ scaling through $R=\sigma_L/\sigma_T$ is not as rigorous as the scaling test of the individual cross sections

- Current knowledge of $\sigma_L$ and $\sigma_T$ above the resonance region is insufficient

- Current models not sufficient for understanding reaction mechanism

- Difficult to draw a conclusion from current $K^+ \sigma_L/\sigma_T$ ratios
  - Limited $W$ and $Q^2$ coverage
  - Uncertainties from scaling in $x$, $t$

High quality $\sigma_L$ and $\sigma_T$ data for both kaon and pion would provide important information for understanding the meson reaction mechanism.
JLab 12 GeV: Factorization Tests in $\pi^+$ Electroproduction

- JLab experiment E12-07-105 will search for the onset of factorization
- Measure the $Q^2$ dependence of the $p(e,e'\pi^+)n$ cross section at fixed $x_B$ and $-t$ to search for evidence of hard-soft factorization
  - Separate the cross section components: L, T, LT, TT
  - The highest $Q^2$ for any L/T separation in $\pi$ electroproduction
- Also determine the L/T ratio for $\pi^-$ production to test the possibility to determine $\sigma_L$ without an explicit L/T separation

<table>
<thead>
<tr>
<th>x</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>W (GeV)</th>
<th>$-t$ (GeV/c)$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.31</td>
<td>1.5-4.0</td>
<td>2.0-3.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.40</td>
<td>2.1-5.5</td>
<td>2.0-3.0</td>
<td>0.2</td>
</tr>
<tr>
<td>0.55</td>
<td>4.0-9.1</td>
<td>2.0-2.9</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Is the partonic description applicable at JLab?
Can we extract GPDs from pion production?
Approved experiment E12-09-011 will provide first L/T separated kaon data above the resonance region.

- Onset of factorization
- Understanding of hard exclusive reactions
  - QCD model building
  - Coupling constants

E12-09-011: Precision data for $W > 2.5$ GeV
L/T separations from nuclear targets

- L/T separation from nuclear targets from JLab 6 GeV/12 GeV data
- MC model including a parameterization in missing mass, Mx, using fit to data.