Experimental Manifestations
– Focus of this talk

- In medium parton propagation and fragmentation: Hadronization
- Creation and evolution of small size hadrons: Color Transparency (CT)
- In medium modification of quark distributions: EMC Effect
- Short Distance Structure of Nuclei: Short range correlations (SRC)
- 3D mapping of nuclei: Nuclear Generalized Parton Distributions (GPDs)
Making sense of things …

- Medium modification of quark distributions – EMC
- Short range structure – SRC
- 3D mapping – Nuclear GPD

- Color confinement dynamics – Hadronization
- Creation and evolution of small size hadrons – CT
Probe (1): "How do quarks transform “hadronize” into hadrons?"

Nuclei are used as detectors providing multiple scattering centers separated by only 1 – 2 fm

- What is the interaction and the lifetime $\tau_p$ of the struck quark before it neutralizes its color? – partonic energy loss
- How long does it take to form the color field of a hadron $\tau_f$ and which kind of interaction is in play?
Three processes for complementary studies

Deep Inelastic scattering
- Quark propagation
- Hadron formation
- Final state effects

Drell-Yan
- Quark propagation
- Initial state effects

Relativistic Heavy ion collisions
- Quark propagation in strongly interacting matter
- Hadron formation
- Initial and final state effects

Semi-Inclusive Deep Inelastic scattering (SIDIS) in the vacuum (nucleons) – Flavor tagging techniques

- Flavor decomposition of longitudinal unpolarized and polarized distributions
- Transverse momentum dependent distribution (TMDs)
- Parton fragmentation in the vacuum

Parton energy loss via Gluon radiation in the vacuum
Semi-Inclusive Deep Inelastic scattering in the medium

- Parton energy loss in the medium: Medium induced gluon emission
- Modification of the fragmentation functions in the medium
- Hadron/pre-hadron formation and interaction with the medium
- Low energy DIS offers a unique kinematic window with hadronization time scales comparable to the nuclei sizes
SIDIS observables

Leptonic variables: $\nu$ (or $x$), $Q^2$
Hadronic variables: $z$ and $p_T$
Different nuclei: size and density
Different hadrons: quark’s flavor

Transverse momentum broadening

$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

Multiplicity ratio

$$R_M(z, \nu, Q^2, p_T^2) = \frac{N_h(z, \nu, Q^2, p_T^2)}{N_{DIS} \mid_A}$$

Deuterium target
Heavy target
General features of multiplicity ratios – Attenuation (1 – R)

HERMES: All three pions and K^- undergo similar attenuation
K^+ is less attenuated

Mass effect
Lorentz boost effect

• Partonic: energy loss and modified fragmentation functions
• Hadronic: Hadron formation length and absorption

HERMES NPB 780 (2007)
Cronin effect?

Fragmentation region contamination or a proof of its partonic origin?

Positive pions

No z but strong v dependence

5 GeV electron beam

Thesis of R. Dupre
Transverse Momentum Broadening

- No broadening at high $z$
  → Effect at the partonic level

Saturation for large nuclei

- Dependence in $A$ not conclusive
  → Compatible with $A^{1/3}$ and $A^{2/3}$
- Flavor dependence?
Probe (2): The creation and propagation of small size configurations

QCD predicts the existence of \textit{hadron-like configuration} which under specific conditions, will pass through nuclear matter \textbf{with dramatically reduced interaction}.

\textbf{These configurations} are of \textit{small size} and their interactions with the nucleus are suppressed because of the \textit{small spatial extent of their color field}.

The 3 Pillars of Color Transparency

- Creation of Small Size Configurations (SSC)
- SSC experiences reduced interaction with the medium
- SSC does not evolve rapidly as it propagates out of the nucleus

The signature of Color Transparency is the increase of the medium “nuclear” Transparency $T_A$ as a function of the momentum transfer.

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

$\sigma_N$ is the free (nucleon) cross section
$\sigma_A$ is the nuclear cross section
The power of hard exclusive reactions in CT studies

Hard exclusive processes play a key role in QCD

- They allow the study of quark and gluons scattering and their formation into hadrons at the amplitude level
- They depend in detail on the composition of the hadron wave functions themselves

- For the reaction to be elastic, all partons in the proton wave function have to be located within the same transverse interval \( b \leq 1/Q \)
- At large \( Q^2 \), the transverse size of the ejectile can be much smaller than the equilibrium radius of the proton
Pillar # 2: Color screening: the SSC experiences reduced attenuation

- In QCD the color field of a color neutral object vanishes with decreasing size of the object

- The ionization produced by the pair was small near the decay point, increasing with distance from vertex (Perkins 1955)

- A pair of oppositely charged particles interacts in the medium with a dipole cross-section proportional to $b^2$ (Chudakov 1955)

- In Perturbative QCD two-gluon exchange is believed to be the dominant scattering mechanism

- The SSC-nucleon cross section is $\sigma_{SSCN} \approx \sigma_{h,N} \frac{b^2}{R_h^2}$, $R_h$ is the hadron radius

200 GeV $\pi^0$ produced in cosmic rays
Pillar # 3: Lifetime of Small-Size-Configuration

Naïve parton model:

- Quarks expand back to their usual separation at the speed of light
  \[ \tau \approx \frac{R_h}{c} \]  (with time dilation it becomes \( E_{h^*} \tau / M_h \))
- If the hadron is a nucleon \( R_h \approx 0.8 \text{ fm} \), probability of SSC escaping the nucleus is significant even for modest values of Lorentz factor

More realistic “quantum diffusion” model:

- The expansion takes a total time of \( 1/(E_{h^*} - E_h) \), where \( E_{h^*} \) is the energy of the typical intermediate state
- The key point is that the SSC is not the ground state of the free hadron Hamiltonian. Therefore it is a fluctuation to a state with larger mass.
Medium Energy searches for Color Transparency

A(p, 2p) BNL

A(e, e′p) Bates, SLAC and JLab

A(e, e′p) DESY

Kawtar Hafidi
Latest results from Jefferson Lab

- Create **color-singlet** small size configuration (SSC)
- SSC has **reduced interaction** with the medium
- SSC does not expand immediately

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

- Diffractive electroproduction of the vector meson $\rho^0$ off nuclei offers a tool of choice to study CT
- The **small** size pre-hadron $\rho^0$ is **directly produced** from the virtual photon since both are **vector particles**
- The higher the space-time resolution ($Q^2$) of the virtual photon, the smaller the size of the produced pre-hadron
CT Signature is the **rising** of the nuclear transparency with $Q^2$. However...
Evidence for the onset of Color Transparency

FMS (Glauber Model): Frankfurt, Miller & Strikman, PRC 78, 015208 (2008)
GKM (Transport Model): Gallmeister, Kaskulov & Mosel, PRC 83, 015201 (2011)
## Comparison of 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>

The most statistically significant result for the pion experiment is for $^{197}$Au with a slope of 0.012 ± 0.004
The European Muon Collaboration (EMC) effect

DIS cross section per nucleon in nuclei ≠ DIS off a free nucleon
New insight on the EMC effect

J. Seely et al., PRL 2009
J. Arrington et al. PRC 2012

- Rules out previously-assumed scaling with $A^{-1/3}$ or average density
- Suggests ‘local density’ is important, two-body effects may generate the EMC effect
Short Range Correlations (SRC) via (e,e’) ratios

Magnitude of the plateaus proportional to the probability for finding pairs in the nucleus

Consistent with the idea that the functional form of these pairs is the same in all nuclei
Experimental connection between EMC and SRC

L. Weinstein et al. PRL 2011

- The data show that EMC effect slopes are proportional to the SRC plateaus.
- EMC effect and SRCs might be both a consequence of the local QCD effects within the nucleus.
Generalized EMC Ratio – Nuclear Generalized Parton Distributions (GPDs)

Measure Beam Spin Asymmetry for coherent $^4$He(e,e' $\rightarrow$ $^4$He) and incoherent $^4$He (e,e' $\rightarrow$ p) channels.

- Model independent extraction of the real and imaginary part of the Compton Form Factor from coherent channel since $^4$He is spin zero and therefore has only one chirally even GPD.
- Determine the $x_B$ and $t$ dependences of the “generalized EMC ratio” $R(4\text{He}) = A_{LU}(4\text{He})/A_{LU}(p)$.

Gomez et al., PRD49, 1994

S. Liuti & S. K. Taneja PRC72, 2005
Experimental Setup
A newly built Radial Time Projection Chamber

- 4.6 Tesla Solenoid magnet for momentum analysis and shielding of Moller electrons

Raphaël Dupré
IPN Orsay

- Lead-tungstate calorimeter for small angle photon detection

\[ Q^2 > 1 \text{ GeV}^2 \quad W > 2 \text{ GeV} \quad \text{and} \quad \theta_{\min} = 4 \text{ deg} \]

- \( P_{\text{min}}(^4\text{He}) = 0.27 \text{ GeV/c} \quad \theta_{\min} \approx 0.08 \text{ GeV}^2 \)

- RTPC based on cylindrical GEMs
- Open geometry detector, 3 cm drift region
- Working gas Ne-DME (80:20)
- Target 6mm diameter, 30 cm long kapton straw with 30 µm thick walls

\[ \text{Target gas} \quad ^4\text{He at 1 atm} \]
Coherent DVCS off He-4 @ JLab

Analysis by Nathan Baltzell

Kinematic Range
1 < $Q^2$ < 2.3 GeV$^2$
0.05 < -$t$ < 0.2 GeV$^2$
0.1 < $x_B$ < 0.25

Guzey & Strikman, PRC 2003
Liuti & Taneja, PRC 2005
HERMES, Airapetian et al. PRC 2010
The Generalized EMC ratio for coherent DVCS production off He-4

Graduate students: Mohammed Hattawy (IPN/Orsay) & Cristina Moody (ANL)

Analysis by Nathan Baltzell
The Generalized EMC ratio for incoherent DVCS production off He-4 (projections)

Stay Tuned!
Outlook – Hadronization @ CLAS12: 10 times larger luminosity than CLAS and 1000 times than HERMES

Examples of Experimental Data and Theoretical Predictions
Outlook – Color Transparency

A(e, e'π) projections for JLab 12 GeV

JLab 12 GeV $\rho^0$ electroproduction measurements C, Fe and Sn
Upcoming EMC & SRC Experiments

- E12-10-103 & E12-11-112 plans \(^3\)He & \(^3\)H(e,e’) SRC & EMC Measurements
- E12-10-008 & E12-06-105 plans a survey of nuclei from light to heavy
  - Goal is to cover EMC x < 1 and SRC x > 1 for each nucleus
- E12-11-107 will use a Large Acceptance Device (LAD) to tag recoiling nuclei
  - Goal to directly show if the cause of the EMC effect is due to SRC pairings
Summary
SSC vs. formation effects

**Long $l_c$ and fixed**

$Q^2$ increases $\nabla$ $T_A$ increases because the mean transverse separation of the $\{q,q\text{-bar}\}$ fluctuation decreases.

$\begin{align*}
l_c &\text{ small and fixed (at low } Q^2 \text{)} \\
Q^2 &\text{ increases } \triangledown \text{ } l_f \text{ increases}
\end{align*}$

$\rho$ CT increases for two reasons:

$\rho$ transverse separation and $l_f$ effects

Coherence length

$l_c = 2\nu/(Q^2 + M(\rho)^2)$

Formation length

$l_f = 2\nu/(M(\rho')^2 - M(\rho)^2)$

Radius (C) = 2.7 fm

Radius (Fe) = 4.6 fm

Radius (Sn) = 5.7 fm
DVCS-BSA

\[ A_{LU}(\phi) = \frac{d\sigma(\phi) - d\sigma(\phi)}{d\sigma(\phi) + d\sigma(\phi)} \]

Leading order in $x_s$ and neglecting DVCS and interference part in denominator

\[ C^I = F_1 \mathcal{H} + \frac{x_B}{2 - x_B} (F_1 + F_2) \mathcal{H} - \frac{\Delta^2}{4M^2} F_2 \mathcal{E} \]

nucleon

\[ C^I = \mathcal{H} F \]

\[ ^4\text{He nucleus} \]

\[ A_{LU}(\phi) = \frac{\alpha_0(\phi) \Im}{\alpha_1(\phi) + \alpha_2(\phi) \Re + \alpha_3(\phi) (\Re^2 + \Im^2)} \]

\[ \Im = \Im \{ \mathcal{H}_{^4\text{He}} \} \]

\[ \Re = \Re \{ \mathcal{H}_{^4\text{He}} \} \]
Model Independent Extraction of the $^4$He CFF

Tomographic images of the target nucleus

$\gamma^*(q) \rightarrow \gamma(q')$

$\gamma(\vec{q})$

$p \rightarrow p' = p + \vec{y}$

$q(x,b) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i\Delta_\perp \cdot \vec{b}} H(x,-\Delta_\perp^2)$

$q(x,b)$ is the probability density to find a quark with momentum fraction $x$ at a transverse distance $b$ from the transverse center of momentum of the target (CM)

$x$ is the longitudinal momentum fraction of the active quark

$\vec{y}$ is the longitudinal fraction of the momentum transfer


In the infinite momentum frame and for $\vec{y}=0$, $t = -\Delta_\perp^2$

GPDs describe quantum mechanical correlations within the target.


The impact parameter $b$ gives the location where a quark or anti-quark is pulled out of and put back into the target.

The shift of the transverse target position depends on $\vec{y}$.