Hadrons in the Nuclear Medium

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Duke University

HUGS, June 2003
Lecture - 1
Outline

- Historical overview and Motivation
- Some Definitions
- Matter at high densities
- Exclusive processes at high momentum transfer
- Probing the limits of nucleon based description of nuclei
Historical Overview

The goal of **Nuclear Physics** is to understand the forces holding atomic nuclei together.

Modern era began in the **1930s** with the discovery of the **neutron**

**First attempt:** Yukawa’s original idea - nucleons interact by **exchanging massive particles** (mesons).

\[
\text{Range} \approx c \Delta t \approx \frac{\hbar}{2mc} \implies m_\pi \approx 100 \text{ MeV}
\]
The pion was discovered in 1947 by Cecil Powell followed by Explosion of particle discoveries (1947–1960s) led by Gell-Mann and Zweig introducing quarks to organize the spectrum (particle zoo).

and

$\Delta^{++}(u,u,u) \Rightarrow$ additional quantum number (color).

eventually in the 1970s At SLAC deep-inelastic electron-nucleon scattering results indicate point like constituents.
# The Standard Model

## FERMIONS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ electron neutrino</td>
<td>$&lt;1 \times 10^{-8}$</td>
<td>0</td>
</tr>
<tr>
<td>e electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\mu$ muon neutrino</td>
<td>$&lt;0.0002$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$ tau neutrino</td>
<td>$&lt;0.02$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

## Quarks

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>d down</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>c charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>t top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

## BOSONS

### Unified Electroweak

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W^-$</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>$W^+$</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>91.187</td>
<td>0</td>
</tr>
</tbody>
</table>

### Strong (color)

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>g gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

---
Quantum Chromo Dynamics (QCD): The fundamental theory describing the strong force in terms of quarks and gluons carrying color charges.

Strongly attractive at all distances except at very short distances.

Force at distances $> 1 \text{ fm} = 18 \text{ tons}$

At short distances or high energies, QCD is asymptotically free

Perturbative methods can be applied
Introduction

"Real World": nucleons + mesons + interactions

Matter is colorless

Potential between two nucleons

Quark interactions cancel at large distances making Hadronic interactions finite.
Two "Realms" of Nuclear Physics

Both realms are well described but there is no roadmap from QCD land to the "Real world."
Drawing the Roadmap

Understanding **nucleons & nuclei** in terms of **quarks and gluons** is the most important unsolved problem of the **Standard Model of nuclear and particle physics**.

*in other words*

**We need data that will connect QCD land to real world.**

**Unique opportunity exists in studying hadrons in nuclear matter** and comparing them with hadrons in free space.

*& Look for*

- **Modifications in the structure and interactions of hadrons in the nucleus.**
- **The transition from quark gluon to nucleon-meson degrees of freedom.**
Drawing the Roadmap

- **Matter at high densities**
  - Modification of nuclear structure at high densities
  - High density fluctuations in nuclei
  - Deep inelastic scattering at $x > 1$
  - Tagged structure functions

- **Exclusive processes at high momentum transfer**
  - Color transparency
  - Nuclear Filtering

- **Charm production in nuclei**

- **Probing the limits of nucleon based description of nuclei**
Some Definitions

Exclusive vs Inclusive Scattering

**Exclusive**: Completely determined initial and final states

Eg. $e + p \rightarrow e' + p$

all final states detected

**Inclusive**: all final states are not measured $e + p \rightarrow e' + X$

- elastic
- resonance
- deep inelastic
Scattering Kinematics

\[ \nu = E - E' \] (energy transferred by photon)

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

\[ Q^2 = 4EE'\sin^2(\theta/2) \]
X and $Q^2$

$Q^2$ : Square of four momentum of the virtual photon, or momentum transfer square (higher $Q^2$ probes shorter distances)

$X$ : Fraction of nucleon momentum carried by the struck quark.

$0 < X < 1$
Form Factors

One can image an object by scattering electrons off it and measuring the angular distribution of the scattered electrons.

\[ \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_\text{Point} \left| F(q) \right|^2 \]

For a static charge the Form factor \( F(q) \) is the Fourier transform of the charge distribution.
Elastic Scattering

For $e\ p \rightarrow e'\ p'$ the cross-section can be written as

$$\frac{d\sigma}{d\Omega} = (K)\left[\frac{G_E^2 + \tau G_M^2}{1 + \tau} \cos^2 \frac{\theta}{2} + 2\tau G_M^2 \sin^2 \frac{\theta}{2}\right]$$

$G_E$ and $G_M$ Related to the charge and magnetic moment distribution of the proton.
Deep Inelastic Scattering

For $e\, p \rightarrow e\, X$ the cross-section can be written as

$$d\sigma \over dE'\, d\Omega = (K)[2W_1(\nu, Q^2)\sin^2(\theta/2) + W_2(\nu, Q^2)\cos^2(\theta/2)]$$
Structure Functions

\[
\frac{d\sigma}{dE'd\Omega} = (K)[2W_1(\nu, Q^2)\sin^2(\theta/2) + W_2(\nu, Q^2)\cos^2(\theta/2)]
\]

\[W_1(\nu, Q^2), W_2(\nu, Q^2)\] are the two structure functions which describes what’s inside the proton.

As \(Q^2\) increases the structure functions simplify and depend only on the fraction of momentum carried by the partons.

at large \(Q^2\): 

\[mW_1(\nu, Q^2) \rightarrow F_1(x)\]
\[\nu W_2(\nu, Q^2) \rightarrow F_2(x)\]

\[2xF_1 = F_2\]
Structure Functions

\[ F_2(x) = \sum_i e_i^2 x f_i(x) \]

probability of finding a quark with a fraction \( x \) of the proton momentum.
$F_2$ probability of finding a quark with momentum fraction $x$.

Quark-antiquark pairs from the glue.

$x \sim$ momentum fraction carried by struck quark.

$1/3, 3$ quarks.
Phases of Nuclear Matter

- Early universe
- LHC
- RHIC
- SPS
- AGS
- SIS
- Chemical freeze-out
- Thermal freeze-out
- Deconfinement
- Chiral restoration

Temperature/Kinetic Energy (MeV)

NET BARYON DENSITY (0.17 GeV/fm³)
Drawing the Roadmap

- **Matter at high densities**
  - Modification of nuclear structure at high densities
  - High density fluctuations in nuclei
  - Deep inelastic scattering at $x > 1$
  - Tagged structure functions
The European Muon Collaboration was the first experiment to measure the structure functions in iron and in deuterium from deep inelastic scattering of muons.

In 1983 they announced their first results as a ratio of $F_2(\text{Fe})/F_2(\text{D})$ as a function of $x$. 

$AF_2^A = ZF_2^p + (A - Z)F_2^n$
The EMC Effect

\[ AF_2^A \neq ZF_2^p + (A - Z)F_2^n \]

\( F_2 \sim \) probability of finding a quark with momentum fraction \( x \) in iron vs deuterium

\( x \sim \) momentum fraction carried by struck quark
The EMC Effect

- SLAC (solid)
- EMC (open circles)
- BCDMS (square)

Graph showing the variation of $(\sigma_A/\sigma_D)_{is}$ with $x$ in the context of the EMC effect.
Nuclear Shadowing

Length scales of the problem:

- Spacing between nucleons: \( \approx 2 \text{fm} \Rightarrow x \approx 0.1 \)
- Diameter of heavy nuclei: \( \approx 10 \text{fm} \Rightarrow x \approx 0.02 \)
- Average separation in deuterium: \( \approx 4 \text{fm} \Rightarrow x \approx 0.05 \)

\[
\Delta l = \frac{\hbar c}{\Delta E} = \frac{\hbar c}{xM} = \frac{0.2}{x} \text{ fm}
\]
Models of the EMC Effect

Nucleon structure is modified in the nuclear medium

- Swollen nucleons
- Parton recombination (multiquark clusters)
- Dynamical rescaling

or

Nuclear structure is modified in the convolution due to multinucleon effects.

- Binding
- Nuclear pions
- N-N Correlations
Does EMC Effect Vary with $\rho_A$ or $A$?

\[ \frac{\sigma_A}{\sigma_D} \text{ at } x = 0.6 \]
Does EMC Effect Vary with $\rho_A$ or $A$?

$\frac{\sigma_A}{\sigma_D}$ at $x = 0.6$
Plans to Measure EMC Effect at JLab

- JLab 6
- JLab 12

- determine the A and $\rho$ dependence
- help evaluate models of EMC
- determine the nuclear effects in deuterium
What We Know So Far

- The nucleus is not just a collection of nucleons
- Deviations from the nucleonic model grows linearly with the nuclear density.

BUT

Average nuclear densities are well below phase transition

REALLY?
Average Nuclear Density

Nucleon charge radius $\approx 0.86$ fm, separation $\approx 1.7$ fm
Nucleons already closely packed in nuclei.
Small Distance Fluctuations in Nuclei

Nucleon separation is only limited by the short range repulsive core \( \rightarrow 1 \text{ GeV at } \sim 0.4 \text{ fm} \)

- \( 0.6 \text{ fm separation} > 5 \text{ times nuclear matter density} \)
- Average Nuclear density

Inset: Potential between two nucleons \( \sim 1 \text{ fm} \)
Short Range Correlations

High momentum components of the nuclear wave function should be sensitive to correlated nucleons.
 SRC vs FSI & MEC

When using any scattering process to probe for SRC:
Have to distinguish from Final State Interactions and multi step processes.

The contributions from FSI and MEC decrease with increasing $Q^2$
How to Look for SRC?

• A(e,e’$^\prime$) reaction at $x > 1$  
  (Can be used to measure probability of 2N, 3N corr)

• D(e,e’pn) with $p_m \geq 400(MeV/c)$

• A(e,e’N) and A(e,e’NN) for $A > 2$  
  (probe detailed structure of SRC)

• A(e,e’ $N_fN_b$) reaction
A(e,e’) Reactions at $x > 1$

$$x = \frac{Q^2}{2M_N}$$

$x$ is the fraction of the nucleon momentum carried by the struck quark in the large $Q^2$ and $\nu$ limit.

In the nucleus the nucleons share momentum, so $x$ can vary between 0 and $A$ (the total number of nucleons).

$x > 1$ corresponds to the quarks carrying momentum fraction larger than that of a nucleon at rest in the nucleus.
A(e,e′) Reactions at x > 1

Measurements at x > 1 are sensitive to the high momentum nucleons in the nucleus.

The ratio of (e,e′) cross-sections should be independent of x and Q^2 (for Q^2 > 1 and x >> 1) and

The ratio is related to the relative per–nucleon probability of SRC in nucleus A relative to d
A(e,e′) Reactions at $x > 1$

Ratio of cross-sections to 3He

Egiyan et al, Nucl-Ex/0301008
A(e,e’) Reactions at $x > 1$

A and $Q^2$ dependence of ratios

No $x$ or $Q^2$ dependence for $x > 1.5$

SRC model valid

5 times more SRC for $A > 10$ than in deuterium

Egiyan et al, Nucl-Ex/0301008
Extension to 12 GeV

Look for 3N correlations at $2 < x < 3$

Relative probability of 3N correlations in A and in 3He

$R_A^3$

2N correlation
Plateau

3N correlation
plateau

$X$

1

2

3

x
**A(e,e’N) and A(e,e’NN)**

The range of $\gamma^*$ is: $\frac{\hbar}{2Q}$, hence, $1.5 \leq Q^2 \leq 4.0$ is ideal range.

Inclusive reactions cannot probe the details of the structure of SRC but Exclusive processes can.

\[ E_m = E_e - E_{e'} - T_{p'} - T_{A-1} \]
\[ \mathbf{p}_m = \mathbf{p}_{p'} - \mathbf{q} \]
A(e,e’N) and A(e,e’NN)

d(e,e’pn) is the simplest of the exclusive processes, the deuteron wavefunction is also reasonably well known. This process at $p_m \geq 400\text{(MeV/c)}$ will provide the ultimate test of our understanding of NN correlations.

For A(e,e’p) for A > 2 the $E_m - p_m$ correlations at high $Q^2$ will provide one of the signatures for scattering from SRC.

A(e,e’ N_f N_b ) reaction with one nucleon moving forward and one moving backward is expected to be dominated by NN correlations and can be used to compare pp, pn and nn correlations.
Quark Structure of SRC

In electron scattering from quarks at

\[ x \geq 1 + \frac{K_F}{m_N} \approx 1.2 \]

all quarks involved are from nucleons with momentum larger than the Fermi momentum of the nucleus.

At large Q^2 contribution from electrons scattering quasi-elastically from nucleons is very small.

These superfast quarks can only come from multiple nucleons with large relative momentum which are closer than the average inter-nucleon separation (i.e. a super dense configuration or some multi-quark configuration.)
Superfast Quarks

Signature can be found by measuring $F_2(x, Q^2)$ in nuclei at large $Q^2$ and at $x > 1$.

$^{56}\text{Fe}(e,e')X$

Model with no SRC

Model with 2N correlations

Model with multi N correlations

- JLab data (E89-008)
- JLab12 projected data
Quark Distribution of SRC

$D(e,e')$ at very high $Q^2$ and $x > 1$ can provide a clear signature of exotic states in nuclei such as 6 quark bags.

\[ q(x) \]

- Two-nucleon only
- 5% 6 quark bag

Graphs with data points and fitted curves showing the distribution $q(x)$ for different scenarios.
Modification of SRC Structure

\[ e + d \rightarrow e' + N + X \]

Detect backward proton (spectator proton)

Slow backward proton \( P_s^{\text{small}} \) tags free neutron

Fast backward proton \( P_s^{\text{large}} \) tags high density conf. (SRC)

Measure \( F_2 \) for fast and slow spectator protons to form the ratio

\[ \frac{F_2^n(P_s^{\text{large}})}{F_2^n(P_s^{\text{small}})} \]
Tagged EMC effect probes modification of SRC structure in the medium

\[ R_n = \frac{F_2^{\text{Bound}}}{F_2^{\text{Free}}} \]
D(e,e'p_s) with CLAS

D(e,e'p_b)X in CLAS++

Counts vs X plot with various lines and markers for different alpha values: n = 1.15, l = 1.25, s = 1.35, u = 1.45, t = 1.55, Q = 1.65, q = 1.75.
Summary

- Nuclear structure is modified in the nuclear medium
- One of the reasons could be SRC
- SRC can be studied in many different reactions
- SRC probability, SRC structure, SRC quark structure and modification of SRC structure all continue to be studied at Jlab.
- 12 GeV upgrade will allow even more extensive coverage.
Hadrons in the Nuclear Medium

Dipangkar Dutta
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HUGS, June 2003
Lecture - 2
Drawing the Roadmap

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In other words

We need data that will connect QCD land to real world

Unique opportunity exists in studying hadrons in nuclear matter and comparing them with hadrons in free space.

& Look for

Modifications in the structure and interactions of hadrons in the nucleus.

& The transition from quark gluon to nucleon-meson degrees of freedom.
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- **Matter at high densities**
  - Modification of nuclear structure at high densities
  - High density fluctuations in nuclei
  - Deep inelastic scattering at $x > 1$
  - Tagged structure functions

- **Exclusive processes at high momentum transfer**
  - Color transparency
  - Nuclear Filtering

- **Probing the limits of nucleon based description of nuclei**
From Quarks to Nuclei

Quantum Chromo Dynamics (QCD) with quark-gluon degrees of freedom is very successful at the high energy, perturbative regime.

Nucleon-meson degrees of freedom work better at lower energies.
What Is the Energy Threshold for the Transition?

Exclusive processes (processes with completely determined initial and final states), are used to study the transition region.

- Quark counting rules
- Hadron helicity conservation
- Color transparency
- Nuclear filtering
How Transparent is Your Nucleus?

Exclusive processes on nucleons and nuclei can be used to measure transparency of nuclei.
Nuclear Transparency

Ratio of cross-sections for exclusive processes from nuclei and nucleons is termed as Transparency

\[ T = \frac{\sigma_N}{A \sigma_0} \]

\( \sigma_0 \) = free (nucleon) cross-section
\( \sigma_N \) parameterized as = \( \sigma_0 A^\alpha \)

Experimentally \( \alpha = 0.72 - 0.78 \), for \( \pi, \kappa, p \)
Total Cross-sections

\[ \alpha = 0.72 - 0.78, \text{ for } \pi, \kappa, p \]

\( \alpha < 1 \) interpreted as due to the strong interaction nature of the probe

Traditional nuclear physics calculations (Glauber calculations) predict transparency to be energy independent.

**Ingredients**

- $\sigma_{hN}$ h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.

**Glauber approx:**

- Energy of particle much larger than interaction potential
- Particle wavelength larger than width of potential
- Scattering at small angles with respect to incident direction.
CT refers to the vanishing of the h-N interaction for h produced in exclusive processes at high Q.

- At high Q, the hadron involved fluctuates to a small transverse size – called the PLC (quantum mechanics).

- The PLC experiences reduced interaction with the nucleus – it is color screened (nature of the strong force).

- The PLC remains small as it propagates out of the nucleus (relativity).
Why is the PLC Selected Out?

Using e-p scattering as an example:

- The momentum is distributed roughly equally among the quarks, (for it to be elastic scattering) $\Rightarrow$ lifetime $\approx \frac{\hbar}{cQ}$
  range $\approx \frac{\hbar}{Q}$

- At high $Q$ an elastic interaction can occur only if the transverse size of the hadron involved is smaller than the equilibrium size.
Color Screening of the PLC

The color field of a color neutral object vanishes with decreasing size of the object.

\[ \sigma_{PLC} \approx \sigma_{hN} \frac{b^2}{R^2 h} \]

(Analogues to electric dipole in QED)
Lifetime of the PLC

In the frame of the nucleus the lifetime of the PLC is dilated.

\[ \gamma t_f = \frac{E}{m} t_f \]

The PLC can propagate out of the nucleus before returning to its equilibrium size.
Color Transparency - Experimental Status

CT refers to the vanishing of the h-N interaction for h produced in exclusive processes at high Q

h can be : qq system (e e in QED)
            qqq system (unique to QCD)

• Color Transparency in $A(p,2p)$ BNL
• Color Transparency in $A(e,e'p)$ JLab, SLAC
• Color Transparency in $A(e,e'\rho)$ FNAL, HERMES
• Color Transparency in di-jet production FNAL
• Color Transparency in $A(e,e'\pi)$ JLab
• Color Transparency in $A(\gamma,\pi p)$ JLab
Transparency in $A(p,2p)$ Reaction

First experiment to look for color transparency

Experiment performed at Brookhaven

Using:

\[ p + A \rightarrow p + p + X \quad \text{Proton knockout} \]

\[ p + p \rightarrow p + p \]

\[ T = \frac{\sigma_{pA}}{A \sigma_{pp}} \]
Transparency in $A(p,2p)$ Reaction

First experiment to look for color transparency

Results inconsistent with CT but explained in terms of nuclear filtering or charm resonance states.
Transparency in $A(e,e'p)$ Reaction

The prediction of CT implies: Fast protons have reduced final state interactions.

$e + A \rightarrow e' + p + X$

At JLab search for CT focused on $A(e,e'p)$
E91-013 & E94-139
Transparency in $A(e,e'p)$ Reaction

The prediction of CT implies: Fast protons have reduced final state interactions.

At JLab search for CT focused on $A(e,e'p)$ E91-013 & E94-139

$e + A \rightarrow e' + p + X$

$Q^2$ is square of the momentum transfer
A(e,e’p) Results

$Q^2$ dependence consistent with standard nuclear physics calculations

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

K. Garrow et al. PRC 66, 044613 (2000)
A(e,e’p) Results -- A Dependence

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

$\alpha = \text{constant} = 0.76$ for $Q^2 > 2 \text{ (GeV/c)}^2$
qqq vs q\bar{q} systems

- There is no unambiguous, model independent, evidence for CT in qqq systems.
- Small size is more probable in 2 quark system such as pions than in protons.
- Onset of CT expected at lower $Q^2$ in q\bar{q} system.
- Formation length is $\sim 10$ fm at moderate $Q^2$ in q\bar{q} system.
Pion-photoproduction

\[ \gamma \ n \rightarrow \pi^- p \ \text{in} \ ^4\text{He} \]
Pion Photoproduction

Assume \( X \) remains in the ground state

\[
\gamma + ^4\text{He} \rightarrow \pi^- + p + X
\]

\[
T \approx \frac{\gamma + ^4\text{He} \rightarrow \pi^- + p + X}{\gamma + n \rightarrow \pi^- + p}
\]
Results

$70^0$ pion C.M. angle

$90^0$ pion C.M. angle

\begin{figure}
\centering
\begin{subfigure}{0.45\textwidth}
\includegraphics[width=\textwidth]{fig1}
\caption{$70^0$ pion C.M. angle}
\end{subfigure}
\quad
\begin{subfigure}{0.45\textwidth}
\includegraphics[width=\textwidth]{fig2}
\caption{$90^0$ pion C.M. angle}
\end{subfigure}
\end{figure}
Future Searches: 12 GeV Upgrade of JLab

Projections for photo-pion production at 12 GeV

$^4$He Nuclear Transparency

- 12 GeV Projected
- E94104
- with CT
- no CT
The $A(e,e'\pi)$ Reaction

$e + A \rightarrow e + \pi + X$

These predictions are consistent with existing data and independent calculations.

- Most of the CT effect is at $Q^2 > 10 \ (GeV/c)^2$
- Two different quark distributions predict effects $> 40\%$ at $Q^2$ between $1 - 5 \ (GeV/c)^2$ for Gold nucleus.
A Pion Transparency Experiment

JLab Experiment E01-107: $A(e,e' \pi)$ on H, D, C, Cu, Au

Projected combined statistical & systematic uncertainty of $5 - 10\%$ and the combined $A$ & $Q^2$ effect measurable.

Measurable effect predicted for $Q^2 < 5$ (GeV/c)$^2$
A(e,e’p) at 12 GeV

With HMS and SHMS @ 12 GeV
What Is the Energy Threshold for the Transition?

Exclusive processes (processes with completely determined initial and final states), are used to study the transition region.

- Quark counting rules
- Hadron helicity conservation
- Color transparency
- Nuclear filtering
The Constituent Quark Counting Rule

Exclusive two body reactions \((A+B \rightarrow C+D)\) at large momentum transfers should scale as:

\[
\frac{d\sigma}{dt} = f(\theta_{\text{CM}}) \frac{1}{s^{n-2}}
\]

- First derived based on dimensional analysis (Brodsky, Farrar,....)
- Confirmed within short distance pQCD framework (Brodsky, Le page)
- Many exclusive process seem to exhibit global quark counting rule behavior
Elastic $p-p$ Scattering

From data compilation of Landshoff and Polkinghorn

Quark counting rule predicts

$$\frac{d\sigma}{dt} \propto s^{-10}$$
Deuteron Photo-disintegration

\[ \gamma + d \rightarrow p + n \]

Studied at SLAC, and most recently at JLab.

Quark counting rule predicts:

\[ \frac{d\sigma}{dt} \propto S^{-11} \]

Studied at SLAC, and most recently at JLab.
Deuteron Photo-disintegration

\[ \gamma + d \rightarrow p + n \quad @ \quad 90 \text{ deg CM angle} \]

JLab E89-012

C. Bochna et al., PRL 81, 4576 (1998)
Hadron Helicity Conservation

Short distance pQCD predicts helicity conservation in exclusive two-body processes (A+B→C+D)

\[ \lambda_A + \lambda_B = \lambda_C + \lambda_D \]

- Based on quark helicity conservation.
- Experimental data tends not to agree with HHC.
Hadron Helicity Conservation

\[ \vec{\gamma} + d \rightarrow \vec{p} + n \]

K. Wijesooriya et al., PRL 86, 2975 (2001)
Elastic $p-p$ Scattering

From data compilation of Landshoff and Polkinghorn

quark counting rule predicts

$$\frac{d\sigma}{dt} \propto s^{-10}$$
Elastic $p-p$ Scattering

$$R_i \propto s^{10} \frac{d\sigma}{dt}$$

J. P. Ralston and B. Pire, PRL 61, 1823 (1988)
Oscillatory Scaling Behavior

The oscillations in the scaled cross-section explained as:

- Resonance state production near the charm threshold (*Brodsky, Schmidt*, ……).

- Interference between short distance (*Born*) and long distance (*Landshoff*) amplitudes, (*Ralston & Pire and Carlson, Myhrer*, …….)
Born vs Independent Scattering Amplitude in $p-p$ Scattering

- Born amplitude

- Independent scattering (Landshoff) amplitude

  Corrections due to gluon radiation (Sudakov Effect)
What happens to the oscillatory scaling behavior in the nuclear medium?

- It has been suggested that they are damped out because the long distance amplitude is suppressed in the nuclear medium.

- This is called “Nuclear Filtering.”

- This implies there should be oscillations in nuclear transparency $180^\circ$ out-of-phase with the oscillations in the free cross-section.
Transparency in $A(p,2p)$ Processes

\[ p + {}^A_{\text{N}}z_p \rightarrow p + p + X \] @ BNL

- BNL results explained in terms of Nuclear Filtering (Ralston & Pire)
- In terms of charm resonance states (Brodsky & Le page).
Nuclear Filtering with Photo-pions

Large oscillations in photo-pion transparency predicted by Jain, Kundu and Ralston.

- Amplitude depends on an additional nuclear phase.
- Can be tested with photo-pion production from Carbon.
Nuclear Filtering vs CT

- **Nuclear filtering** uses the medium *actively* to suppress the long-distance amplitude.

- In **CT** the large momentum transfer selects the short distance amplitude which is then free to propagate through the *passive* medium.

- The CT limit is $Q \rightarrow \infty$, and the onset of CT is expected to be sooner on lighter nuclei.

- The nuclear filtering limit is $A \gg 1$, and the effect bigger in heavier nuclei.
Drawing the Roadmap

- **Matter at high densities**
  - Modification of nuclear structure at high densities
  - High density fluctuations in nuclei
  - Deep inelastic scattering at x > 1
  - Tagged structure functions

- **Exclusive processes at high momentum transfer**
  - Color transparency
  - Nuclear Filtering

- **Probing the limits of nucleon based description of nuclei**
The Nucleon Meson Picture

Nucleus: made of individual nucleons interacting via 2 and 3 body potentials

Describes data from KeV (e.g. Solar reactions) to GeV (e.g. Deuteron form factors) range.

but

Short range interactions are poorly constrained

EM probe: Interacts via 1, 2 and many body currents

Questions:
• How do these potentials and currents arise from the underlying quark-gluon degrees of freedom?

• At what length scales ($Q^2$) does this model fail?
The existence of quarks in the nucleus will be shown by the failure of nucleon-meson models.

Possible measurements

- Few body elastic form factors at high $Q^2$
- Deuteron photodisintegration
- $A(e,e')X$ ratios at $x > 1$ and $x > 2$
- $He(e,e'pp)n$ to measure correlated pp pairs
Deuteron and Helium Form Factors

\[ \frac{d\sigma}{d\Omega} = (K)[A(Q^2)\cos^2(\theta/2) + B(Q^2)\sin^2(\theta/2)] \]

Forward angle scattering \( \rightarrow A(Q^2) \)

Backward angle scattering \( \rightarrow B(Q^2) \)

High precision measurements of formfactors at high \( Q^2 \) will test nucleonic vs quark-gluon models.
Deuteron Form Factors

\[ A(Q^2) \]

- JLab Hall A
- SLAC E101
- Saclay
- Bonn
- CEA
- JLab Hall C

RIA+MEC

- VDG
- HT
- PW

\[ B(Q^2) \]

- JLab Hall A
- SLAC NE4
- Saclay
- Bonn

RIA+MEC

- VDG
- HT
- PW

M Petratos
Deuteron Form Factors

\begin{align*}
A(Q^2) &\sim 10^{-5} \\
B(Q^2) &\sim 10^{-5}
\end{align*}

\begin{align*}
Q^2 &\sim [\text{GeV}/c]^2
\end{align*}

\text{Data Sources:}
- JLab Hall A
- SLAC E101
- Saclay
- Bonn
- CEA
- JLab Hall C

\text{Projected Data:}
- JLab Projected
- ECAL (e)
- MAD (d)
Deuteron Photo-disintegration

\[ \gamma + d \rightarrow p + n \quad \text{at 90 degree CM angle} \]

JLab E89-012

C. Bochna et al., PRL 81, 4576 (1998)
\[ ^3\text{He}(e,e'pp)n \]

Detect 3 fast nucleons \((p > 250 \text{ MeV/c})\)

\[
p_N > 250 \text{MeV/c} \]

\[
T_N < 0.2 \omega
\]

L.B. Weinstein
\[ ^3\text{He}(e,e'pp)n \]

When one nucleon has most of the energy, the other two are preferentially back to back.

Opening angle of the fast pn pair

Might be the first direct measurement of NN correlations.

Studies at higher \( Q^2 \) will be effective tests of nucleonic models.
Summary

- Studying hadrons in the nuclear medium and comparing them to free hadrons provides a unique opportunity for understanding nucleons and nuclei in terms of quarks and gluons.

- One can look for modifications in the structure and interactions of hadrons in the nucleus.

- There are hints of such modifications from experiments, but precision experiments at JLab will provide a more complete picture.

- One can also look for signatures of transition from the nucleon-meson to the quark-gluon picture, such as color transparency and nuclear filtering.
Summary

- So far there is no unambiguous evidence for color transparency but the program at JLab is likely to provide definitive answers.

- JLab also has an impressive array of experiments looking for the limits of the nucleon-meson description of nuclei.