Quark Structure of the Nucleon

Wally Melnitchouk

Jefferson Lab
Lecture 1

- QCD and the strong nuclear force

- Electron-nucleon scattering

- Quark distributions in the nucleon
  - valence quarks at large $x$
  - nuclear effects on quark structure
Outline

Lecture 2

- Quark-hadron duality
- “Bloom-Gilman” duality in structure functions
- Duality in QCD
- Resonances & local quark-hadron duality
  - “truncated” moments in QCD
- Duality in the neutron
  - extraction of neutron resonance structure from nuclear data
Lecture 3

- Elastic $ep$ scattering
- Two-photon exchange
  - Rosenbluth separation vs. polarization transfer
- Global analysis of form factors
- Parity-violating electron scattering
  - strangeness in the proton
  - constraints on “new” physics
QCD and the strong nuclear force
Building Blocks of the Universe

Each quark comes in 3 “colours”: red, green and blue.

Leptons do not carry color charge.

<table>
<thead>
<tr>
<th>FERMIONS</th>
<th>matter constituents spin (= \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leptons</strong> spin (= \frac{1}{2} )</td>
<td><strong>Quarks</strong> spin (= \frac{1}{2} )</td>
</tr>
<tr>
<td><strong>Flavor</strong></td>
<td><strong>Mass GeV/c^2</strong></td>
</tr>
<tr>
<td>(\nu_e) electron neutrino</td>
<td>(&lt;1 \times 10^{-8})</td>
</tr>
<tr>
<td>(e) electron</td>
<td>0.000511</td>
</tr>
<tr>
<td>(\nu_\mu) muon neutrino</td>
<td>(&lt;0.0002)</td>
</tr>
<tr>
<td>(\mu) muon</td>
<td>0.106</td>
</tr>
<tr>
<td>(\nu_\tau) tau neutrino</td>
<td>(&lt;0.02)</td>
</tr>
<tr>
<td>(\tau) tau</td>
<td>1.7771</td>
</tr>
</tbody>
</table>
Building Blocks of the Universe

Each quark comes in 3 “colours”: red, green and blue.

Leptons do not carry color charge.

Most of visible matter made up of these

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c^2</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>e electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>μ muon</td>
<td>0.106</td>
<td>-1</td>
</tr>
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<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c^2</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>
Force Carriers of the Universe

**BOSONS**

<table>
<thead>
<tr>
<th>Unified Electroweak</th>
<th>spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td><strong>Mass GeV/c²</strong></td>
</tr>
<tr>
<td>$\gamma$ photon</td>
<td>0</td>
</tr>
<tr>
<td>$W^-$</td>
<td>80.4</td>
</tr>
<tr>
<td>$W^+$</td>
<td>80.4</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>91.187</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strong (color)</th>
<th>spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td><strong>Mass GeV/c²</strong></td>
</tr>
<tr>
<td>g gluon</td>
<td>0</td>
</tr>
</tbody>
</table>

- The massless photon mediates the long-range e.m. interactions.
- Gluons carry color and mediate the strong interaction.
- The very massive $W^-$, $W^+$, and $Z^0$ bosons mediate the weak interaction.
• The massless photon mediates the long-range e.m. interactions.
• Gluons carry color and mediate the strong interaction.
• The very massive $W^-$, $W^+$, and $Z^0$ bosons mediate the weak interaction.
Quantum Chromodynamics (QCD)

- Photons do not carry electric charge.
- Gluons do carry colour charge!
- Gluons can directly interact with other gluons!
- This is new!

A red quark emitting a red anti-blue gluon to leave a blue quark.

Quark-quark force grows WEAKER as quarks come close “Asymptotic Freedom”
Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Page 16

Pentaquark Summary

• Existence or otherwise is a CRUCIAL question in strong interaction physics
• Wilczek, Jaffe: That we cannot say whether such exotica exist or not shows HOW LITTLE WE UNDERSTAND NON-PERTURBATIVE QCD
• Jefferson Lab is the ideal facility to definitively answer this question!
**Operated by the Southeastern Universities Research Association for the U.S. Department of Energy**

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**2004 Nobel Prize for discovery of asymptotic freedom (1973)**
(Gross, Politzer, Wilczek)
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Calculate observables using perturbation theory as power series in small expansion parameter \( \alpha_s \)
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BUT - only part of the story... at low energy \textit{confinement}!
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→ $\alpha_s \sim 1$ so cannot use perturbative expansion
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BUT - only part of the story...

at low energy $\rightarrow$ confinement!

$\alpha_s \sim 1$ so cannot use perturbative expansion

here QCD said to be “nonperturbative”
QCD: Unsolved in Nonperturbative Regime

• 2004 Nobel Prize awarded for “asymptotic freedom”

• BUT in nonperturbative regime QCD is still unsolved

• One of the top 10 challenges for physics!

• Is it right/complete?

• Do glueballs, exotics and other apparent predictions of QCD in this regime agree with experiment?

central to answering these questions is the need to understand how quarks form hadrons
Looking for quarks in the nucleon is like looking for the Mafia in Sicily - everybody *knows* they’re there, but it’s hard to find the evidence!

Anonymous
"Quarks, neutrinos, mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them."
How to probe the structure of hadrons?
How to probe the structure of hadrons?

collide hadrons
How to probe the structure of hadrons?

collide hadrons

probe with leptons
How to probe the structure of hadrons?

collide hadrons

probe with leptons
Electron Scattering Provides an Ideal Microscope for Nuclear Physics

- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is weak
- Vary $q$ to map out Fourier Transforms of charge and current densities:

$$\frac{1}{q} \int \frac{d^3 \rho}{(2\pi)^3} \left\langle \frac{\rho}{q} \right\rangle$$

22

4-Momentum Transfer $Q q = e = \ldots$ CEBAF's e and CW beams dramatically enhance the power of electron scattering
Electron scattering
(at Jefferson Lab)
located in Newport News, Virginia

“discovery” of America, Jamestown (1607)
Thomas Jefferson National Accelerator Facility (Jefferson Lab)

located in Newport News, Virginia

“discovery” of America, Jamestown (1607)

first naval battle with metal ships (Civil War, 1865)
Newport News, Virginia
Thomas Jefferson National Accelerator Facility (Jefferson Lab)
Thomas Jefferson National Accelerator Facility (Jefferson Lab)

my office

electron linacs

Hall A
Hall B
Hall C
Experimental Halls

*Hall A*

- high luminosity
  $> 10^{38} \text{ cm}^{-2} \text{ s}^{-1}$

- very high precision measurements

*Hall C*

- high $Q^2$ form factors, parity-violating $e$ scattering, precision structure functions
Experimental Halls

- Large acceptance
- Lower luminosity
  \[ \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \]
- Collect all data “at once”
- \( N^* \) spectroscopy
  (multi-hadron final states),
  deep exclusive reactions
  (generalized parton distributions)

Hall B

CLAS
(CEBAF Large Acceptance Spectrometer)
Experimental Halls

- new Hall to be constructed as part of 12 GeV Upgrade

- $4\pi$ acceptance

- photon beam

- exotic meson spectroscopy ($q\bar{q}g$ states)
JLab Central to all of Nuclear Science

Nature of Confinement
- Exotic mesons and baryons
- Vacuum
- Quarks and gluons
- Few-body
- Precise few-nucleon calculations
- Correlations
  - n-radii: $N \neq Z$
  - Hypernuclei
  - Hadrons in-medium
  - Effective NN (+ HN) force

Quark-Gluon Structure
- Of Nucleons and Nuclei
- Heavy nuclei
- ...n-stars
Electron scattering

_theory_
**Electron scattering**

**Inclusive cross section for** \( eN \rightarrow eX \)

most likely event at high energy

one-photon exchange approximation
Electron scattering

Inclusive cross section for $eN \rightarrow eX$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2 \frac{\theta}{2}}{Q^4} \left( 2 \tan^2 \frac{\theta}{2} \frac{F_1}{M} + \frac{F_2}{\nu} \right)$$

$$\nu = E - E'$$

$$Q^2 = q^2 - \nu^2 = 4EE' \sin^2 \frac{\theta}{2}$$

$$x = \frac{Q^2}{2M\nu} \quad \text{“Bjorken scaling variable”}$$

$F_1, F_2$ “structure functions”

contain all information about structure of nucleon

functions of $x, Q^2$ in general
Parton model

scatter from individual quarks ("partons") in hadron

\[ F_2(x, Q^2) = x \sum_q e_q^2 \ q(x, Q^2) \quad (q=u,d,s...) \]
Parton model

scatter from individual quarks ("partons") in hadron

\[ F_2(x, Q^2) = x \sum_q e_q^2 q(x, Q^2) \quad (q=u,d,s...) \]

\[ q(x,Q^2) = \text{probability to find quark type "q" in nucleon, carrying (light-cone) momentum fraction } x \]

\[ x = \frac{p_q^+}{p_N^+} = \frac{p_q^0 + p_q^z}{p_N^0 + p_N^z} \]
**Parton model**

→ scatter from individual quarks ("partons") in hadron

\[ F_2(x, Q^2) = x \sum_q e_q^2 q(x, Q^2) \quad (q=u,d,s...) \]

\[ \rightarrow Q^2 \text{ dependence given by (perturbatively calculable) QCD evolution equations} \quad (\rightarrow \log Q^2 \text{ behavior}) \]

\[ \rightarrow \text{ at large } Q^2, \text{ "Callan-Gross relation" } \quad F_2 \approx 2x F_1 \]
Structure function data

Spin dependent scattering

- Nucleon polarized along \( z \)-axis

\[
\frac{d^2 \sigma}{d\Omega dE'} (\uparrow \uparrow - \downarrow \uparrow) = \frac{4\alpha^2 E'}{M\nu EQ^2} \left[ (E + E' \cos \theta) g_1 - 2Mx g_2 \right]
\]

- Electron spin parallel or anti-parallel to nucleon spin

- Usually measure polarization asymmetry \( A_1 = \frac{g_1}{F_1} \)
Spin dependent scattering

Parton model

\[ g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \Delta q(x, Q^2) \]

\[ \Delta q = q^{\uparrow\uparrow} - q^{\downarrow\uparrow} \]

probability to find quark “q” with spin aligned vs. antialigned with nucleon spin

gives total spin of nucleon carried by quarks

\[ \Delta \Sigma = \Delta u + \Delta d + \Delta s \]
Spin dependent scattering

Spin sum rule

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]
Spin dependent scattering

Spin sum rule

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

- spin carried by gluons
- \( q \) and \( g \) orbital angular momentum
Spin dependent scattering

Spin sum rule

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

- spin carried by gluons
- \( q \) and \( g \) orbital angular momentum

→ naive (nonrelativistic) expectation: \( \Delta \Sigma \sim 1 \)

→ early experiments: \( \Delta \Sigma \sim 0 \) “proton spin crisis”

→ latest data: \( \Delta \Sigma \sim 0.3 \) (RGI scheme)

→ where is the proton spin?
STAR (RHIC) data on $\vec{p} \vec{p} \rightarrow$ jets

$\Delta g \approx 0$

“statistically consistent with zero”


HERMES proton + JLab neutron data on deeply virtual Compton scattering

$J_u \sim 0.4 \pm 0.2$

$J_d \sim 0.1 \pm 0.2$

“model-dependent extraction”
Parton distributions functions

- PDFs extracted in global analyses of structure function data from electron, muon & neutrino scattering (also from Drell-Yan & W-boson production in hadronic collisions)
  - determined over large range of $x$ and $Q^2$

- provide basic information on structure of QCD bound states

- needed to understand backgrounds in searches for physics beyond the Standard Model in high-energy colliders
  - *e.g.* neutrino oscillations
recent parameterization

virtual “sea” of $q\bar{q}$ pairs & gluons at small $x$

structure of hadron or structure of probe?
$x f(x, Q)$

\[ Q^2 = 25 \text{ GeV}^2 \]

- $u_v$
- $d_v$
- $\bar{u}$
- $\bar{d}$
- $s$
- $g/15$

**Sea quarks & gluons**

$q = u, d, s...$

$\bar{q} = \bar{u}, \bar{d}, \bar{s}...$

**Valence quarks**

$p$ - $u$

$p$ - $u$

$p$ - $d$
Quark distributions

valence quarks
Valence quarks

- Most direct connection between quark distributions and models of the nucleon is through *valence* quarks.
- Nucleon structure at intermediate & large $x$ dominated by valence quarks.
At large $x$, valence $u$ and $d$ distributions extracted from $p$ and $n$ structure functions

\[ F_2^p \approx \frac{4}{9} u_v + \frac{1}{9} d_v \]

\[ F_2^n \approx \frac{4}{9} d_v + \frac{1}{9} u_v \]
Valence quarks

- At large $x$, valence $u$ and $d$ distributions extracted from $p$ and $n$ structure functions

\[
F_{2}^{p} \approx \frac{4}{9}u_{v} + \frac{1}{9}d_{v}
\]

\[
F_{2}^{n} \approx \frac{4}{9}d_{v} + \frac{1}{9}u_{v}
\]

- $u$ quark distribution well determined from $p$

- $d$ quark distribution requires $n$ structure function

\[
\frac{d}{u} \approx \frac{4 - F_{2}^{n}/F_{2}^{p}}{4F_{2}^{n}/F_{2}^{p} - 1}
\]
Valence quarks

- Ratio of $d$ to $u$ quark distributions particularly sensitive to quark dynamics in nucleon
- SU(6) spin-flavor symmetry

**Proton wave function**

$$p^\dagger = -\frac{1}{3} d^\dagger (uu)_1 - \frac{\sqrt{2}}{3} d^\downarrow (uu)_1$$

$$+ \frac{\sqrt{2}}{6} u^\dagger (ud)_1 - \frac{1}{3} u^\downarrow (ud)_1 + \frac{1}{\sqrt{2}} u^\dagger (ud)_0$$
Valence quarks

- Ratio of $d$ to $u$ quark distributions particularly sensitive to quark dynamics in nucleon

- $\text{SU}(6)$ spin-flavor symmetry

**Proton wave function**

\[
p_{\uparrow} = -\frac{1}{3} d_{\uparrow}^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3} d_{\downarrow}^{\downarrow}(uu)_1
\]
\[
+ \frac{\sqrt{2}}{6} u_{\uparrow}^{\uparrow}(ud)_1 - \frac{1}{3} u_{\downarrow}^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}} u^{\uparrow}(ud)_0
\]

\[u(x) = 2 \ d(x) \quad \text{for all } x\]

\[
\frac{F_n^2}{F_p^2} = \frac{2}{3}
\]
**scalar diquark dominance**

\[ M_\Delta > M_N \implies (qq)_1 \text{ has larger energy than } (qq)_0 \]

\[ \implies \text{ scalar diquark dominant in } x \to 1 \text{ limit} \]
Valence quarks

- **scalar diquark dominance**

\[ M_\Delta > M_N \implies (qq)_1 \text{ has larger energy than } (qq)_0 \]

\[ \implies \text{scalar diquark dominant in } x \to 1 \text{ limit} \]

since only \( u \) quarks couple to scalar diquarks

\[ \frac{d}{u} \to 0 \]

\[ \frac{F_2^n}{F_2^p} \to \frac{1}{4} \]

Valence quarks

- **hard gluon exchange**

At large $x$, helicity of struck quark = helicity of hadron

$q^\uparrow \gg q^\downarrow$
Valence quarks

- **hard gluon exchange**

at large $x$, helicity of struck quark = helicity of hadron

$\rightarrow$ **helicity-zero diquark dominant in $x \rightarrow 1$ limit**

\[
\begin{align*}
\frac{d}{u} & \rightarrow \frac{1}{5} \\
\frac{F_2^n}{F_2^p} & \rightarrow \frac{3}{7}
\end{align*}
\]

Farrar, Jackson 1975
Polarized valence quarks

SU(6) symmetry

\[ A_p^1 = \frac{5}{9}, \quad A_n^1 = 0 \]

\[ \frac{\Delta u}{u} = \frac{2}{3}, \quad \frac{\Delta d}{d} = -\frac{1}{3} \]
SU(6) symmetry

\[ A^p_1 = \frac{5}{9}, \quad A^n_1 = 0 \]

\[ \Delta u = \frac{2}{3}, \quad \Delta d = -\frac{1}{3} \]

scalar diquark dominance

\[ A^p_1 \rightarrow 1, \quad A^n_1 \rightarrow 1 \]

\[ \Delta u \rightarrow 1, \quad \Delta d \rightarrow -\frac{1}{3} \]
Polarized valence quarks

**SU(6) symmetry**

\[ A_1^p = \frac{5}{9}, \quad A_1^n = 0 \]

\[ \Delta u = 2, \quad \Delta d = -\frac{1}{3} \]

**scalar diquark dominance**

\[ A_1^p \rightarrow 1, \quad A_1^n \rightarrow 1 \]

\[ \Delta u \rightarrow 1, \quad \Delta d \rightarrow -\frac{1}{3} \]

**hard gluon exchange**

\[ A_1^p \rightarrow 1, \quad A_1^n \rightarrow 1 \]

\[ \Delta u \rightarrow 1, \quad \Delta d \rightarrow 1 \]
No **FREE** neutron targets
(neutron half-life ~ 12 mins)

- use deuteron as “effective” neutron target

**BUT** deuteron is a nucleus, and $F_2^d \neq F_2^p + F_2^n$

- nuclear effects (nuclear binding, Fermi motion, shadowing)
  *obscure neutron structure* information

- “nuclear EMC effect”
Quark distributions

nuclear effects
Nuclear “EMC effect”

\[ F_2^A(x, Q^2) \neq AF_2^N(x, Q^2) \]

Original EMC data

Later SLAC data


Nuclear “EMC effect”

- Shadowing
- Anti-shadowing
- Multiple scattering

\[ \frac{F_2^A}{F_2^d} \]

\[ x \]

anti-shadowing pions?

Fermi motion

“EMC effect”

binding, \( N \) off-shell
Nuclear “EMC effect”

anti-shadowing pions?

shadowing
multiple scattering

what about $d/N$?

Fermi motion

“EMC effect”

binding, $N$ off-shell
EMC effect in deuteron

Nuclear “impulse approximation”

incoherent scattering from individual nucleons in deuteron
Nuclear “impulse approximation”

incoherent scattering from individual nucleons in deuteron

\[ F_2^d(x) = \int dy \, f_{N/d}(y) \, F_2^N(x/y) + \delta^{(\text{off})} F_2^d(x) \]

nucleon momentum distribution

off-shell correction
Nucleon momentum distribution in deuteron

- relativistic $dNN$ vertex function

$$f_{N/d}(y) = \frac{1}{4}M_d \ y \int_{-\infty}^{p_{\text{max}}^2} dp^2 \frac{E_p}{p_0} \left| \Psi_d(p^2) \right|^2$$
Nucleon momentum distribution in deuteron

relativistic $dNN$ vertex function

$$f_{N/d}(y) = \frac{1}{4} M_d y \int_{-\infty}^{p_{\text{max}}^2} dp^2 \frac{E_p}{p_0} |\Psi_d(\vec{p}^2)|^2$$

momentum fraction of deuteron carried by nucleon
Nucleon momentum distribution in deuteron

\[ f_{N/d}(y) = \frac{1}{4} M_d \ y \int_{-\infty}^{p_{\text{max}}^2} dp^2 \frac{E_p}{p_0} \left| \Psi_d(p^2) \right|^2 \]
EMC effect in deuteron

Nucleon momentum distribution in deuteron

- relativistic $dNN$ vertex function

$$f_{N/d}(y) = \frac{1}{4} M_d \ y \int_{-\infty}^{p_{\text{max}}^2} dp^2 \frac{E_p}{p_0} \left| \Psi_d(p^2) \right|^2$$

Wave function dependence only at large $|y-1/2|

- sensitive to large-$p$ components of wave function
EMC effect in deuteron

Nucleon momentum distribution in deuteron

\[ f_{N/d}(y) = \frac{1}{4} M_d \ y \int_{-\infty}^{p_{\text{max}}^2} \ dp^2 \frac{E_p}{p_0} |\Psi_d(p^2)|^2 \]

Nucleon off-shell correction

\[ \delta^{(\text{off})} F_{2d} \]
Nucleon momentum distribution in deuteron

\[ f_{N/d}(y) = \frac{1}{4} M_d \ y \int_{-\infty}^{p_{\text{max}}^2} dp^2 \frac{E_p}{p_0} \left| \Psi_d(p^2) \right|^2 \]

Nucleon off-shell correction

\[ \delta^{(\text{off})} F_2^d \rightarrow \delta^{(\Psi)} F_2^d \]

negative energy components of \( d \) wave function
EMC effect in deuteron

Nucleon momentum distribution in deuteron

→ relativistic $dNN$ vertex function

$$f_{N/d}(y) = \frac{1}{4} M_d \ y \int_{-\infty}^{p_{\max}^2} dp^2 \frac{E_p}{p_0} |\Psi_d(p^2)|^2$$

Nucleon off-shell correction

$$\delta^{(\text{off})} F_2^d \rightarrow \delta^{(\Psi)} F_2^d$$

negative energy components of $d$ wave function

$$\delta(p^2) F_2^d$$

off-shell $N$ structure function
Off-shell correction

\[ \delta(p^2) F_2^d \]

\[ \delta(\Psi) F_2^d \]

\[ \leq 1 - 2\% \text{ effect} \]

EMC effect in deuteron

- full model
- light-cone

Fermi motion only

with binding + off-shell

larger EMC effect (smaller $d/N$ ratio)

with off-shell + binding corrections
Neutron to proton ratio

$F_2^n$ underestimated at large $x$!
$Q^2 = 10 \text{ GeV}^2$

- **QCD fit**
- **CTEQ4M**
- **CTEQ4M (modified)**

The graph shows the fitted range for $x$ from 0 to 0.8.
large uncertainty from nuclear effects in deuteron (range of nuclear models) beyond $x \sim 0.5$
“Cleaner” methods of determining $d/u$

\begin{align*}
e^+ p & \to \nu(\bar{\nu})X \\
\nu(\bar{\nu}) p & \to l^+ X \\
p p(\bar{p}) & \to W^\pm X \\
\bar{e}_L(\bar{e}_R) p & \to e X \\
e^- p & \to e \pi^\pm X \\
e^{-3}He(^{-3}H) & \to e X \\
e^- d & \to e p_{\text{spec}} X
\end{align*}

\begin{align*}
\{ & \text{weak current as flavor probe} \\
\to & \text{difficult to get high rates/luminosities} \\
\text{need } z \sim 1, \text{factorization} \\
3He^{-\text{tritium mirror nuclei}} & \\
\to & \text{semi-inclusive DIS from } d \\
\to & \text{tag “spectator” protons}
\end{align*}
“Cleaner” methods of determining $d/u$

\[
\begin{align*}
  e^+ p &\rightarrow \nu(\bar{\nu}) X \\
  \nu(\bar{\nu}) p &\rightarrow l^\pm X \\
  p p(\bar{p}) &\rightarrow W^{\pm} X \\
  \bar{e}_L e_R p &\rightarrow e X \\
  e p &\rightarrow e \pi^{\pm} X \\
  e \, ^3\text{He}(^3\text{H}) &\rightarrow e X \\
  e d &\rightarrow e \, p_{\text{spec}} X
\end{align*}
\]

- weak current as flavor probe
- difficult to get high rates/luminosities

- need $z \sim 1$, factorization

- $^3\text{He}$-tritium mirror nuclei

- semi-inclusive DIS from $d$
- tag “spectator” protons
EMC ratios for $A=3$ mirror nuclei

\[ R(\text{He}) = \frac{F^3\text{He}}{2F_p^p + F_n^n} \]

\[ R(\text{H}) = \frac{F^3\text{H}}{F_p^p + 2F_n^n} \]

Extract $n/p$ ratio from measured $^3\text{He}-^3\text{H}$ ratio

\[ \frac{F_n^n}{F_p^p} = \frac{2R - \frac{F^3\text{He}}{F^3\text{H}}}{\frac{2F^3\text{He}}{F^3\text{H}} - R} \]

\[ R = \frac{R(\text{He})}{R(\text{H})} \]
\[ R(\textsuperscript{3}He) / R(\textsuperscript{3}H) \]

- PEST + CSB
- PEST

\[ x \]

→ nuclear effects cancel to < 1% level

Afnan et al.,
PRC 68 (2003) 035201
$^3\text{He} - ^3\text{H}$ mirror

$F_{2n}/F_{2p}$ vs. $x$

- Green triangles: Frankfurt and Strikman
- Red circles: Melnitchouk and Thomas
- Blue squares: Bodek et al.

$F_{2n}/F_{2p}$ vs. $x$

- Black circles: JLab Projected Data

$^3\text{H}/^3\text{He}$ DIS
Spectator proton tagging

$e\, d \rightarrow e\, p\, X$

target $d$

recoil $p$

slow backward $p$

→ neutron nearly on-shell

→ minimize rescattering
Spectator proton tagging

\[ e \, d \rightarrow e \, p \, X \]

target \( d \)

recoil \( p \)

slow backward \( p \)

neutron nearly on-shell

minimize rescattering

JLab Hall B experiment ("BoNuS")
run completed Dec. 2005

\[ Q^2 = 4-9 \text{ GeV}^2 \]

\[ Q^2 = 9-15 \text{ GeV}^2 \]
Spectator proton tagging

\[ e \, d \rightarrow e \, p \, X \]

- **Spectator proton tagging**
- **inclusive cross section**
- **semi-inclusive cross section**

- **Target d**
- **Recoil p**
- **Slow backward p**
- **Neutron nearly on-shell**
- **Minimize rescattering**

\[ W^*, \text{GeV} \]

- **More pronounced neutron resonance structure visible**
Spectator proton tagging

\[ e d \rightarrow e p X \]

- Target d
- Recoil p
- Slow backward p
- Neutron nearly on-shell
- Minimize rescattering

\[ 1.6 < W \text{ (GeV)} < 2.9 \]

First "proof of principle" data

Extend to \( x \sim 0.85 \) after 12 GeV Upgrade
Polarization asymmetries

\[ A_1^n \rightarrow 1 \]

pQCD (helicity conservation)

\[ A_1^n \rightarrow 1 \]

scalar diquark dominance

SU(6) symmetry

\[ A_1^n = 0 \]

Zheng et al., PRL 92 (2004) 012004
Polarization asymmetries

at large $x$, $A_1^n$ is essentially unknown!

pQCD (helicity conservation)

$A_1^n \rightarrow 1$

scalar diquark dominance

$A_1^n \rightarrow 1$

SU(6) symmetry

$A_1^n = 0$

Zheng et al., PRL 92 (2004) 012004
**Polarization asymmetries**

pQCD (helicity conservation)

\[
\frac{\Delta u}{u} \rightarrow 1 \quad , \quad \frac{\Delta d}{d} \rightarrow 1
\]

scalar diquark dominance

\[
\frac{\Delta u}{u} \rightarrow 1 \quad , \quad \frac{\Delta d}{d} \rightarrow -\frac{1}{3}
\]

SU(6) symmetry

\[
\frac{\Delta u}{u} = \frac{2}{3} \quad , \quad \frac{\Delta d}{d} = -\frac{1}{3}
\]
Polarization asymmetries

\[
\frac{\Delta u}{u} \to 1, \quad \frac{\Delta d}{d} \to 1
\]

scalar diquark dominance

\[
\frac{\Delta u}{u} \to 1, \quad \frac{\Delta d}{d} \to -\frac{1}{3}
\]

SU(6) symmetry

\[
\frac{\Delta u}{u} = \frac{2}{3}, \quad \frac{\Delta d}{d} = -\frac{1}{3}
\]

no evidence yet of pQCD behavior!
Polarization asymmetries

pQCD (helicity conservation)
\[ \frac{\Delta u}{u} \rightarrow 1, \quad \frac{\Delta d}{d} \rightarrow 1 \]

scalar diquark dominance
\[ \frac{\Delta u}{u} \rightarrow 1, \quad \frac{\Delta d}{d} \rightarrow -\frac{1}{3} \]

SU(6) symmetry
\[ \frac{\Delta u}{u} = \frac{2}{3}, \quad \frac{\Delta d}{d} = -\frac{1}{3} \]
Electron scattering

→ clean probe of quark structure of nucleon
→ new era of experiments with unprecedented precision

Valence quarks at large $x$

→ $d$ quark properties unknown at large $x$
→ nuclear corrections in deuteron important
  \textit{(deuteron is a nucleus!)}
→ long-standing puzzles about $x \to 1$ behavior of valence quarks will soon be solved!