The Quark-Parton Model of the Nucleon Missing Links*

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Electron-Nucleon (Nucleus) Inelastic Scattering: Interaction is mediated via exchange of a virtual photon absorbed by one of the constituent quarks. Nucleon (Nucleus) breaks up into X hadrons. A typical experiment detects only scattered electrons.
Electron-Nucleus Inelastic Scattering

• Cross section for inelastic electron-nucleus scattering \([E (E')]:\) incident (scattered) electron energy, \(\theta:\) electron scattering angle, \(M: \) nucleon mass] in terms of nuclear \(F_1\) and \(F_2\) structure functions:

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

\[R = \frac{F_2M}{F_1\nu} \left(1 + \frac{\nu^2}{Q^2} \right) - 1\]

\[\nu = E - E'\]

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

• \(R\) has been measured to be the same for all nuclei. Therefore, the cross section ratio for any two nuclei, e.g. 3H and 3He, becomes equal to ratio of their \(F_2\) structure functions:

\[
\left[ \frac{d\sigma(3H)}{d\Omega dE'} / \frac{d\sigma(3He)}{d\Omega dE'} \right] = \left[ F_2(3H) / F_2(3He) \right]
\]
Deep Inelastic Scattering and Quark Parton Model

• In the Quark Parton Model (QPM) of the nucleon, as established from the SLAC experiments, the electron scatters from one of its 3 valence quarks, which interact through exchange of massless gluons, the carriers of the strong force in nature.

• In Deep Inelastic Scattering (DIS), where both $Q^2$ and $\nu$ are large, the structure functions depend only on the Bjorken scaling variable $x=Q^2/2M\nu$, which is the fraction of the nucleon momentum carried by the struck quark.

• QPM interpretation of the nucleon structure functions in terms of the probability distribution functions, $q_i(x)$, of the $i$ quarks [up $u(x)$, down $d(x)$, and strange $s(x)$] and their electric charges $e_i$:

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x) \quad F_2(x) = x \sum_i e_i^2 q_i(x)$$
**$F_2^n/F_2^p$ in Quark Parton Model**

- **Assume isospin symmetry:**
  
  \[
  u^p(x) \equiv d^n(x) \equiv u(x) \quad \bar{u}^p(x) \equiv \bar{d}^n(x) \equiv \bar{u}(x)
  \]
  
  \[
  d^p(x) \equiv u^n(x) \equiv d(x) \quad \bar{d}^p(x) \equiv \bar{u}^n(x) \equiv \bar{d}(x)
  \]
  
  \[
  s^p(x) \equiv s^n(x) \equiv s(x) \quad \bar{s}^p(x) \equiv \bar{s}^n(x) \equiv \bar{s}(x)
  \]

- **Proton and neutron structure functions (from definition):**

  \[
  F_2^p = x \left[ \frac{4}{9} (u + \bar{u}) + \frac{1}{9} (d + \bar{d}) + \frac{1}{9} (s + \bar{s}) \right]
  \]

  \[
  F_2^n = x \left[ \frac{4}{9} (d + \bar{d}) + \frac{1}{9} (u + \bar{u}) + \frac{1}{9} (s + \bar{s}) \right]
  \]

- **Nachtmann inequality:**

  \[
  1/4 \leq F_2^n / F_2^p \leq 4
  \]
$F_{2n}/F_{2p}$ extracted from proton and deuterium deep inelastic data using Hamada-Johnston potential with a non-relativistic Fermi-smearing model.

Data in disagreement with $SU(6)$ prediction: $2/3 = 0.67!$
SLAC End Station A
1.6, 8, and 20 GeV/c Magnetic Spectrometers
SLAC/CERN Data Interpretation in QPM

• Nachtmann inequality satisfied:
  \[ \frac{F_2^n}{F_2^p} \leq 4 \]

• For \( x \to 0 \): \( \frac{F_2^n}{F_2^p} \to 1 \): Sea quarks dominate with:
  \[ u + \bar{u} = d + \bar{d} = s + \bar{s} \]

• For \( x \to 1 \): \( \frac{F_2^n}{F_2^p} \to 1/4 \): High momentum partons in proton (neutron) are up (down) quarks, and:
  \[ s + \bar{s} = 0 \]

• For medium and high \( x \), safe to assume that (with \( d \) and \( u \) denoting now quark plus antiquark distributions):
  \[ \frac{F_2^n}{F_2^p} = \frac{[1 + 4(d/u)]}{[4 + (d/u)]} \]
Nucleon $F_2$ Ratio Extraction Revisited

**SLAC DIS Data**

**Bodek:** Non-relativistic Fermi-smearing-only model with Paris nucleon-nucleon potential (1972).

**Melnitcouk & Thomas:** Relativistic convolution model with empirical binding effects (1996).

**Whitlow:** Assumes EMC effect in deuteron (Frankfurt and Strikman data-based Density Model) (1993).
Theoretical uncertainties introduce tremendous uncertainties in high-$x$ behavior of $F_2^n/F_2^p$ and $d/u$ ratios ... $d/u$ essentially unknown at large $x$!

Knowledge of $d/u$ ratio is essential for Quark Model and perturbative QCD tests, and for the interpretation of high energy hadron collider data.
Polarized Electron-Nucleus Inelastic Scattering

- DIS cross section asymmetry is given for longitudinally (→ or ←) or transversely (↑ or ↓) polarized electrons and nuclear targets in terms of the nuclear polarized $g_1$ and $g_2$ structure functions, and the degree of the longitudinal polarization, $\varepsilon$, of the virtual photon:

$$A_p = \frac{1 - \varepsilon}{(1 + \varepsilon R)\nu F_1} \left[ g_1(\nu, Q^2)(E + E'\cos\theta) - \frac{Q^2}{\nu} g_2(\nu, Q^2) \right]$$

$$A_T = \frac{(1 - \varepsilon)E'}{(1 + \varepsilon R)\nu F_1} \left[ g_1(\nu, Q^2) + 2\frac{E}{\nu} g_2(\nu, Q^2) \right] \sin\theta$$

- Parallel and Transverse Asymmetries, $A_p$ and $A_T$, are standard ratios for different incident electrons and target nuclei spin orientations:

$$A_p = \left[ \frac{\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow) + \sigma(\uparrow\downarrow)} \right] \quad A_T = \left[ \frac{\sigma(\uparrow \rightarrow) - \sigma(\uparrow \leftarrow)}{\sigma(\uparrow \rightarrow) + \sigma(\uparrow \leftarrow)} \right]$$
Polarized DIS and QPM

- In the Bjorken scaling limit, the nucleon $g_1$ and $g_2$ structure functions should also become functions only of the Bjorken $x$. If $L$ ($T$) stands for a longitudinally (transversely) polarized nucleon, and $+$ (-) denotes quarks with spin parallel (antiparallel) to the nucleon spin:

\[
g_1(x) = \frac{1}{2} \sum_i e_i^2 \left[ q_i^{+L}(x) - q_i^{-L}(x) \right]
\]

\[
g_1(x) + g_2(x) = \frac{1}{2Mx} \sum_i e_i^2 m_i \left[ q_i^{+T}(x) - q_i^{-T}(x) \right]
\]

- Of particular interest is the asymmetry $A_1$, which is a measure of the probability that the quark spins are aligned with the nucleon spin:

\[
A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\sum_i e_i^2 \left[ q_i^{+L}(x) - q_i^{-L}(x) \right]}{\sum_i e_i^2 \left[ q_i(x) - q_i(x) \right]}
\]
$g_1^p(x, Q^2) + c_i$

$x = 0.0036 \quad (i = 0)$

$x = 0.0045$

$x = 0.0055$

$x = 0.0070$

$x = 0.0090$

$x = 0.012$

$x = 0.017$

$x = 0.024$

$x = 0.035$

$x = 0.049$

$x = 0.077 \quad (i = 10)$

$x = 0.12$

$x = 0.17$

$x = 0.22$

$x = 0.29$

$x = 0.41$

$x = 0.57$

$x = 0.74$

$c_i = 0.7 \cdot (17.3 - i(x))$

$Q^2 (\text{GeV/c})^2$
Experimental data on the proton $A_1$ asymmetry from experiments with polarized electrons/positrons or muons, and polarized protons (hydrogen, ammonia or butanol).

As $x$ increases, the spins of the proton's quarks tend to be aligned with the proton spin. High-$x$ quarks in the proton are highly polarized!
Experimental data on the neutron $A_1^n$ asymmetry from experiments with polarized electrons/positrons or muons, and polarized neutrons (helium-3, deuterated butanol or ammonia).

Low-$x$ neutron quarks are mildly polarized in a direction opposite to the neutron spin. Medium-$x$ quarks seem to be unpolarized. But, we cannot say anything about the polarization of the high-$x$ quarks in the neutron!
### $F_2^n / F_2^p$, $d/u$ Ratios and $A_1$ Limits for $x \to 1$

<table>
<thead>
<tr>
<th>THEORY MODEL</th>
<th>$F_2^n / F_2^p$</th>
<th>$d/u$</th>
<th>$A_1^n$</th>
<th>$A_1^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>SU(6) Symmetry</em></td>
<td>$2/3$</td>
<td>$1/2$</td>
<td>$0$</td>
<td>$5/9$</td>
</tr>
<tr>
<td>Diquark Feynman Model</td>
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<td>$1$</td>
<td>$1$</td>
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<tr>
<td>Quark Model/Isgur</td>
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<td>$0$</td>
<td>$1$</td>
<td>$1$</td>
</tr>
<tr>
<td>Perturbative QCD</td>
<td>$3/7$</td>
<td>$1/5$</td>
<td>$1$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

See E12-10-103, E12-06-109, E12-06-110 JLab Proposals
Nucleon $F_2$ Ratio Extraction from $^3\text{He}/^3\text{H}$

- Form the “SuperRatio” of EMC-type ratios for $A=3$ mirror nuclei:

$$R'(^3\text{He}) = \frac{F_2^{^3\text{He}}}{2F_2^p + F_2^n} \quad R'(^3\text{H}) = \frac{F_2^{^3\text{H}}}{F_2^p + 2F_2^n} \quad R^* = \frac{R'(^3\text{He})}{R'(^3\text{H})}$$

- Solve above equations for the $A=3$ structure function ratio:

$$\frac{\sigma^{^3\text{He}}}{\sigma^{^3\text{H}}} = \frac{F_2^{^3\text{He}}}{F_2^{^3\text{H}}} = R^* \frac{2F_2^p + F_2^n}{F_2^p + 2F_2^n}$$

- Solve for the nucleon $F_2^n/F_2^p$ ratio and extract it, using $R^*$ from a reliable theoretical model (value of $R^*$ is very close to unity with an uncertainty of $1\text{-}2\%$), and the measured $A=3$ cross sections:

$$\frac{F_2^n}{F_2^p} = \frac{2R^* - \sigma^{^3\text{He}}/\sigma^{^3\text{H}}}{2\sigma^{^3\text{He}}/\sigma^{^3\text{H}} - R^*}$$

- **Note:** The $F_2^n/F_2^p$ (and $d/u$) ratio at high $x$ can also be extracted by employing proton-spectator tagging in electron-deuteron DIS (forthcoming JLab BoNuS experiment). The $d/u$ ratio at high $x$ can also be extracted directly from parity-violating electron-proton DIS (forthcoming JLab SOLID experiment).
SuperRatio $R^* = R^{(3He)} / R^{(3H)}$ has been calculated by three expert groups to deviate from 1 only up to ~1.5% taking into account all possible effects:

* E. Pace, G Salme, S. Scopetta, A. Kievsky, Phys. Rev. C64, 055203 (2001)
JLab Hall A High Resolution Spectrometers

Identical 4 GeV systems

Electron Spectrometer

Detector Hut

Hadron Spectrometer

Q1

Q2

Q3

Dipole

Scattering Chamber

Beamline

11 GeV Beam - Tritium/Helium targets

DETECTORS
Cherenkov, Calorimeter, 2 Scintillator planes, and Drift Chamber set

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Cherenkov, Calorimeter, 2 Scintillator planes, and Drift Chamber set
Projected JLab Hall A Data for $F_2^n/F_2^p$ and $d/u$ Ratios

11 GeV beam; Left and Right High Resolution Hall A Spectrometers; $^3$H and $^3$He gas target system; 3 months of data taking (E12-10-103)
A Dependence
EMC Effect

SLAC E-139, 1984
J. Gomez et al.

Quark momentum probability distributions in nuclei different from those in deuterium. Effect increases with mass number $A$. 
EMC Effect for $A=3$ Mirror Nuclei

Hall A JLab expected EMC effect data on $^3\text{H}$, $^3\text{He}$ (E12-10-103) will be of **similar precision** to the shown $^3\text{He}$ JLab Hall C data.
PROJECTED JLab DATA on the Neutron $A_1$ Asymmetry

Experiment E12-06-110

Experiment to be performed in the **Hall C** Facility using the new SHMS electron detection system and a helium-3 polarized target.
PROJECTED JLab DATA on the Proton $A_1$ Asymmetry

Experiment E12-06-109

Experiment to be performed in the Hall B Facility using the new CLAS-12 electron detection system and a polarized ammonia target.
Summary - Outlook

- Upcoming Jefferson Lab experiments will perform unpolarized and polarized DIS electron scattering from nuclear targets to measure unpolarized and polarized structure functions of the nucleon at large values of the Bjorken-\(x\) (valence quark region).

- A new novel technique using a tritium target with an 11 GeV electron beam in the JLab Hall A Facility can provide:
  - Best measurements of \(F_2^n/F_2^p\) and \(d/u\) ratios
  - Discrimination between differing predictions of Quark Model and Quantum Chromodynamic
  - Reliable data for structure function parametrizations, needed for interpretation of high energy hadron collider data

- Hall B/C experiments using established methods of polarizing nucleons in nuclear targets will also provide complementary high-\(x\) data for the proton and neutron \(A_1\) asymmetries.