Nucleon Form Factors and the Nuclear Medium

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What do we know about their internal structure?

Mass: ~ 940 MeV, but u- and d-quark mass only a few MeV each!

1 MeV = 1.602 x 10^{-13} J

Charge: proton, +1; neutron, 0

Magnetic moment: large part is anomalous, > 150%!

Spin-1/2: but total quark spin contributes only ~ 30%!

Sum of the parts is not equal to the whole!
Proton FFs Including JLab Data

cross-section data: open circles
polarization data: filled circles
Neutron FFs Including JLab Data

\[ G_{En} \text{ and } G_{Mn/\mu} \sim G_D \]

Requires the use of light nuclei such as the deuteron and \(^3\text{He}\)
Quark Flavor Decomposition

- General Parton Distribution (GPD) models are constrained by nucleon form factors:
  \[ F_{1,2}^p = \frac{2}{3} F_{1,2}^u - \frac{1}{3} F_{1,2}^d \]
  \[ F_{1,2}^n = -\frac{1}{3} F_{1,2}^u + \frac{2}{3} F_{1,2}^d \]

- High $Q^2$ for $G_E^n$ data allows for quark decomposition
- Lattice QCD is better suited for isovector FF

Lattice: Bratt et al., arXiv: 1001.3620, $m_\pi = 140$ MeV
JLab 12 GeV Upgrade

- JLab’s 12 GeV upgrade is currently in the construction phase
- Hall D will be added
- The three current experimental halls are being upgraded
- Several new experiments are already approved to run after the 12-GeV upgrade with 6 approved form factor experiments
Approved FF Experiments: 12 GeV

Proton

- E12-07-108: elastic cross section experiment $H(e,e')p$
- E12-07-109: FF ratio experiment using Super BigBite Spectrometer (SBS)
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- E12-09-019: also cross section ratio to measure $G_{Mn}$ using SBS
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**Proton**
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- E12-09-019: also cross section ratio to measure $G_{Mn}$ using SBS
- E12-09-016 (GEn II): polarized $^3He(e,e'n)$ using SBS, ratio $G_{En}/G_{Mn}$
- E12-11-009: D($e,e'n$) using recoil polarimetry in Hall C to measure ratio $G_{En}/G_{Mn}$
Motivations to Study FFs

- Form factors are a fundamental property of the nucleon
- Are not yet calculable from first principles
- Provide excellent testing ground for QCD and QCD-inspired models
- Gives constraints on models of nucleon structure
- Electromagnetic form factors of the proton were thought to be well understood prior to Jefferson Lab data:
  - At high $Q^2$, discovery of significant difference between techniques
  - Proton radius puzzle at low $Q^2$; experiments at JLab and PSI (MUSE) continue the investigation
Questions to Ponder

1) Do protons and neutrons behave differently inside a nucleus?
2) Do nucleons form pairs inside the nucleus?
3) What can we learn from correlated pairs of protons and neutrons?
Protons, neutrons, and electrons seem like our fundamental particles.
Nucleons in the Nucleus

• How do free nucleons differ from those in nuclei?
• Does the interplay between the attractive long-range and repulsive short-range components of the nucleon-nucleon (N-N) potential force cause some of the nucleons inside the nucleus to form pairs?
• Do the pairs favor a particular combination of nucleons: proton-proton, neutron-neutron or proton-neutron?
Tools of the Trade

Electron Scattering

Target: nucleus such as helium, carbon or lead
A(e,e’p)A-1 Kinematics

scattering plane

reaction plane

"out-of-plane" angle

Four-momentum transfer squared: \( Q^2 \equiv -q_\mu q^\mu = q^2 - \omega^2 \)

Missing momentum: \( p_m = q - p = p_{A-1} \)

Difference between transferred and detected momentum

Missing energy: \( \varepsilon_m = \omega - T_p - T_{A-1} \)

Difference between transferred and detected energy

Bjorken \( x \):

\( x_B = \frac{Q^2}{2m\omega} \) (just kinematics!)

Counts minimum number of nucleons involved
Electron Scattering at Fixed $Q^2$

Electron-Nucleon

Cross Section

$\frac{Q^2}{2m}$

$\frac{Q^2}{2m} + 300\text{MeV}$

$\omega = (e - e')$
Electron Scattering at Fixed $Q^2$

Electron-Nucleus

Cross Section

$\omega = (e - e')$

$\frac{Q^2}{2M}$

$\frac{Q^2}{2m}$

$\frac{Q^2}{2m} + 300$ MeV

Elastic

Nuclear Resonances

Quasi elastic

Deep Inelastic

Electron-Nucleon

Cross Section

$\omega = (e - e')$

$\frac{Q^2}{2m}$

$\frac{Q^2}{2m} + 300$ MeV

Elastic

Resonance Region

Deep Inelastic
Simple Theory Of Nucleon Knock-out

Plane Wave Impulse Approximation (PWIA)

\[ q - p = p_{A-1} = p_m = -p_0 \]
In nonrelativistic PWIA:

\[
\frac{d^6 \sigma}{d\omega d\Omega_e dp d\Omega_p} = K \sigma_{ep} S(p_m, \varepsilon_m)
\]

e-p cross section

nuclear spectral function

For bound state of recoil system:

\[
\rightarrow \frac{d^5 \sigma}{d\omega d\Omega_e d\Omega_p} = K' \sigma_{ep} |\Phi(p_m)|^2
\]

proton momentum distribution
Reaction Mechanisms in (e,e’p)

A more accurate description of the (e,e’p) reaction includes:

- **Final-State Interactions:**
  Interactions of the extracted proton with the residual nucleus.

- **Coulomb Distortion and Internal Radiative Corrections:**
  The momentum of the electrons at the reaction point is different to their asymptotic measured values.

- **External Effects (From atomic interactions in the target):**
  Energy Loss, External Radiative Corrections, Straggling, Proton Absorption.

- **Meson Exchange Currents (MEC)**

- **Intermediate excited nucleonic configurations:**
  e.g. Delta-isobar contributions
Example: Final State Interactions (FSI)

\[ \mathbf{q} - \mathbf{p} = \mathbf{p}_{A-1} \neq \mathbf{p}_0 \]
Distorted Wave Impulse Approximation (DWIA)

This is modeled by an optical potential from elastic $(p,p)$ data. Proton is described by Distorted Waves.

\[ \frac{d^6\sigma}{d\Omega_e d\Omega_p dp d\omega} = K \sigma_{ep} S^D(p_m, \varepsilon_m, p) \]

“Distorted” spectral function

**DWIA:** If the struck nucleon re-interacts with the rest of the nucleus, then the cross section still factorizes (mostly) but we measure a *distorted* spectral function.
Classic Result from \((e,e'p)\) Measurements


Independent-Particle Shell-Model is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons.

The \((e,e'p)\) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are $60 – 70\%$ of the mean field prediction.

**Solution:** Correlations Between Nucleons
Long-range (> 2 fm) and short-range (< 1 fm)
Short-Range Correlations

SRC depletes states below the Fermi sea and makes the states above this level partially occupied.
Short-Range Correlations

Single nucleon knock-out

Correlated pair knock-out
Realistic Momentum Distribution

- What fraction of the momentum distribution is due to 2N-SRC?
- What is the relative momentum between the nucleons in the pair?
- What is the ratio of pp to pn pairs?
- Are these nucleons different from free nucleons (e.g. size)?

**BUT** other effects such as Final State Rescattering have masked the signal in the past.

To observe the effects of correlations one must probe beyond the Fermi level:

\[ P_{\text{min}} > 275 \text{ MeV/c} \]
Calculation of Nucleon Initial Momentum


Nuclear Scaling at High Initial Momentums: $n_A(k) = R n_D(k)$
Inclusive Scattering at Large $x_B$

Define $y$ as the $x_B$-value at which the minimum $p_{\text{miss}}$ exceeds $k_F$

SRC model predicts:
• Scaling for $x_B > y$ and $Q^2 > 1.5$ GeV$^2$
• No scaling for $Q^2 < 1$ GeV$^2$
• In scaling regime ratio $Q^2$-independent and only weakly $A$-dependent

Glauber Approximation predicts:
• No scaling for $x_B < 2$ and $Q^2 > 1$ GeV$^2$
• Nuclear ratios should vary with $A$ and $Q^2$
Inclusive Cross Section involving SRC:
- $k > k_F$ for $x_B > 1.3$, so QE electron-nucleus scattering probes SRC:

$$
\sigma_A(x_B, Q^2) = \sum_{j=2}^{A} \frac{A}{j} a_j(A) \sigma_j(x_B, Q^2) = \frac{A}{2} a_2(A) \sigma_2(x_B, Q^2) + \frac{A}{3} a_3(A) \sigma_3(x_B, Q^2) + ..., 
$$

- $a_j(A)$: the probability of a nucleon in a jN-SRC
- $\sigma_j(A)$: the cross section of an electron scattering off a nucleon in a jN-SRC

Ratios:
- $a_2$ and $a_3$ are independent of $x_B$ and $Q^2$, and only depend on $A$ → Scaling plateau

**2N-SRC** ($1.3 < x_B < 2$)

$$
a_2(A, D) = \frac{2 \sigma_A(x, Q^2)}{A \sigma_D(x, Q^2)},
$$

**3N-SRC** ($2 < x_B < 3$)

$$
a_3(A, ^3\text{He}) = K \cdot \frac{3\sigma_A}{A \sigma_{^3\text{He}}},
$$
**$^3\text{He}(e,e'p)d$ and $^3\text{He}(e,e'p)np$**


$$Q^2 = 1.5 \text{ [GeV/c]}^2$$

$$x_B = 1 \text{ (Q.E. Peak)}$$

$$\frac{d^6 \sigma}{dE_e dE_p d\Omega_e d\Omega_p} = K \cdot \sigma_{ep} \cdot S^D(E_m, p_m)$$

$$\eta(p_m) = \int \left( \frac{d^6 \sigma}{dE_e dE_p d\Omega_e d\Omega_p} / K \cdot \sigma_{ep} \right) dE_m$$

Compare $S^D(E_m, p_m)$, $\eta(p_m)$ to model
Hall B (CLAS) D(e,e’p)n, x<1 Data


\[ Q^2 = 4 \text{ [GeV/c]}^2 \]

Black Paris Potential
Red AV-18 Potential

\[ Q^2 = 5 \text{ [GeV/c]}^2 \]

From Lowest To Highest
PWIA
PWIA+FSI
PWIA+FSI+MEC+NΔ
CLAS A(e,e’) Data


\[ x = \frac{Q^2}{2M\omega} > 1.5 \quad \text{and} \quad Q^2 > 1.4 \text{ [GeV/c]}^2 \]

then

\[ r(A, ^3\text{He}) = \frac{a_{2n}(A)}{a_{2n}(^3\text{He})} \]

The observed scaling means that the electrons probe the high-momentum nucleons in the 2N-SRC phase, and the scaling factors determine the per-nucleon probability of the 2N-SRC phase in nuclei with \( A > 3 \) relative to \(^3\text{He}\).
Results From JLab Hall-C

Estimate of $^{12}$C Two-Nucleon SRC

Scaling onset corresponds to $P_{\text{min}} \approx 275$ MeV/c

$$\int_0^{P_{\text{min}}} n_d(k) k^2 dk = 100\% \implies \int_0^\infty n_d(k) k^2 dk = 4\%$$

- K. Egiyan et al. related the known correlations in deuterium and previous $r(^3\text{He},D)$ results to find:
- $^{12}$C, 20% of nucleons are in a 2-N SRC

Results on $^{12}$C From the (e,e’) and (e,e’p)

- 80 +/- 5\% single particles moving in an average potential
  - 60 – 70\% independent single particle in a shell model potential
  - 10 – 20\% shell model long range correlations

- 20 +/- 5\% two-nucleon short-range correlations
  - No $Q^2$ Dependence Of Ratio Magnitude $Q^2$: 1 to 4 GeV to few percent
  - Plateaus Start When Minimum Missing Momentum > Fermi Momentum
Customized (e,e’pN) Measurement

To study nucleon pairs at close proximity and their contributions to the large momentum tail of nucleons in nuclei.

A pair with “large” relative momentum between the nucleons and small center of mass momentum relative to the Fermi-sea level:

\[ \sim 275 \text{ MeV/c} \]
Suppression of Non-SRC Two Body Effects

- High $Q^2$ to minimize MEC ($1/Q^2$) and FSI
- $x>1$ to suppress isobar contributions
Experimental Hall A
Hall A’s two High resolution Spectrometers can detect scattered electrons with momentum up 4 GeV/c with a resolution of $10^{-4}$.

Can detect particles scattered from $6^\circ$ to $120^\circ$. 
Add BigBite and Neutron Detector
Kinematics
HAND

- Hall A Neutron Detector
- First Neutron Detector in Hall A
- Measuring D(e,e'p) and detecting the neutron, the detector was tested and calibrated.

![Graph showing Neutron TOF]

**Neutron TOF [ns]**

**D(e,e’pn)**
(e,e’p) & (e,e’pp) Data

- $^{12}\text{C}(e,e’p)$
- Quasi-Elastic Shaded In Blue
- Resonance Even at $x_B > 1$

$^{12}\text{C}(p, 2p+n)$ Reaction

$p_f = p_1 + p_2 - p_0$

$p_0$ = incident proton

$p_1$ and $p_2$ are detected

Correlated Pair Factions from $^{12}$C

From the \((e,e')\), \((e,e'p)\), and \((e,e'pN)\) Results

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
Importance of Tensor Correlations