Nuclear Structure and Short-Range Correlations (Day 1)

Or Hen – MIT

Hampton University Graduate School (HUGS), June 6th 2017, JLab, Newport-News VA.
Course Outline

Day I: Overview of Nuclear Systems and EM Probes.

Day II: Nuclear Structure.
   (Short / Long Range)
   (Experiment / Theory)

Day III: Cross Connections.
   (QCD in Nuclei: Modification and Transparency)
   (Contact Formalism and Short-Range Universality)
   (Neutrino Physics)
   (Neutron Stars)
Course Outline

Day I: Overview of Nuclear Systems and EM Probes.

Day II: Nuclear Structure.
   (Short / Long Range)
   (Experiment / Theory)

Day III: Cross Connections.
   (QCD in Nuclei: Modification and Transparency)
   (Contact Formalism and Short-Range Universality)
   (Neutrino Physics)
   (Neutron Stars)
Course Outline

Day I: Overview of Nuclear Systems and EM Probes.

After today’s overview, I want to hear from you what you want to learn!

Theory / Detectors / High energy / low energy
Modern nuclear physics: From nothing to everything

- Quark-Gluon Structure Of Nucleons and Nuclei
- Nature of Confinement
- Correlations n-radii: N ≠ Z
- Hypernuclei
- Hadrons in- medium
- Effective NN (+ HN) force
- Precise few-nucleon calculations
- ...n-stars
- Exotic mesons and baryons
- Few body
- Heavy nuclei
- Vacuum
This Course: Two Systems and Their Interactions

Systems:
- *nucleus* as a collection of bound protons and neutrons,
- *nucleon* as a collection of bound quarks.

Interactions:
- Nuclear Interactions from quark interactions,
- Nuclear Medium Effects on quarks distributions.
(Some) Quantities of Interest

Nuclear structure:
• Shape (radii / deformation / ...),
• Electro-magnetic charge distribution (form factor),
• Nucleon momentum distribution (wave function),
• Clustering and correlations,
• ....

Nucleon Structure:
• Nuclear forces from quark interactions
• Quark structure of bound and free nucleons
• ....
Nuclear Challenge

Nuclei are a low energy phenomena, => QCD is non perturbative!
Nuclear Many-Body Challenge

Many-body Schrödinger Equation

\[
\sum_i \left\{ -\frac{\hbar^2}{2m_i} \nabla_i^2 \Psi(\vec{r}_1, ..., \vec{r}_N, t) \right\} + U(\vec{r}_1, ..., \vec{r}_N) \Psi(\vec{r}_1, ..., \vec{r}_N, t) = i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}_1, ..., \vec{r}_N, t)
\]

Main Challenges:

1. No ‘fundamental’ Interaction.

2. Complex phenomenological parametrizations (e.g. over 18 operators)
Solution: Effective Theories

Fermi Gas Model

Liquid Drop Model

Shell Model

Chiral Perturbation Theory*

* Should converge to exact solution
Development of any theory is guided by experiment!

=> Theory alone has very little stand without experiment 😊

* Should converge to exact solution
**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** using high energy lepton scattering

Reaction determined by two variables:
- \( Q^2 = -q^2 \) Interaction-Scale
- \( x_B = Q^2/(2m_p v) \) Dynamics
**Electron Scattering: Nuclear Microscope**

---

**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** using high energy lepton scattering

---

Reaction determined by two variables:

- $Q^2 = -q^2$ Interaction-Scale
- $x_B = Q^2/(2m_p\nu)$ Dynamics
**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** using high energy lepton scattering

Reaction determined by two variables:
- \( Q^2 = -q^2 \) Interaction-Scale
- \( x_B = Q^2/(2m_p\nu) \) Dynamics
Electron Scattering: Nuclear Microscope

**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** using high energy lepton scattering

Reaction determined by two variables:
- \( Q^2 = -q^2 \)  Interaction-Scale
- \( x_B = Q^2/(2m_p\nu) \)  Dynamics
**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** using high energy lepton scattering

Reaction determined by two variables:

- \( Q^2 = -q^2 \) Interaction-Scale
- \( x_B = Q^2/(2m_p v) \) Dynamics
Electron Scattering: Nuclear Microscope

**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** using high energy lepton scattering

100s eV – 100s keV: Material structure

100s MeV – 10s GeV: Nuclear structure

[Image: Electron Scattering: Nuclear Microscope]
**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** using high energy lepton scattering

100s eV – 100s keV: 
Material structure

100s MeV – 10s GeV: 
Nuclear structure

Energy = Resolution!
Worldwide Effort

- Jefferson Lab: $E_e = 6 \text{ GeV}$
- SLAC: $E_e = 25 \text{ GeV}$
- MIT (BATES): $E_e = 1.2 \text{ GeV}$
- ELSA: $E_e = 3.5 \text{ GeV}$
- MAX-lab: $E_e = 0.15 \text{ GeV}$
- SPring-8: $E_e = 8 \text{ GeV}$
- + others...!
\[(e,e')\): Energy transfer defines physics

\[
\frac{d\sigma}{d\omega} \quad \frac{Q^2}{2A} \quad \frac{Q^2}{2m} \quad \frac{Q^2}{2m} + 300 \text{ MeV}
\]

\[
\frac{d\sigma}{d\omega} \quad \frac{Q^2}{2m} \quad \frac{Q^2}{2m} \quad \text{Deep Inelastic}
\]

Generic Electron Scattering at fixed momentum transfer
Everything is interesting...
...But we will focus on 3 regions
1. Elastic
   • structure of the nucleon / nucleus
     • Form factors, charge distributions, spin dependent FF

2. Quasielastic (QE)
   • Shell structure
     • Momentum distributions
     • Occupancies
   • Short Range Correlated nucleon pairs
   • Nuclear transparency and color transparency

3. Deep Inelastic Scattering (DIS)
   • The EMC Effect and Nucleon modification
   • Quark hadronization in nuclei
Quick Overview: Elastic

- Nuclear charge (proton) radius
- Nuclear Neutron radius
- Nucleon Form-Factors and charge densities
Diffraction Measurements of Small Radii

Intensity: \( \Phi^2 \propto \left( \frac{J_1((2\pi a / \lambda) \sin \theta)}{\sin \theta} \right)^2 \)

Minima occur at zeroes of Bessel function. 1\(^{st}\) zero: \( x = 3.8317 \)

...some algebra...

Hence \( 2a \approx \frac{1.22 \lambda}{\sin \theta} \)
Diffraction Measurements of Small Radii

Cross Section ↔ Charge Form Factor

1st minimum = 1.3 fm\(^{-1}\)

\[ \theta = 32.8^\circ \]

Electron energy = 454.3 MeV

\[ \lambda = 2.73 \text{ fm} \]

Calculated radius = 3.07 fm

Measured rms radius = 3.19 fm
Charge Distribution, \( r_{\text{CH}}(r) \), is a Fourier Transform of the Charge Form Factor, \( F(q) \)

Diffraction Measurements of Small Radii
Diffraction Measurements of Small Radii

10s – 100s Million Dollar Machines
Weak Interaction: Neutron Distribution

Parity Violating Asymmetry

\[ \sigma \approx \left| \begin{array}{c} e^- \\ \gamma \\ e^- \\ + \\ Z^0 \end{array} \right| 2 \]

Applications of PV at Jefferson Lab

- Nucleon Structure (strangeness) -- HAPPEX / G0
- Standard Model Tests (\( \sin^2 \theta_W \)) -- e.g. Qweak
- Nuclear Structure (neutron density) : PREX
Weak Interaction: Neutron Distribution

$Z^0$ of Weak Interaction:
Clean Probe Couples Mainly to Neutrons

$$A = \frac{\left( \frac{d\sigma}{d\Omega} \right)_R - \left( \frac{d\sigma}{d\Omega} \right)_L}{\left( \frac{d\sigma}{d\Omega} \right)_R + \left( \frac{d\sigma}{d\Omega} \right)_L} = \frac{G_F Q^2}{2\pi \alpha \sqrt{2}} \left[ 1 - 4\sin^2 \theta_W - \frac{F_W(Q^2)}{F_p(Q^2)} \right] \approx 0$$

$F_W(Q^2)$: $^{208}\text{Pb}$
Weak Form Factor

$F_p(Q^2)$: $^{208}\text{Pb}$
Charge Form Factor

Clean Probe Couples Mainly to Neutrons

<table>
<thead>
<tr>
<th></th>
<th>proton</th>
<th>neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric charge</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Weak charge</td>
<td>0.08</td>
<td>1</td>
</tr>
</tbody>
</table>
Weak Interactions: Neutron Distribution

\[ A = \frac{\frac{d\sigma}{d\Omega}}{R} - \frac{\frac{d\sigma}{d\Omega}}{L} + \frac{\frac{d\sigma}{d\Omega}}{L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[ 1 - 4\sin^2 \theta_W - \frac{F_W(Q^2)}{F_P(Q^2)} \right] \]

\( Z^0 \) of Weak Interaction: Clean Probe Couples Mainly to Neutrons

\[ F_W(Q^2): ^{208}\text{Pb} \]

Weak Form Factor

\[ F_P(Q^2): ^{208}\text{Pb} \]

Charge Form Factor

Clean Probe Couples Mainly to Neutrons

<table>
<thead>
<tr>
<th></th>
<th>proton</th>
<th>neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric charge</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Weak charge</td>
<td>0.08</td>
<td>1</td>
</tr>
</tbody>
</table>

High Accuracy:

\[ \frac{dA}{A} = 3\% \rightarrow \frac{dR_n}{R_n} = 1\% \]

\( R_n = \) neutron matter radius
Lab frame kinematics

\[ k'_{\mu} = (E', \vec{k}') \]

\[ p'_{\mu} = (E_p, \vec{p}_p) \]

(not always detected)

\[ q^\mu = (\omega, \vec{q}) \]

\[ q^\mu = k^\mu - k'^\mu \]

\[ p^\mu = (M, \vec{0}) \]

Invariants:

\[ p^\mu p_\mu = M^2 \]

\[ p_\mu q^\mu = M\omega \]

\[ Q^2 = -q^\mu q_\mu = |\vec{q}|^2 - \omega^2 \]

\[ W^2 = (q^\mu + p^\mu)^2 = p'_\mu p'^\mu \]
Recoil factor

\[
\frac{d\sigma}{d\Omega} = \sigma_M \left( \frac{E'}{E} \right) \left\{ \left[ F_1^2(Q^2) + \frac{Q^2}{4M^2} \kappa^2 F_2^2(Q^2) \right] + \frac{Q^2}{2M^2} \left[ F_1(Q^2) + \kappa F_2(Q^2) \right]^2 \tan^2 \frac{\theta}{2} \right\}
\]

\[
= \sigma_M \left( \frac{E'}{E} \right) \left[ \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau \tan^2 \frac{\theta}{2} G_M^2(Q^2) \right]
\]

\[
= \sigma_M \left( \frac{E'}{E} \right) \left[ \frac{Q^4}{q^4} R_L(Q^2) + \left( \frac{Q^2}{2q^2} + \tan^2 \frac{\theta}{2} \right) R_T(Q^2) \right]
\]

Mott cross section: \( \sigma_M = \frac{\alpha^2 \cos^2 \left( \frac{\theta_e}{2} \right)}{4E^2 \sin^4 \left( \frac{\theta_e}{2} \right)} \)

**Form factors**

\( F_1, F_2 \): Dirac and Pauli form factors

\( G_E, G_M \): Sachs form factors (electric and magnetic)

\[
G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \quad \tau = \frac{Q^2}{4M^2}
\]

\[
G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \quad \text{(more standard definition of } F_1 \text{ and } F_2)\]

\( R_L, R_T \): Longitudinal and transverse response fn
Form Factors: Cross-Sections

\[ \frac{\varepsilon}{\tau} G_E^2 + G_M^2 = \frac{\varepsilon(1+\tau)}{\tau} \left[ \frac{d\sigma}{d\Omega} \left/ \frac{d\sigma}{d\Omega} \right|_{Mott+recoil} \right] \]

\[ \sigma_R \]

\[ \tau G_M^2 \]

\[ G_E^2 = \tan \beta \]
Form Factors: Polarization Transfer

\[
I_0 P_x = -2 \sqrt{\tau(1+\tau)} G_E G_M \tan(\theta/2)
\]

\[
I_0 P_z = \frac{1}{M} (E-E') \sqrt{\tau(1+\tau)} G_M^2 \tan^2(\theta/2)
\]

\[
\frac{G_E^2}{G_M^2} = \frac{-P_x}{P_z} \frac{E+E'}{2M} \tan(\theta/2)
\]
Form Factors: Polarization Transfer

\[ I_0 P_x = -2 \sqrt{\tau(1+\tau)} G_E G_M \tan(\theta/2) \]
\[ I_0 P_z = \frac{1}{M} (E-E') \sqrt{\tau(1+\tau)} G_M^2 \tan^2(\theta/2) \]

\[ \frac{G_E^2}{G_M^2} = \frac{-P_x}{P_z} \frac{E+E'}{2M} \tan(\theta/2) \]

LARGE Discrepancy!
(2 photon exchange? More on this if we have time at the end)
Electric charge distribution

Proton

EM charge radius!

Neutron
Neutron is negative in its center and positive in the edge!!!
Quick Overview: Quasi-Elastic

- Momentum Densities: Fermi Gas
- Y-Scaling
- Shell Structure and spectroscopic factors
What is a Nucleus?

Fermi Gas Model

Liquid Drop Model

Shell Model

Chiral Perturbation Theory*

* Should converge to exact solution
Fermi gas model:
how simple a model can you make?

Initial nucleon energy: $KE_i = p_i^2 / 2m_p$

Final nucleon energy: $KE_f = p_f^2 / 2m_p = (\vec{q} + \vec{p}_i)^2 / 2m_p$

Energy transfer: $\nu = KE_f - KE_i = \frac{\vec{q}^2}{2m_p} + \frac{\vec{q} \cdot \vec{p}_i}{m_p}$

Expect:
• Peak centroid at $\nu = \frac{q^2}{2m_p} + \varepsilon$
• Peak width $2q \rho_{\text{fermi}} / m_p$
• Total peak cross section = $Z \sigma_{ep} + N \sigma_{en}$
Early 1970’s Quasielastic Data
-> getting the bulk features

\[ \langle \vec{q} \rangle \sim 500 \text{MeV/c} \]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>( k_F ) (MeV/c)</th>
<th>( \bar{e} ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^6\text{Li})</td>
<td>169</td>
<td>17</td>
</tr>
<tr>
<td>(^{12}\text{C})</td>
<td>221</td>
<td>25</td>
</tr>
<tr>
<td>(^{24}\text{Mg})</td>
<td>235</td>
<td>32</td>
</tr>
<tr>
<td>(^{40}\text{Ca})</td>
<td>251</td>
<td>28</td>
</tr>
<tr>
<td>nat(^{58}\text{Ni})</td>
<td>260</td>
<td>36</td>
</tr>
<tr>
<td>(^{89}\text{Y})</td>
<td>254</td>
<td>39</td>
</tr>
<tr>
<td>nat(^{113}\text{Sn})</td>
<td>260</td>
<td>42</td>
</tr>
<tr>
<td>(^{181}\text{Ta})</td>
<td>265</td>
<td>42</td>
</tr>
<tr>
<td>(^{205}\text{Pb})</td>
<td>265</td>
<td>44</td>
</tr>
</tbody>
</table>

compared to Fermi model: fit parameter \( k_F \) and \( \bar{e} \)
Scaling

• The dependence of a cross section, in certain kinematic regions, on a single variable.
  • **scaling** validates the scaling assumption.
  • **Scale-breaking** indicates new physics.

• At moderate $Q^2$ and $x>1$ we expect to see evidence for **y-scaling**, indicating that the electrons are scattering from quasifree nucleons
  • $y =$ minimum momentum of struck nucleon

• At high $Q^2$ we expect to see evidence for **x-scaling**, indicating that the electrons are scattering from quarks.
  • $x = Q^2/2mv =$ fraction of nucleon momentum carried by struck quark (in infinite momentum frame)
Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus.

\( y \) is the momentum of the struck nucleon parallel to the momentum transfer:
\( y \approx -q/2 + m\nu/q \) (nonrelativistically)

IF the scattering is quasifree, then \( F(y) \) is the integral over all perpendicular nucleon momenta (nonrelativistically).

Goal: extract the momentum distribution \( n(k) \) from \( F(y) \).
Assumptions & Potential Scale Breaking Mechanisms

- No Final State Interactions (FSI)
- No internal excitation of (A-1)
- Full strength of Spectral function can be integrated over at finite $q$
- No inelastic processes (choose $y<0$)
- No medium modifications (discussed later)
Y-scaling works!

Cross section $\frac{d\sigma}{d\Omega dE}$ vs. Energy transfer $\nu$ (GeV) for $^3\text{He}$ and Iron.
Final State Interactions (FSI) complicate this simple picture

$^4\text{He}(e,e')$ at 3.595 GeV, 30°

Benhar et al. PRC 44, 2328
Benhar, Pandharipande, PRC 47, 2218
Benhar et al. PLB 3443, 47
But what about the Shell Model?

• Many-Body Hamiltonian:
  \[ H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i<j=1}^{A} v_{2\text{body}}(i,j) + \sum_{i<j<k=1}^{A} v_{3\text{body}}(i,j,k) + \ldots \]

• Mean-Field Approximation:
  \[ H = \sum_{i=1}^{A} \frac{p_i^2}{2m_N} + \sum_{i=1}^{A} V(i) \]

Results in an “atom-like” shell model:
  • Ground state energies
  • Excitation Spectrum
  • Spins
  • Parities
  • ...

E. Wigner, M. Mayer, and J. Jenson, 1963 Nobel Prize
And then there were four (response functions, that is)

(When you include electron and proton spin, there are 18!)

(And if you scatter from a polarized spin-1 target, there are 41. Double Yikes!!)

\[
\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_{\text{miss}} d\omega} = K \sigma_{\text{Mott}} \left[ v_L R_L + v_T R_T + v_{LT} R_{LT} \cos(\phi) + v_{TT} R_{TT} \cos(2\phi) \right]
\]

where

- \(K = \) (phase space)
- \(\sigma_{\text{Mott}} = \) (relativistic Rutherford scattering)
- \(v = v(q, \omega)\) (electron kinematics)

Each \(R\) now depends on more variables

\(R = R(q, \omega, p_{\text{miss}}, E_{\text{miss}})\)
$^{16}\text{O}(e,e'p)$ and shell structure

$1p_{1/2}$, $1p_{3/2}$ and $1s_{1/2}$ shells visible

Momentum distribution as expected for $l = 0, 1$

Fișum et al, PRC 70, 034606 (2003)
But we do not see enough protons!
But we do not see enough protons! (More to come...)
Quick Overview: Deep Inelastic

- Structure Functions
- EMC Effect
Partonic Structure

Quark – Anti-quark Pair

Gluon

Quark
Partonic Structure: 
\[ F_2(x, Q^2) = \sum_i e_i^2 \cdot x \cdot f_i(x) \]
Partonic Structure: \( F_2(x, Q^2) = \sum_i e_i^2 \cdot x \cdot f_i(x) \)
Partonic Structure: \( F_2(x, Q^2) = \sum_i e_i^2 \cdot x \cdot f_i(x) \)

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

Quark – Anti-quark Pair

Gluon

Quark
Quiz: What is the simplest example of nuclear interaction affecting partonic properties?

(winner gets a beer)
Quiz: What is the simplest example of nuclear interaction affecting partonic properties?

Answer: The nuclear interaction that binds the deuteron also makes the neutron stable.
• Simplest nuclear system = Deuteron,
• Free neutron is unstable: decays in ~ 10 minuets,
• Bound in the Deuteron, a neutron can live forever!
Interplay Challenge: ‘Strength ’ ‘Scales

- Weak Binding
- External Field
- Strong Binding
Interplay Challenge: ‘Strength ’Scales

Nuclear Field

Proton

Quark Piglets
EMC Effect

- Deviation of the per-nucleon DIS cross section ratio of nuclei relative to deuterium from unity.
- Universal shape for 0.3<x<0.7 and 3<A<197.
- ~Independent of $Q^2$.
- Overall increasing as a function of A.
- No fully accepted theoretical explanation.

\[
\frac{d^2\sigma}{d\Omega dE'} = \sigma_A = \frac{4\alpha^2 E'^2}{Q^4} \left[ 2 \frac{F_1}{M} \sin^2\left(\frac{\theta}{2}\right) + \frac{F_2}{v} \cos^2\left(\frac{\theta}{2}\right) \right] \quad F_2(x, Q^2) = \sum_i e_i^2 \cdot x \cdot f_i(x)
\]
EMC Effect

- Deviation of the per-nucleon DIS cross section ratio of nuclei relative to deuterium from unity.
- Universal shape for $0.3 < x < 0.7$ and $3 < A < 197$.
- ~Independent of $Q^2$.
- Overall increasing as a function of $A$.
- No fully accepted theoretical explanation.

$$
\frac{d^2\sigma}{d\Omega dE'} = \sigma_A = \frac{4\alpha^2 E^2}{Q^4} \left[ 2 \frac{F_1}{M} \sin^2 \left( \frac{\theta}{2} \right) + \frac{F_2}{v} \cos^2 \left( \frac{\theta}{2} \right) \right] \quad F_2(x,Q^2) = \sum_i e_i^2 \cdot x \cdot f_i(x)
$$
EMC: Nuclear Effect on Partons

JLab

SLAC

More later in the week!


Theory: 1000 papers, 3 Ideas

1. Proper treatment of ‘known’ nuclear effects
   [explain some of the effect, up to x≈0.5. Sensitive to SRCs]
   • Nuclear Binding and Fermi motion, Pions, Coulomb Field.
   • No modification of bound nucleon structure.

2. Bound Nucleons are ‘larger’ than free nucleons.
   • Larger confinement volume => slower quarks.
   • Mean-Field effect.
   • Momentum Independent.
   • Static.

3. Short-Range Correlations
   • Beyond the mean-field.
   • Determined by SRC pairs counting.
   • Dynamical!

EMC – Everyone’s Model is Cool (G. A. Miller)
1. Proper treatment of ‘known’ nuclear effects
   [explain some of the effect, up to $x\approx 0.5$. **Sensitive to SRCs**]
   - Nuclear Binding and Fermi motion, Pions, Coulomb Field.
   - No modification of bound nucleon structure.

2. Bound Nucleons are ‘larger’ than free nucleons.
   - Larger confinement volume $\Rightarrow$ slower quarks.
   - Mean-Field effect.
   - Momentum Independent.
   - Static.

3. Short-Range Correlations
   - Beyond the mean-field.
   - Momentum dependent.
   - Dynamical!

Theory: 1000 papers, 3 Ideas
Theory: 1000 papers, 3 Ideas

1. Proper treatment of ‘known’ nuclear effects
   [explain some of the effect, up to $x\approx 0.5$. Sensitive to SRCs]
   - Nuclear Binding and Fermi motion, Pions, Coulomb Field.
   - No modification of bound nucleon structure.

2. Bound Nucleons are ‘larger’ than free nucleons.
   - Larger confinement volume => slower quarks.
   - Mean-Field effect.
   - Momentum Independent.
   - Static.

3. Short-Range Correlations
   - Beyond the mean-field.
   - Determined by SRC pairs counting.
   - Dynamical!

EMC – Everyone’s Model is Cool (G. A. Miller)
Summary (1): Modern nuclear physics - From nothing to everything

- Quark-Gluon Structure Of Nucleons and Nuclei
- Nature of Confinement
- Correlations n-radii: $N \neq Z$
- Hypernuclei
- Hadrons in-medium
- Effective NN (+ HN) force
- Exotic mesons and baryons
- Precise few-nucleon calculations
Summary (2): Today’s overview

Elastic scattering (Form Factors, FF):
- Nuclei + virtual photon => Nuclear charge FF
- Nuclei + Z boson => Nuclear neutron FF
- Nucleons + virtual photon => Nucleon charge FF
- Nucleons + Z boson => Nucleon strange FF + ...

Quasielsatic scattering:
- Scaling and momentum distributions
- Shell structure and spectroscopic factors
- Correlations
- ...

Deep Inelastic Scattering:
- Nucleons => Structure functions and PDFs
- Nuclei => In-medium structure functions and nuclear PDFs
Summary (3): Never mix between what we Know / Measure / Reconstruct / Extract

• Know:
  • Beam probe (particle type + energy)
  • Target

• Measure:
  • Scattered probe
  • Additional particles emitted
  • Cross-sections

• Reconstruct:
  • Short Lived particles
  • Missing momentum
  • Missing Energy

• Extract:
  • Physics! (momentum distribution, shell occupancies ...)
Summary (3): Never mix between what we Know / Measure / Reconstruct / Extract

• Know:
  • Beam probe (particle type + energy)
  • Target

• Measure:
  • Scattered probe
  • Additional particles emitted
  • Cross-sections

• Reconstruct:
  • Short Lived particles
  • Missing momentum
  • Missing Energy

• Extract:
  • Physics! (momentum distribution, shell occupancies ...)

Increasing level of assumptions (i.e. model dependencies)
Tomorrow: Short-Range nuclear Structure

**Theory:**
1. Beyond the mean-field: NN Correlations,
2. Effective vs. ab-initio calculations
3. Phase-equivalent NN interactions
4. Reaction theory: confronting theory and experiment.

**Experiment:**
1. \((e,e'), (e,e'N), (e,e'NN)\) => Details of NN correlations,
2. Correlations in asymmetric nuclei,
3. NN interactions at short distances.

**Contact Formalism:** Effective theory for short-distance.