Using the (e,e’X) reaction to understand nucleons in the nucleus

by

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Thoughts in my head from yesterday...

• In electron scattering, how would I get the correct free proton form factors (or cross section) from (e,e’) if I didn’t even know my beam energy?! Wow!

• Electron scattering physicists have become masters of enhancing or suppressing effects such as FSI, MEC, etc. by tuning the kinematics of the experiment. (Forced on us by nature not being a simple as we would like).

• The kinematics of two final-state high momentum nucleons is extreme.

• Neutrino energies are close to JLab electron energies.

• At high energy continuum dominates over the bound states.

• FSI is constrained by electron data. (i.e. you can fold Ingo’s spectral function with Omar’s FSI calculations to cross sections, we do not just “tweak” the FSI to match data)

• CLAS (e,e’), (e,e’p), (e,e’pn) data at high energy coming soon for a variety of nuclei! (was just shown at CLAS meeting last week and will be discussed at photonuclear Gordon conference)

• In electron scattering we worry a lot about getting neutron information from D & 3He.
Electron Scattering Kinematics

Energy transfer: \( \omega = e - e' \)

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

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

Bjorken x:

\( x_B = Q^2/2m\omega \) (just kinematics!)
Electron Scattering Regions

Electron-nucleon scattering

Electron-nucleon scattering

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

\( x_B > 1 \) \( x_B = 1 \) \( x_B < 1 \)
Nuclear Charge Distributions

In ‘70s large data set was acquired on elastic electron scattering (mainly at Saclay) over large $Q^2$-range and for variety of nuclei.
Classic A(e,e’p)A-1 Results


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.

Next Step: Add Correlations Between Nucleons
A Toy Model Momentum Distribution

By Uncertainty Principle High Momentum Region Dominated by Short Distance Phenomena
Realistic Momentum Distribution

Vector Polarized Deuterium

Spin-1 Particle, 2 spin-$\frac{1}{2}$ Nucleons (Proton and Neutron)

S

D

l=0

\sim 90\%

l=2

\sim 10\%
Deuteron Asymmetry Data

(repeated at MIT Bates with BLAST and better statistics)

\[ 2 \vec{H}(\vec{e}, e'p) \]

\[ A_{ed}^V \]

\[ p_m \text{[MeV/c]} \]

\[ Q^2 = 0.2 \text{ GeV/c} \]

\[ x_B = 1 \]

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Momentum Distributions


At high initial momentums $n_A(p) = N \times n_D(p)$
Minimum Missing Momentum

Assuming a (e,e’p) reaction, inclusive (e,e’) can set limits on recoiling system’s momentum.
Nuclear Scaling Plateaus from CLAS


New Results From JLab Hall-C


\[
\frac{\sigma_A(A)}{\sigma_D/2} = \begin{cases} 
0.8 & 1.2 \\
1.4 & 1.8 \\
\end{cases}
\]

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Analysis in Progress

- **E07-006**: SRC 2nd Generation (e,e’pN) Triple Coincidence Experiment
  - Goal to further probe the repulsive part of the nucleon-nucleon potential with a few body, $^4$He, target.

- **E08-014**: SRC (e,e’) $x_B > 1$ & 2 data on $^3$He, $^4$He, $^{40}$Ca, & $^{48}$Ca
  - Goal to study $Q^2$, $x_B > 2$ region, and the A/Z dependence of the SRC plateaus.

![Graph showing the analysis in progress](Preliminary)
It’s this just final-state interactions?

• You definitely need final-state interactions.
• And models will show final-state interactions are important even in these kinematics BUT
• The final-state interactions are part of the story with the rest of the nuclear physics taken together correctly [i.e. you wouldn’t get the correct cross section in most kinematics without putting all the ingredients together correctly]
E89-044 $^3$He(e,e'p)pn Results (HallA)

F. Benmokhtar et al., Phys. Rev. Lett. 94 (2005) 082305. [ $x=1$, $q=1.5$ GeV, $w=0.84$ GeV.]

[Graphs showing data and results for $E_\text{m} - E_\text{thr}$ vs. $p_m$ (MeV/c) for different $p_m$ values.]
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

From Lowest To Highest
PWIA
PWIA+FSI
PWIA+FSI+MEC+NΔ

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

\[ dσ/dQ^2 dp_n \text{ (nb/GeV)} \]
Calculation of $D(e,e'p)n$ FSI Ratio

By Misak Sargasian using AV18 to get a momentum distribution and $x>1$ kinematics

\[ Q^2 = 3.5 \left( \frac{GeV}{c} \right)^2 \]
E12-10-003: D(e,e'p)n at \( x>1 \) & \( Q^2=4 \) GeV/c

21 PAC Days, 11 GeV beam and Hall C with 6 settings of the spectrometers

Kinematics where FSI is minimized (though still calculated) and sensitive to initial state ingredients.
Coincidence \((e,e'pN)\) Measurement

To study nucleon pairs and the fraction that contribute to momentum tail.

\[ x > 1, \quad Q^2 = 1.5 \text{ [GeV/c]}^2 \text{ and missing momentum of 500 MeV/c} \]
Acceptance matched np detectors.
(e,e’p) & (e,e’pp) Data


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

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Brookhaven EVA Collaboration Result


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

$p_f = p_1 + p_2 - p_0$

$p_0$ = incident proton

$p_1$ and $p_2$ are detected
High $p_m (e,e'p)$ events have recoiling neutrons.

$^{12}\text{C}$ From $(e,e')$, $(e,e'p)$, 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 (quasi-deuteron)
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
- Less than 1% multi-nucleon correlations
Importance of Correlations

If the $x>1$ results are proportional to local density effects, then it seems reasonable to look for connections to other possible local density effects.
What is the EMC effect?

Effect Reproduced Many Times

- EMC effect is simply the fact the ratio of DIS cross sections is not one
  - Simple Parton Counting Expects One
  - MANY Explanations
- SLAC E139
  - J. Gomez et al., PRD 49 (1994) 4348.
  - Precise large-x data
  - Nuclei from A=4 to 197
- Conclusions from SLAC data
  - $Q^2$-independent
  - Universal x-dependence (shape)
  - Magnitude varies with A
  - Average Nuclear Density Effect
New Jefferson Lab EMC Effect Data

New Jefferson Lab EMC Effect Data


- Plot shows slope of ratio $\sigma_A/\sigma_D$ at EMC region.
- EMC effect correlated with local density not average density.
So How These “DIS” Results Relate To The “SRC” Results?!
Holistic View of the EMC & SRC Data

D. Higinbotham et al., arXiv:1003.4497

$Q^2 = 2.5 \ [GeV/c]^2$

- Scaling plateaus are likely due to proton-nucleon **local density** correlations
- So could the **EMC slopes** ($x_B<0.7$) and **SRC plateaus** ($x_B>1.5$) correlated?!
SRC and EMC Correlation

EMC Slopes & SRC Plateaus
Medium Modified Form Factors

Polarization Transfer Measurements on $^4\text{He}(e,e'p)^3\text{H}$ around the QE peak

Answer depends on your basis as both Madrid and Schiavilla can describe the data.
Summary

• There is a wealth of electron scattering data available and MANY codes with parameterizations of the measured cross sections. (e.g. XEMC has a amazing amount of (e,e’) data parameterized)

• Mean field is a great starting point, but it is not the whole story.

• Interest new results show EMC & SRC effects to be strongly correlated. (i.e. nuclear effects even in DIS kinematics!)

• Open Questions
  – What exactly is the high momentum tail?
    ( i.e. for momentum p >> $p_{\text{fermi}}$, $n_A(p) = N * n_D(p)$ )
  – Is it hadronic, partonic, or some combination both?!
  – Can we use this correlation to make even more insights?!

• Many New EMC ($x<1$) and SRC ($x>1$) Experiments Coming with 12GeV Jefferson Lab, including $^3$H & $^3$He also well as A(e,e’X) data mining of 6 GeV CLAS data.

• And yes, Jefferson Lab could do argon measurements of (e,e’X) but it would need to be well thought out experiment [range of Q2, parallel & perp. kinematics, etc].
Select Upcoming 12GeV Experiments

- **E12-10-103 & E12-11-112** plans $^3$He & $^3$H (e,e') SRC & EMC Measurements
  - DIS $^3$He/$^3$H is a text book u/d experiment
  - $x>1$ to further investigate SRC and possible link EMC effect
- **E12-10-008 & E12-06-105** plans a survey of (e,e') nuclei from light to heavy.
  - Exact list being optimized, but goal is to cover EMC $x < 1$ and SRC $x > 1$ for each nucleus
- **E12-11-002** recoil polarization in the $4^\text{He}(e,e'p)^3\text{H}$, $2^\text{H}(e,e'p)n$, and $1^\text{H}(e,e'p)$ reactions
  - Classic medium modification experiment pushed to higher precision and higher missing momentum
- **E12-10-003** will measure D(e,e'p)n to extreme large missing momentum.

\[ \frac{\sigma_{^3\text{He}}}{\sigma_{^3\text{H}}} \times B \times F_2^n/F_2^p \]
Backup Slides
Revisiting the bag model (v2.0).

Discussions with A. Kerman with artwork by Joanne Griffen (Jefferson Lab)
Using SRC & EMC to get d/u ratios


Result is between the SU(6) symmetry limit of ½ and the scalar di-quark dominance limit of 0.
Quark State of Overlapping Nucleons

Deuteron Has Quadripole Moment In All Frames Of Reference

\[ l = 0 \quad + \quad l = 1 \]
$^{40}\text{Ca}$ to $^{48}\text{Ca} \ (e,e')$ Preliminary Ratios

$\sigma_{^{40}\text{Ca}} / \sigma_{^{40}\text{Ca}}$ Ratio:

- $21^\circ$: $1.248 < Q^2 < 1.418 \ (\text{GeV}/c^2)$
- $23^\circ$: $1.462 < Q^2 < 1.686 \ (\text{GeV}/c^2)$
- $25^\circ$: $1.522 < Q^2 < 1.962 \ (\text{GeV}/c^2)$

Very Preliminary