Future SRC Measurements

Lawrence Weinstein
Old Dominion University

- Existing SRC data
- What we want to learn
- The CaFe experiment
- Tagged DIS
- Measuring everything with CLAS12
  - New physics
  - Old physics done better
- Questions for discussion
Status

What we know:

- Almost all protons with $p > 300$ MeV/c belong to SRC
  - $300 < p_{rel} < 500$ MeV/c: Almost all have a neutron partner
  - $p_{rel} > 500$ MeV/c: tensor $\rightarrow$ scalar transition
- $P_{cm}$ consistent with adding two “mean field” nucleons
  - $\sigma_x = \sigma_y = \sigma_z \approx 150$ MeV/c
- pn pair dominance $\rightarrow$ protons move faster than neutrons in asymmetric nuclei
- The strength of the EMC effect is correlated with the probability of finding a nucleon in an SRC pair
  - The EMC effect can be explained by a universal modification of the structure of nucleons in pn SRC pairs
L. Weinstein, Quantitative SRC 2019

PRL 106, 052301 (2011),
PRC 85, 047301 (2012),

Submitted to PRL

PRL 113, 022501 (2014),


Science 320, 1476 (2008),
PRL 108, 092502 (2012),
PLB 772, 63 (2013),
PRC 92, 024604 (2015).

Nature 560, 617 (2018)
Existing data

How we know it:

→ a few hundred $A(e, e'pp)$ and $A(e, e'pn)$ events each at $x > 1.1$ and $Q^2 > 1.7$ GeV$^2$ on

- $^4$He and C (Hall A)
- C, Al, Fe and Pb (CLAS6 eg2)
- $^3$He, $^4$He, C and Fe (CLAS6 e2)
What we want to learn

- More precision on existing measurements

96 ± 22% of protons have a neutron partner
What we really want to learn

- The NN interaction and the nuclear wave function* at short distances,
- SRC pair formation mechanisms,
- Nuclear asymmetry-dependence of SRCs,
- Three-Nucleon SRCs,
- The EMC Effect and its relation to SRCs

And finally

- More precision on existing measurements

* The wave function is not an observable. This assumes the one-body operator, high momentum wave function picture.
What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

Two-body currents are **not** Correlations (but add coherently)

Need to calculate or minimize the effect of 2-body currents to make quantitative statements about SRC
Upcoming experiments: (1) CaFe

- How do 8 extra neutrons change the fraction of high-momentum protons?
- How do $1f_{7/2}$ neutrons pair with $s, p, d$ core protons?
- $A(e,e'p)$ on $^{40}\text{Ca, }^{48}\text{Ca and }^{54}\text{Fe}$
  - $Q^2 \approx 2 \text{ GeV}^2$
  - $\theta_{pr} < 40^\circ$
  - $x > 1$
  - Low and hi $\vec{p}_{miss} = \vec{q} - \vec{p}_p$

| $E_{\text{Beam}}$ (GeV) | $E'_e$ (GeV) | $\theta_e$ (°) | $|\vec{p}_p|$ (GeV/c) | $\theta_p$ (°) | $p_{\text{miss}}$ (GeV/c) | $Q^2$ (GeV²) |
|--------------------------|-------------|----------------|---------------------|----------------|-------------------------|--------------|
| 11                       | 9.85        | 8.0            | 1.43                | 63.0           | 0.40                    | 2.1          |
| 11                       | 9.85        | 8.0            | 2.01                | 44.5           | 0.15                    | 1.8          |

- Take double ratios of hi $\vec{p}_{miss}$ to low $\vec{p}_{miss}$ cross sections for $^{48}\text{Ca}$ relative to $^{40}\text{Ca}$ (and $^{54}\text{Fe}$)
How to do interpretable expts (in the absence of a comprehensive theory)

- Minimize unwanted reaction mechanisms
  - $Q^2 \approx 2 \text{ GeV}^2$: reduces MEC and $\Delta$ contributions
  - $\theta_{pr} < 40^\circ$: reduces FSI
  - $x > 1$: reduces MEC and $\Delta$ contributions
  - Take ratios of cross sections: further reduces FSI
  - Take ratios of ratios of cross sections ...

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Expected CaFe uncertainties

E12-17-005, approved for four(!) *entire* days of beam time
Upcoming experiments: (2) Tagged DIS

• Measure DIS from a nucleon in deuterium
• “Tag” that nucleon by measuring the other “spectator” backward nucleon
• How do bound nucleon structure functions vary with nucleon momentum or virtuality $\nu = p^2 - m^2$?
  – Mean field vs SRC pairs
• Tag backward neutrons: BAND + CLAS12 (running now)
• Tag backward protons: LAD + HMS and SHMS in Hall C
Experimental Method

d\(e,e'N_S\) cross section \textbf{Factorizes} into the cross section \((\sigma \propto F_2)\) times the distorted spectral function \(S^D(p,E)\).

Cross section \textbf{ratio} at fixed nucleon momentum

\(\Rightarrow\) distorted spectral function cancels:

\[
F_2^*(x_1',\alpha_S,p_T,Q_1^2)/F_2^*(x_2',\alpha_S,p_T,Q_2^2) = \left(\frac{d^4\sigma}{dx_1'dQ^2d\vec{p}_S} / K_1\right) / \left(\frac{d^4\sigma}{dx_2'dQ^2d\vec{p}_S} / K_2\right)
\]

Measure \(\alpha_s\) dependence at \(\theta_{pq} > 107^\circ\) \(\text{(small FSI)}\)

\[
x' = \frac{Q^2}{2p_\mu q^\mu} = \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_S \cdot \vec{q}]} \quad x'\text{ is } x\text{-Bjorken in the moving struck-nucleon frame}
\]

\[
\alpha_s = (E_s - p_s^z) / m_s 
\]

\(\vec{p}_s\) \text{ maps to} \((\alpha_s, p_T)\)
Experimental Method (cont.)

- Minimize experimental and theoretical uncertainties by measuring cross-section ratios

\[
\frac{\sigma_{DIS}(x'_{high}, Q^2, \vec{p}_s)}{\sigma_{DIS}(x'_{low}, Q^2, \vec{p}_s)} \cdot \frac{\sigma_{DIS}^{free}(x_{low}, Q^2)}{\sigma_{DIS}^{free}(x_{high}, Q^2)} \cdot R_{FSI} = \frac{F_{2}^{bound}(x'_{high}, Q^2, \vec{p}_s)}{F_{2}^{free}(x_{high}, Q^2)}
\]

- \( x' = x \) from a moving nucleon
- \( x'_{high} \geq 0.45 \)
- \( 0.25 \geq x'_{low} \geq 0.35 \) No EMC effect is expected

\[
x'_{B} = \frac{Q^2}{2p_\mu q^\mu} \quad (\text{For d}) \quad \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_s \cdot \vec{q}]}
\]

\[
x_B = \frac{Q^2}{2m_N \omega}
\]

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LAD and BAND expected results

\[ \alpha_s = \frac{(E_S - p_S^Z)}{m_S} \]

\[ \frac{G_{\text{eff}}}{G_n} \]

\[ \frac{G_{\text{eff}}}{G_p} \]

See Florian’s talk Saturday for details

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Upcoming experiments: (3) CLAS12 SRC/$e4\nu$
Upcoming experiments: (3) CLAS12 SRC/e4ν

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- Increase statistics by ~10 (per nucleus) over CLAS6 data
- Expand range of nuclei
  - Separate $A$ and asymmetry effects
  - $^{48}$Ca and Sn have the same asymmetry
\textit{e4\nu}: Electrons for neutrinos

- Use electron scattering data to constrain neutrino event generators
  - Cross sections
  - Incident energy reconstruction
$e4\nu$: $E_{beam}$ Reconstruction

$$E_{QE} = \frac{2ME_l + 2M\varepsilon - m^2}{2(M - E_l + |k_l|\cos\theta)}$$

**C(e,e’p)**

**GENIE**
- $p_\perp < 0.2$
- $0.2 < p_\perp < 0.4$
- $0.4 < p_\perp$

**Data**
- $p_\perp < 0.2$
- $0.4 < p_\perp$
- $0.2 < p_\perp < 0.4$

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**e4ν: Electrons for neutrinos**

- Use electron scattering data to constrain neutrino event generators
  - GENIE has both electron and neutrino modes

- Cross sections
- Incident energy reconstruction
- C, O, Ar targets
- Range of energies
New Expt, New and New-ish Physics

- Do 3N SRC exist?
  - Low abundance, hard to find
  - Important for neutron stars and NNN interactions
  - Expect few-100 (e,e’ppn) events at most

- NN interaction and nuclear wave fn at short distances
  - Study d and 4He, compare to heavier nuclei to prove A independence
New Expt, New and New-ish Physics

- SRC pair formation mechanisms
- Nuclear asymmetry dependence
  - Compare nn and pp pairs in symmetric and neutron-rich nuclei
  - Separate A and asymmetry dependence
    - Previous nuclei were C, Al, Fe, and Pb
    - Now: (4He, C, 28Si, 40Ca), (48Ca, Sn), (Pb)
- EMC-SRC studies
  - Many nuclei
  - Tagged (new) and inclusive (new-ish)
- Reaction mechanism studies
  - Need much better theory support to become quantitative
All the new experiments

• New physics (30%)
  – 3N SRC
  – Tagged DIS
  – Superfast quarks in nuclei
  – $x>2$ inclusive measurements

• New-ish physics (70%)
  – More nuclei
  – More statistics
  – Need more theory support to fully exploit the increased precision
But …

Can we relate \((Q^2, x_B)\) to minimum \(p_{miss}\) in \((e,e')\)?

275 to 600 MeV/c assuming d target

No binding energy, no A-2 excitation, no pair motion
But ...

- Can we relate \((Q^2, x_B)\) to minimum \(p_{miss}\) in \((e,e')\)?

Deuterium allowed region

\(C(e,e')\) including pair motion, A-2 excitation energy (\(E^*\)) and binding energy

- Different A-2 excitation energies \(\rightarrow\) 50 MeV/c variation in \(p_{miss}\) min
- C and d curves are non-parallel due to C binding energy and pair motion
Statements for discussion

- We can’t relate \((Q^2, x_B)\) to minimum \(p_{\text{miss}}\) in \((e,e')\)
  - How can we interpret a2?
  - How can we relate \((e,e')\) cross sections to momentum distributions?

- We don’t have complete reaction mechanism calculations for \((e,e'p)\) and \((e,e'pN)\)
  - How can we interpret \((e,e'p)\) and \((e,e'pN)\) cross sections and ratios?
CM = 100–200 MeV/c

Min.  \( p_{\text{miss}} \) [GeV/c]

Deuterium allowed region

\( E^* \) (MeV)

\( \sigma_{CM} \) = 100–200 MeV/c