Short Range Correlations in Nuclei
A Survey
Donal Day
University of Virginia

- Short range Correlations Exist!
- Old Subject
- Studied via knock-out reactions
  - Inclusive
  - Ratios
  - Exclusive
    - Isospin dependence
- Source is the Nuclear Potential
- Some details
- Future Prospects
Structure of the nucleus

- Nucleon separation is limited by the short range repulsive core

Determined by N-N potential

- nucleons are bound
  - energy (E)
  - distribution
- shell structure
- nucleons are not static
  - momentum (k)
  - distribution

Densely packed – at small distances multiples of NM

High enough to modify nucleon structure?

Correlations – when 2N are at small $r_{12}$. How is this manifested?
Correlations — Old Topic


“The differential cross section for inelastic scattering summed over nuclear energy levels, is found to depend on the relative location of pairs of particles. Information on possible regularities in the internal "construction" of nuclei might be obtained from this quantity.”

The author related a quantity, φ, which "integrated over all of the coordinates save two to give a "two-particle density" which characterizes the correlation in location of pairs of protons" --- spatial correlations

The determination of the nuclear pair correlation function and momentum distribution
Kurt Gottfried

Inelastic electron scattering from fluctuations in the nuclear charge distribution
Wieslaw Czyż and Kurt Gottfried
Annals of Physics 21, 47 (1963)

\[
\omega_c = \frac{(k + q)^2}{2m} + \frac{q^2}{2m}
\]

\[
\omega'_c = \frac{q^2}{2m} - \frac{q k_f}{2m}
\]

Shaded domain where scattering is restricted solely to correlations

x > 1, low ω side of qep
We know short range correlations exist.

Central density is saturated - nucleons can be packed only so close together: $p_{ch}^* (A/Z) = \text{constant}$

\[ \rho(x, x') = \rho(x)\rho(x')g(x, x') \]

\[ |x - x'| \lesssim r_c \Rightarrow g(x, x') \ll 1 \]

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J.W. Negele RMP 54 (913) 1982

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5th Workshop of the APS Topical Group on Hadronic Physics
April 11, 2013
What else? Occupation Numbers

Density difference between $^{206}\text{Pb}$ and $^{205}\text{Tl}$.

Experiment - Cavedon et al (1982)
Theory: Hartree-Fock orbitals with adjusted occupation numbers is given by the curve.

The shape of the $3s^{1/2}$ orbit is very well given by the mean field calculation.

Occupation numbers scaled down by a factor $\sim 0.65$.

Where does this strength go?
Short Range Correlations reveal themselves in momentum distributions

Mean field contributions: \( k < k_F \) Well understood, SF Factors \( \approx 0.65 \)

High momentum tails: \( k > k_F \)
- Calculable for few-body nuclei, nuclear matter
- Dominated by two-nucleon short range correlations
- Poorly understood part of nuclear structure
- Sign. fraction have \( k > k_F \)

Quasi free Knockout Reactions

\[
\begin{align*}
\text{Initial State} & : m \rightarrow (k_0, E_0) \\
\text{Final State} & : m \rightarrow m, (k_1, E_1), (k_2, E_2)
\end{align*}
\]

proton, pions, electrons inclusive, exclusive

\[
\begin{align*}
M_A & \rightarrow M_{A-1} \\
\theta_1 & = \text{angle of } (k_{A-1}, E_{A-1}) \\
\theta_2 & = \text{angle of } (k_2, E_2)
\end{align*}
\]
Realistic many body calculations of the spectral function contain correlated strength and it is significant.

$k < k_F$: single-particle contribution dominates

$k \approx k_F$: SRC already dominates for $E > 50$ MeV

$k > k_F$: single-particle negligible

Benhar via Rohe $^{12}\text{C}$
Spectral Function

probability to remove a nucleon leaving the residual system with energy $E_R = M_A - m + E = (k^2 + M_R^2)^{1/2}$

Sauer 3He isospin = 0

$3^\text{He}$

$$n(k) = \int S(E_s, k) \, dE_s$$

Strength is spread out in $E$, all of which must be integrated over to get $n(k)$

A ridge at approx $E = k^2/2m$ reflects the correlation in the gs
How to gain access to short range correlations?


Ciofi degli Atti, PRC 53 (1996) 1689

CdA, Day, Liuti, PRC 46 (1045) 1992
In \((e,e')\) flux of outgoing protons strongly suppressed: 20-40\% in C, 50-70\% in Au
In \((e,e')\) the failure of IA calculations to explain \(d\sigma\) at small energy loss

Old problem: real/complex optical potential. Real part generates a shift, imaginary part a folding of cs, reduction of qep.
Role of SRC on Lorentzian tail?? Off-shell effects on NN interaction??
Can they ever be neglected?

Some of this could be resolved by a rearrangement of strength in SE
Inclusive scattering at large $x$

At $x \approx 1$

- Motion of nucleon in the nucleus broadens the peak.
- Little strength from QE above $x \approx 1.3$.

High momentum tails should yield constant ratio if seeing SRC.
**Deuteron momentum distribution**

Virtually no experimental d(e, ep)n data exist for $p_m > 0.5$ GeV/c without large contributions of FSI, MEC and IC.

Inclusive D(e, e') via $\gamma$-scaling provides $n(k)$ well into the SRC region.

$$n(k) = -\frac{1}{2\pi y} \frac{dF(y)}{dy}$$
In the region where correlations should dominate, large $x$,

$$\sigma(x, Q^2) = \sum_{j=1}^{A} \frac{1}{j} a_j(A) \sigma_j(x, Q^2)$$

$$= \frac{A}{2} a_2(A) \sigma_2(x, Q^2) + \frac{A}{3} a_3(A) \sigma_3(x, Q^2) + \cdots$$

$a_j(A)$ are proportional to finding a nucleon in a $j$-nucleon correlation. It should fall rapidly with $j$ as nuclei are dilute.

$$\sigma_2(x, Q^2) = \sigma_{eD}(x, Q^2) \text{ and } \sigma_j(x, Q^2) = 0 \text{ for } x > j.$$  

Assumption is that in the ratios, off-shell effects and FSI largely cancel.

$$2 \frac{\sigma_A(x, Q^2)}{A \sigma_D(x, Q^2)} = a_2(A) \bigg|_{1 < x \leq 2}$$

$$3 \frac{\sigma_A(x, Q^2)}{A \sigma_{A=3}(x, Q^2)} = a_3(A) \bigg|_{2 < x \leq 3}$$

$a_j(A)$ is proportional to probability of finding a $j$-nucleon correlation.
Ratios, SRC’s and \( Q^2 \) scaling

\[
\frac{2 \sigma_A}{A \sigma_D} = a_2(A); \quad (1.4 < x < 2.0)
\]

\( A(e,e') \), \( 1.4 < Q^2 < 2.6 \)

Fe/\(^2\)H

\[
\langle Q^2 \rangle = 0.9 \\
\langle Q^2 \rangle = 1.2 \\
\langle Q^2 \rangle = 1.8 \\
\langle Q^2 \rangle = 2.3
\]

\( \alpha_{2N} \approx 20\% \)

\( \alpha_{3N} \approx 1\% \)

CLAS data

Egiyan et al., PRL 96, 082501, 2006

\( a_j(A) \) is probability of finding a \( j \)-nucleon correlation
Selection by kinematics

Appearance of plateaus is $A$ dependent.

**Kinematics:** heavier recoil systems do not require as much energy to balance momentum of struck nucleon - hence $p_{\text{min}}$ for a given $x$ and $Q^2$ is smaller.

**Dynamics:** mean field part in heavy nuclei persist in $x$ to larger values

Have to go to higher $x$ or $Q^2$ to insure scattering is not from mean-field nucleon
Good agreement in the 2N-SRC region

but potential difference in the 3N-SRC region
Exclusive $A(e,e'p)$

High momentum(!) strength in proton knockout in $(e,e'p)$

$^2$H$(ee'p)n$ Mainz


\[ E = .855 \]
\[ \theta = 45 \]
\[ E' = .657 \]
\[ Q^2 = 0.33 \]
\[ x = .88 \]

Not the best place to look for SRCs – $\Delta$s, MECs FSI dominate

large IC+MEC
Exclusive $A(e,e'p)$

$^3\text{He}(e,e'p)d$  E89-044, Hall A

Measured far into high momentum tail: Cross section is ~5-10x expectation

High momentum pair can come from SRC (initial state)

OR

Final State Interactions (FSI) and Meson Exchange Contributions (MEC), Δ's

M. M. Rvachev et al. PRL 94, 192302 (2005)
Exclusive $A(e,e'p)$

$^3\text{He}(e,e'p)pn$ E89–044, Hall A

$^3\text{He}(e,e'p)np$ F. Benmokhtar et al., PRL 94, 082305 (2005)

- dotted line PWIA
- dash-dot: Laget (PWIA)
- FSI (long dashed line) to full calculation (solid line), including meson-exchange current and final-state interactions: Laget
- In the 620 MeV/c panel
  - short dashed curve is a calculation with PWIA + FSI only within the correlated pair.

Table I. Proton spectrometer kinematic settings.

$$\begin{array}{cccc}
\text{Setting} & \text{Energy} & \text{Proton Mass} & \text{Resolution} \\
\hline
\text{1} & 550 \text{ MeV} & 1171 & 0.0133 \\
\text{2} & 425 \text{ MeV} & 1406 & 0.0134 \\
\text{3} & 300 \text{ MeV} & 1444 & 0.0135 \\
\end{array}$$

FIG. 3 (color online). Proton effective momentum density distribution $K_{\text{p}}$, integrated over $\Omega_{\text{p}}$, $d\sigma/d\Omega_{\text{p}}dE_{\text{p}}$ $(\text{pb/MeV}^2\text{sr}^2) \times 10^{-2}$.

3bbu channel=0

$$d\sigma/d\Omega_{\text{p}}dE_{\text{p}} = \frac{d\sigma}{d\Omega_{\text{p}}dE_{\text{p}}}$$

$E_{\text{m}} - E_{\text{thr}}$ (MeV)

Effective Density (fm$^{-3}$)

$p_{m}$ (MeV/c)

$E_{89-044}$ 3bbu

$Laget$ 3bbu Full

$Laget$ 3bbu PWIA

$Laget$ 2bbu Full

$Laget$ 2bbu PWIA

$E_{89-044}$ 2bbu

$\times = 1$
Parallel kinematics selected to minimize FSI

Data suggests more SRC strength at smaller E than theory

Frick et al. PRC 70, 024309 (2004)

Self consistent Green's Function (SCGF)
Integrated strength in the covered $E_m-p_m$ region:

$$Z_c = 4\pi \int_{\frac{130}{670}} dp \, p_m^2 \int dE_m S(E_m, p_m)$$

"correlated strength" in the chosen $E_m-p_m$ region:

In terms of # of protons in $^{12}\text{C}$

<table>
<thead>
<tr>
<th>$^{12}\text{C}$</th>
<th>exp.</th>
<th>CBF theory</th>
<th>G.F. 2.order</th>
<th>self-consistent G.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>experimental area</td>
<td>0.61</td>
<td>0.64 ≈ 10 %</td>
<td>0.46</td>
<td>0.61</td>
</tr>
<tr>
<td>in total (correlated part)</td>
<td>22 %</td>
<td>12%</td>
<td>≈20%</td>
<td></td>
</tr>
</tbody>
</table>

contribution from FSI: -4 %

• ≈ 10% of the protons in $^{12}\text{C}$ at high $p_m$, $E_m$ found
• first time directly measured

comparing to theory leads to conclusion that
≈ 20% of the protons in Carbon are beyond the IPSM region
Triple Coincidence SRC Measurements

n-p Short-Range Correlations from (p,2p + n)


Correlated pair have equal and opposite momenta

“That neutrons emitted into the backward hemisphere with \( p_n > k_F \) come from n-p SRC, since SRC is a natural mechanism to explain such momentum-correlated pairs”

49 ± 13% of events with \( |p_f| > k_F \) had directionally correlated neutrons with \( |p_n| > k_F \)

Also measured, for first time, the CM motion of 2N pair

Isospin dependence unstated but SRCs must be the source of high-\( k \)

Reconstruct the struck proton before scattering

\[
\vec{p}_f = \vec{p}_1 + \vec{p}_2 - \vec{p}_0
\]

Detect 2 protons along with emerging neutron

\[
\cos \gamma = \frac{\vec{p}_f \cdot \vec{p}_n}{|\vec{p}_f| |\vec{p}_n|}
\]

Events

\( p_n > 0.22 \text{ GeV/c} \)

\[
\cos \gamma = \frac{\vec{p}_f \cdot \vec{p}_n}{|\vec{p}_f| |\vec{p}_n|}
\]

Events

\( p_n < 0.22 \text{ GeV/c} \)
But what of neutron absorption as it moves through the (A–2) system?

Significant possibility that the neutron momentum falls below $k_f$

**Analysis**

- Modeling of the spectral and decay functions of the reaction in light cone approximation
- Extraction of the quantity $P_{pn/px}$
  
  $P_{pn/px}$: the probability of finding a $pn$ correlation in the “$pX$” configuration that is defined by the presence of at least one proton with $p > k_{Fermi}$.

- Results: removal of a proton from the nucleus with initial $275<p<550$ MeV/c is associated by the emission of a correlated neutron with equal and opposite momentum of the proton $92\% \pm 18\%$ of the time.

- Proton recoils (eg $A(p,pp)n$) were not detected but an estimate could be made.
  Probabilities of $pp$ or $nn$ SRCs in the nucleus are at least a factor of 6 smaller than that of $pn$ SRCs.

Isospin dependence of SRC.
Simultaneous measurements of the \((e,e'p), (e,e'p)\), and \((e,e'p)\) reactions

Use \(^{12}\text{C}(e,e'p)\) as a tag to measure \(^{12}\text{C}(e,e'p)/^{12}\text{C}(e,e'p)\)

**Optimized kinematics:**
\[ Q^2 \approx 2.0 \ x_B \approx 1.2 \text{ “Semi anti-parallel” kinematics} \]

Findings

- Almost all protons with $p_i > k_F$ in $^{12}\text{C}(e,e'p)$ have a paired proton or neutron with similar momentum in opposite direction!
- CM momentum of pair $\sigma_{CM} = 136\pm20$ MeV/c
  - (BNL)=143±17
  - (Ciofi degli Atti&Simula)=139 MeV/c

Data show large asymmetry between np, pp pairs.
Qualitative agreement with calculations; effect of tensor force

$$\frac{^{12}\text{C}(e,e'pp)}{^{12}\text{C}(e,e'p)} = 9.5 \pm 2\%$$

$$\frac{^{12}\text{C}(e,e'pn)}{^{12}\text{C}(e,e'p)} = 96^{+4}_{-23}\%$$

$$\frac{^{12}\text{C}(e,e'pn)}{^{12}\text{C}(e,e'pp)} = 9.0 \pm 2.5\%$$

Isospin dependence of SRC
Tensor force responsible for dominant part of SRC and correlations are largely of pn pairs

JLAB A(e,e’NN) data from Hall A
R. Subedi et al.

Schiavilla et al. PRL 98, 132501 (2007), VMC and AV18/UIX

Scaled momentum distribution of the deuteron
The force that holds protons and neutrons together is extremely strong. It has to be strong to overcome the electric repulsion between the positively charged protons. It is also of very short range, acting only when two particles are within 1 or 2 fm of each other.

1 fm (femto meter) = \(10^{-15}\) m = 0.000000000000001 meters.

The qualitative features of the nucleon-nucleon force are shown below. This picture shows a rough sketch of the force between two nucleons. There is an extremely strong short-range repulsion that pushes protons and neutrons apart before they can get close enough to touch. (This is shown in orange.)

There is a medium-range attraction (pulling the neutrons and protons together) that is strongest for separations of about 1 fm. (This is shown in gray.) This attraction can be understood to arise from the exchange of quarks between the nucleons, something that looks a lot like the exchange of a pion when the separation is large.

The density of nuclei is limited by the short range repulsion. The maximum size of nuclei is limited by the fact that the attractive force dies away extremely quickly (exponentially) when nucleons are more than a few fm apart.

Elements beyond uranium (which has 92 protons), particularly the trans-fermium elements (with more than 100 protons), tend to be unstable to fission or alpha decay because the Coulomb repulsion between protons falls off much more slowly than the nuclear attraction. This means that each proton sees a repulsion from every other proton but only feels an attractive force from the few neutrons and protons that are nearby—even if there is a large excess of neutrons.
How can two nucleons combine?

The Pauli principle requires that two-nucleon states be antisymmetric with respect to exchange of the nucleons' space, spin, and isospin coordinates.

<table>
<thead>
<tr>
<th>L</th>
<th>S</th>
<th>J</th>
<th>$\pi = -1^L$</th>
<th>$T(L+S+T$ odd)</th>
<th>$^{2S+1}L_J$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>1</td>
<td>$^1S_0$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>+</td>
<td>0</td>
<td>$^3S_1$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>0</td>
<td>$^1P_1$</td>
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<td>1</td>
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<td>$^3P_1$</td>
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<tr>
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<td>1</td>
<td>2</td>
<td>-</td>
<td>1</td>
<td>$^3P_2$</td>
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<tr>
<td>2</td>
<td>0</td>
<td>2</td>
<td>+</td>
<td>1</td>
<td>$^3D_2$</td>
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<tr>
<td>2</td>
<td>1</td>
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<td>+</td>
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<td>$^3D_1$</td>
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<td>2</td>
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<td>$^3D_2$</td>
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<tr>
<td>2</td>
<td>1</td>
<td>3</td>
<td>+</td>
<td>0</td>
<td>$^3D_3$</td>
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</table>

Two-nucleon states

Without the tensor contribution, the deuteron would not be bound.

And it only contributes to $T=0$ 2N states.

![Graph showing the potential energy of the deuteron and D states](image)
**Possible Two Nucleon states**

<table>
<thead>
<tr>
<th>L</th>
<th>S</th>
<th>J</th>
<th>( \pi = -1 )</th>
<th>( T(L+S+T \text{ odd}) )</th>
<th>( ^{2S+1}L_J )</th>
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<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>1</td>
<td>( ^{1}S_{0} )</td>
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<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>+</td>
<td>0</td>
<td>( ^{3}S_{1} )</td>
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<tr>
<td>1</td>
<td>0</td>
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<td>( ^{1}P_{1} )</td>
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</tr>
</tbody>
</table>

**Symmetric triplet** \( T = 1 \)
\[ ^{3}(T)_{1} = |p_{1}> |p_{2}> \text{ proton-proton state} \]
\[ ^{3}(T)_{-1} = |n_{1}> |n_{2}> \text{ neutron-neutron state} \]
\[ ^{3}(T)_{0} = \frac{1}{\sqrt{2}} (|p_{1}> |n_{2}> + |p_{2}> |n_{1}> ) \text{ neutron-proton state} \]

**Antisymmetric singlet** \( T = 0 \)
\[ ^{1}(T)_{0} = \frac{1}{\sqrt{2}} (|p_{1}> |n_{2}> - |p_{2}> |n_{1}> ) \text{ neutron-proton state} \]

The SR NN attraction dominated by tensor interaction, which yields high-momentum isosinglet (np) pairs.

Absent in the isotriplet channel (pp, nn, np).

2-body distribution in nucleus should be identical to the deuteron and ratio of scattering cross sections between a heavy nucleus A and the deuteron to yield \( a_{2} (A, Z) \).

![Graph showing two-nucleon states and their properties.](image)

**Explain the (e,e’)SRC ratios, and isospin asymmetry?**

**Deuteron S and D**
- \( ^{1}S_{0} \); S=0, T=1
- \( ^{1}P_{1} \); S=0, T=0
- \( ^{3}P_{0} \); S=1, T=1
- \( ^{3}P_{1} \); S=1, T=1
- \( ^{3}P_{2} \); S=1, T=1
- \( ^{3}D_{1} \); S=1, T=0

Generated on 2013-04-09 by Donal Day

*5th Workshop of the APS Topical Group on Hadronic Physics*
spins aligned parallel or perpendicular to the relative distance vector

- strong repulsive core: nucleons cannot get closer than $\approx 0.5$ fm
  - central correlations

- strong dependence on the orientation of the spins due to the tensor force
  - tensor correlations

the nuclear force will induce strong short-range correlations in the nuclear wave function
Coming up

6 GeV (completed in Spring 2011)

[Hall A]

- **E-08-014**: Three-nucleon short range correlations studies in inclusive scattering for $0.8 < 2.8 \text{ (GeV/c)}^2$
  
  $^2\text{H}, \, ^3\text{He}, \, ^4\text{He}, \, ^{12}\text{C}, \, ^{40}\text{Ca}, \, ^{48}\text{Ca}$, isospin dependence

- **E07-006**: Exclusive X-sections $^4\text{He}(e,e'p)$, $^4\text{He}(e,e'pp)$, $^4\text{He}(e,e'pn)$, $^4\text{He}(e,e'p_{\text{recoil}})$

  - Does pp/pn ratio change?! Are there signs of repulsive core? Can the reactions be calculated?

- **E12-06-105**: Inclusive Scattering from Nuclei at $x > 1$ in the quasielastic and deeply inelastic regimes [Hall C], $^1\text{H}, \, ^2\text{H}, \, ^3\text{He}, \, ^4\text{He}, \, ^6\text{Li}, \, ^9\text{Be}, \, ^{10,11}\text{B}, \, ^{12}\text{C}, \, ^{40}\text{Ca}, \, ^{48}\text{Ca}, \, \text{Cu}, \, \text{Au}$

Arrington, DD, Fomin, Solvignon
### Physics goals

**Isospin-dependence**
- ✓ Improved precision: extract \( R(T=1/T=0) \) to 3.8%
- ✓ FSI much smaller (inclusive) and expected to cancel in ratio

**Improved A-dependence in light and heavy nuclei**
- ✓ Average of \(^3\text{H}, \(^3\text{He} \rightarrow A=3\) “isoscalar” nucleus
- ✓ Determine isospin dependence \(\rightarrow\) improved correction for \(N>Z\) nuclei, extrapolation to nuclear matter

**Absolute cross sections (and ratios) for \(^2\text{H}, \(^3\text{H}, \(^3\text{He}\)**
- test calculations of FSI for simple, well-understood nuclei
Isospin study from $^3\text{He}/^3\text{H}$ ratio

Simple mean field estimates for 2N-SRC

Isospin independent

$$\frac{\sigma_{^3\text{He}}/3}{\sigma_{^3\text{H}}/3} = \frac{(2\sigma_p + 1\sigma_n)/3}{(1\sigma_p + 2\sigma_n)/3}$$

with $\sigma_p = 3\sigma_n \rightarrow 1.4$

n-p (T=0) dominance

$$\frac{\sigma_{^3\text{He}}/3}{\sigma_{^3\text{H}}/3} = \frac{(2pn + 1\text{nn})/3}{(2pn + 1\text{pp})/3} = 1.0$$

Left HRS running (380 hours)
Data Mining from CLAS E2

Analysis Goals

1. pp–SRC universality in large A nuclei
   1. Existence
   2. Characteristics (cm and rel. momentum distributions)
   3. Probabilities
2. Extend $|P_{\text{miss}}|$ coverage – transition to scalar force
3. Nuclear transparency – FSI in SRC kinematics
4. and more….
In-Medium Nucleon Structure Functions

- DIS scattering from nucleon in deuterium
- Tag high-momentum struck nucleons by detecting backward “spectator” nucleon in Large-Angle Detector
- $\alpha_s$ related to initial nucleon momentum

Projected uncertainties
In-Medium Nucleon Form Factors
E11-002: E. Brash, G. M. Huber, R. Ransom, S. Strauch

- Compare proton knock-out from dense and thin nuclei: $^4\text{He}(e,e'p)^3\text{H}$ and $^2\text{H}(e,e'p)n$

- Modern, rigorous $^2\text{H}(e,e'p)n$ calculations show reaction-dynamics effects and FSI will change the ratio at most 8%

- QMC model predicts 30% deviation from free nucleon at large virtuality

Sensitivity to non-hadronic components

- 5% 6-quark bag

Graphs showing plots of valence quark distribution and ratio, with and without 6-quark bag, for different values of x.
Summary

- Evidence for SRC seen in inclusive and exclusive reactions
- Isospin asymmetry established experimentally → probably should not be a surprise
- New experiments under analysis and approved that should illuminate both the gross and fine features
- SRC demand high densities (momenta) and, if these rare fluctuations can be captured, they should expose, potentially large, medium modifications