Short-Distance Structure of Nuclei

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\textbf{Abstract.} One of Jefferson Lab’s original missions was to further our understanding of the short-distance structure of nuclei, in particular, to understand what happens when two or more nucleons within a nucleus have strongly overlapping wave-functions – a phenomena commonly referred to as short-range correlations. Herein, we review the results of the \( (e,e') \), \( (e,e'p) \) and \( (e,e'pN) \) reactions that have been used at Jefferson Lab to probe this short-distance structure as well as provide an outlook for future experiments.

1. Introduction

The structure of nuclei is determined by the strong force with repulsion at short distances and attraction at moderate distances. This force, which binds the nucleons together while also keeping the structure from collapsing, makes the nucleus a fairly dilute system. This allows for calculations that treat the nucleus as a collection of hard objects in an average or mean field to describe many of the properties of nuclear matter; however, this simple picture breaks down when detailed features are studied. In particular, the short-distance part of the nucleon-nucleon potential can cause central, tensor and spin-orbit correlations between the nucleons in nuclei which deplete the low momentum states in nuclear systems [1].

Calculations indicate that these short-range correlations can lead to short-term local densities in the nucleus that are several times as high as the average nuclear density of 0.17 GeV/fm\(^3\), and thus, comparable to densities predicted in neutron stars [2]. Isolating the signal of short-range correlated nucleons may therefore lead to a deeper understanding of cold, dense nuclear systems.

Directly identifying short-range correlations has been experimentally challenging. The low duty factors and the sub-GeV energies of previous facilities limited studies of short-range correlations to moderate momentum transfer kinematics. The Jefferson Lab accelerator and experimental facilities permit measurements at high energy and high luminosity with a continuous beam. These parameters have allowed measurements of the \( A(e,e') \), \( A(e,e'p) \) and \( A(e,e'pN) \) reactions in kinematics above the quasi-elastic peak and at high momentum transfer. These kinematics are where the effects of competing mechanisms such as meson-exchange currents, isobar configurations, and final-state interactions are reduced and the signatures of short-range correlations become dominant.

2. Inclusive reactions

The inclusive \( A(e,e') \) process is the simplest electromagnetic reaction for studying short-range correlations; though to use this reaction channel, it is important to be in kinematics where short-range correlations dominate over other reaction mechanisms such as meson-exchange currents.
or delta-isobar contributions. As first shown with the SLAC \((e,e')\) data \([3]\), this is done by requiring \(x_B = Q^2/2m\omega > 1\) and \(Q^2 > 1\) (GeV/c)^2 where \(m\) is the nucleon mass, \(\omega\) is the energy transfer and \(Q^2\) is the four-momentum transfer squared. The high \(x_B\) minimizes the inelastic scattering contributions, while high \(Q^2\) minimizes meson-exchange currents. It was predicted that in these kinematics diagram b) shown in Fig. 1 would dominate the reaction \([4]\).

For large \(Q^2\) and \(x_B > 1\) the value of \(x_B\) kinematically determines a minimum possible missing momentum; thus, by choosing \(x_B\) large enough, only contributions from nucleons with missing momentum above the Fermi sea, corresponding to large excitation energies, can contribute to the reaction.

\[
\frac{Y(A)}{Z\sigma_{ep} + N\sigma_{en}} C^A_{\text{rad}},
\]

where \(Y\) is the normalized yield, \(Z\) and \(N\) are the number of protons and neutrons in a nucleus \(A\), \(\sigma_{eN}\) is the electron-nucleon cross section, and \(C^A_{\text{rad}}\) is the ratio of the radiative correction factors for \(A\) and \(^2\text{H}\). The SLAC data show for \(Q^2 > 1\) (GeV/c)^2 and \(x_B > 1.4\) a scaling in the data which was argued to be due to short-range correlations \([3]\). These events corresponded to nucleon momenta of about 250 – 300 MeV/c. For these measurements the statistics were rather limited and \(x_B\) was less than 2. Also, the deuteron data was measured in a different kinematics and comparisons to the other nuclei required nontrivial extrapolations.

In order to improve upon the SLAC \((e,e')\) data, Jefferson Lab provided higher statistics data and was able to look for a second scaling region due to three-nucleon correlations. The three-nucleon correlation region was accessed by taking the ratios to \(^3\text{He}\) data instead of deuterium. The data was taken with the CEBAF Large Acceptance Spectrometer (CLAS) \([5, 6]\) and is shown in Fig. 2. The new data not only show scaling in the \(1 < x_B < 2\) region, but also show, for the first time, a second scaling in the \(x_B > 2\) region. This second scaling has been interpreted as being due to three-nucleon correlations and further strengthens the argument that the first scaling region is due to short-range two-nucleon correlations \([7]\).

From these ratios, one can determine the probabilities of two-nucleon correlations in the various nuclei by using the relatively well understood deuterium. This is valid due to closure in the interaction of the knocked-out nucleons with nucleons not belonging to correlations and
Figure 2. Weighted cross section ratios of (a) $^4$He, (b) $^{12}$C and (c) $^{56}$Fe to $^3$He as a function of $x_B$ for $Q^2 > 1.4$ GeV$^2$. The horizontal dashed lines indicate the two-nucleon and three-nucleon scaling regions used to calculate the per-nucleon probabilities for two- and three-nucleon short-range correlations in nucleus $A$ relative to $^3$He. Reprinted with permission from K.S. Egiyan et al., Phys. Rev. Lett. 96, 082501 (2006). Copyright 2006 by the American Physical Society.

cancellation of final-state interactions within the correlations in the ratio [4]. The probability of a nucleon-nucleon correlation in deuterium is defined as the probability that a nucleon in deuterium has a momentum $p > 275$ MeV/c. These are momenta that have been shown in $D(e, e'p)$ asymmetry measurements to be dominated by highly correlated nucleons [8]. Thus by integrating the wave function, it has been found that the per-nucleon probability of a nucleon in deuterium, $a_2(^2$H), to be in a nucleon-nucleon correlation is 0.041 ± 0.008. The probability of correlations in deuterium versus $^3$He, $a_2(^3$He/$^2$H) has been determined to be 1.97 ± 0.1 and thus $a_{2N}(^3$He) = 0.08 ± 0.016. From this result, the general $a_{2N}(A)$ probabilities can be calculated from the scaling results for 1.15 < $x_B$ < 2 for $r(A/^3$He) × $r(^3$He/$^2$H). To obtain the absolute probability of three-nucleon short-range correlations, a calculation of the Bochum group [9] using various potentials was used and gave an average value of $a_{3N}(^3$He) = 0.18 ± 0.06%. From this it was concluded that the $3N$ short-range correlations must be less than 1% [6]. These results are summarized in Table 1.

In Jefferson Lab’s Hall C, inclusive data were also taken for $x_B > 1$ and $Q^2$ from 1–7 (GeV/c)$^2$. These data also showed, for initial nucleon momenta greater than 300 MeV/c, a scaling behavior consistent with short-range nucleon-nucleon correlations [10]. Recent calculations show that
Table 1. Shown are the average ratios, $r(A^{3}/He)$, for the scaling regions $1.5 < x_B < 2$ and $2.2 < x_B < 2.7$ along with the extracted absolute probabilities $a_{2N}(A)$ and $a_{3N}(A)$ that in a nucleus $A$ a two- or three-nucleon short-range correlation is taking place at a given instant. Statistical and systematic errors have been combined in quadrature.

|           | $r(A^{3}/He)$ | $a_{2N}(A)$ | $r(A^{3}/He)$ | $a_{3N}(A)$ |
|-----------|---------------|-------------|---------------|-------------|
|           | 1.5 < $x_B$ < 2 | [%] 2.2 < $x_B$ < 2.7 | [%]           |
| $^3$He    | 1             | 8.0±1.6     | 1             | 0.18±0.06   |
| $^4$He    | 1.93±0.03     | 15.4±3.2    | 2.33±0.13     | 0.42±0.14   |
| $^{12}$C  | 2.49±0.15     | 19.8±4.4    | 3.18±0.27     | 0.56±0.21   |
| $^{56}$Fe | 2.98±0.18     | 23.9±5.3    | 4.63±0.33     | 0.83±0.27   |

these scaling regions can be used to obtain useful information about short-range correlations [12]. New high-precision data from Hall C on the $x_B > 1$ ratios should be available soon [11].

3. Proton knock-out

For proton knock-out experiments, it is useful to introduce the concept of an initial state momentum distribution of nucleons within the nucleus. This is done in a factorized approximation with a spectral function $S(p, E)$ which relates the experimental missing momentum, $p$, and missing energy, $E$ to the measured $(e, e'p)$ cross sections by the relation:

$$\frac{d^6\sigma}{dp_e dp_p d\Omega_e d\Omega_p} = K \sigma_{eN} S(p, E) T_A(Q^2),$$

where $K$ is a kinematic factor, $\sigma_{eN}$ is the elementary cross section, and the transparency, $T_A$, acts as the normalization factor between the experimental cross section and a theoretical momentum distribution. The transparency is often interpreted as the probability that a nucleon will be emitted from the nucleus without rescattering, though other effects are included in this factor, as it is experimentally just the scale parameter required to reconcile a theoretical momentum distribution with an experimental cross sections. Having theory calculate both the spectral function and the transparency allows us to further test our understanding of nuclear matter in a many-body system where exact solutions are not yet calculable.

In independent particle (IP) models, the strength of the spectral function is almost entirely limited to momenta and energies less than 250 MeV/c and 80 MeV, namely, the Fermi momentum and energy. In models built up from realistic nucleon-nucleon potentials, which include a repulsive core and medium range tensor component, the spectral function strength in the Fermi-gas region is reduced by about 20% [13, 14]. Measurements with reactions such as $(e, e'p)$ show a reduction of at least 30% [15, 16], which is consistent with the expectation that short-range correlations are an important part of the description of the nucleus. In the Hall A $^{16}$O$(e, e'p)$ experiment, which measured cross sections and response functions for 25 < $E$ < 120 MeV and $p$ < 340 MeV/c, it was found that calculations that included pion exchange currents, isobar currents and two-nucleon correlations were required to account for the shape of the data at high missing momentum, though the calculations still under estimated the measured cross section by a factor of two [17, 18].

Measurements of $A(e, e'p)$ were made in Jefferson Lab’s Hall C to directly identify correlated strength rather than inferring it from the absence of strength predicted by independent particle models. Using the HMS and SOS spectrometers, protons knocked out of $^{12}$C were detected in...
parallel kinematics with missing energy $E > 40$ MeV and missing momentum $k > 240$ MeV/c. The spectral function derived from this measurement, integrated over this range of missing energy and momentum, accounts for approximately 10% of the total strength of scattering from protons in $^{12}$C [19]. This strength is consistent with or larger than the correlated strength predicted for this kinematic range from a Correlated Basis Function approach [13] or Green’s function approach to calculating the spectral function [20]. These calculations both predict more of the correlated strength to be outside of the measured range, including at low missing energy and momentum where strength is indistinguishable from IP model proton knockout.

At Jefferson Lab, $T_A$ has been measured for several nuclei [21, 22] and found to be essentially independent of proton energy for knocked-out protons with over 1 GeV of kinetic energy. The measured transparencies have been found to be somewhat higher than expected for a proton propagating through an independent particle model nucleus. For example, for $^{12}$C the measured $T_A = 0.59$, while the prediction from an independent particle shell model is 0.55 [23]. Calculations with the Correlated Basis Function approach increase the transparency by about 10% due to short-range correlations and bring experiment and theory into much better agreement. This is interpreted as the short-range nucleon-nucleon causing a depletion in density near the point of interaction, giving a lower overall probability that it will interact as it leaves the nucleus.

Hall A measurements of the $^3$He$(e, e'p)d$ and $^3$He$(e, e'p)pm$ reactions were taken with a beam energy of 4.8 GeV, $Q^2 = 1.5$ (GeV/c)$^2$ in $x_B = 1$ kinematics. When this experiment was proposed, it was expected that these kinematics would cleanly show short-range correlations at missing momenta greater than 300 MeV/c. What was observed was a much greater strength in the high missing momentum region then expected [24, 25] as shown in Figure 3. The three-body break-up (3bbu) has been integrated over missing energy so that it could be plotted with the two-body break-up (2bbu) and the strengths of the two reactions compared.

The unexpected strength was explained as an interference between correlations in the initial state and final-state interaction [26], where neither effect alone could explain the observed cross section. Subsequently calculations by Ciofi degli Atti and Kaptari showed that a parameter free calculation which included a realistic wave function [27], i.e. one in which correlations are built in, and final-state interactions calculated with the generalized Eikonal approximation could explain the data [28, 29, 30].

4. Triple coincidence reactions

While the $A(e, e')$ and $A(e, e'p)$ data shown in Sections 2 and 3 clearly suggest strong local correlations, it is the new exclusive data that confirms that the inclusive scaling is indeed due to short-range correlations. Also, with exclusive reactions, it possible to determine types and abundances of nucleon pairs involved in correlations. Such experiments where two nucleons are detected were proposed in the 1960’s [31], but only with the advent of high luminosity and high energy machines were clean kinematics (i.e. $Q^2 > 1$ GeV$^2$ and $x_B > 1$) obtainable.

Experimentally, a high-momentum, small de Broglie wavelength probe can knock out one nucleon of a nucleus while leaving the residual nucleus nearly unaffected; however, if the nucleon being struck is part of an initial-state pair, the high relative momentum of the pair will cause the correlated nucleon to recoil and be ejected [4, 32]. Figure 4 shows an illustration of a high-energy electron knocking out two nucleons from a nucleus.

Historically, the interpretation of triple-coincidence experimental data at low $Q^2$ in terms of short-range correlations has been complicated by contributions from meson-exchange currents, isobar configurations and final-state interactions [33, 34, 35, 36]. The kinematics for the measurements described herein were chosen to minimize these effects. For example, at high $Q^2$, meson-exchange contributions decrease as $1/Q^2$ relative to plane-wave impulse contributions and relative to those due to correlations [37, 38]. Large $Q^2$ and $x_B$ also drastically reduce
Figure 3. Proton effective momentum density distributions in $^3\text{He}$ extracted from $^3\text{He}(e,e'p)pn$ three-body break-up (3bbu) is shown as the open black circles and the $^3\text{He}(e,e'p)d$ two-body break-up (2bbu) is shown as open black triangles. The three-body break-up (3bbu) integration covers $E_M$ from threshold to 140 MeV. The results are compared to calculations from J.-M. Laget [26] which explain the dominance of the continuum cross section at large missing momentum as a strong interference between short-range correlations and final-state interactions. Reprinted with permission from F. Benmokhtar et al., Phys. Rev. Lett. 94, 082305 (2005). Copyright 2005 by the American Physical Society.

isobar currents contributions [39, 40]. Final-state interactions are not small, but, in the chosen kinematics, predominately restricted to be within the correlated pair [2].

The high luminosity Hall A triple coincidence experiment used an incident electron beam of 4.627 GeV and the two Hall A high-resolution spectrometers (HRS) [41] to identify the $^{12}\text{C}(e,e'p)$ reaction. Scattered electrons were detected in the left HRS at a central scattering angle (momentum) of 19.5° (3.724 GeV/c). This corresponds to the quasi-free knockout of a single proton with transferred three-momentum $|\vec{q}| = 1.65$ GeV/c, transferred energy $\omega = 0.865$ GeV, $Q^2 = 2$ (GeV/c)$^2$, and $x_B = 1.2$. Knocked-out protons were detected using the right HRS which was set at 3 different combinations of central angle and momentum: 40.1° & 1.45 GeV/c, 35.8° & 1.42 GeV/c, and 32.0° & 1.36 GeV/c. These kinematic settings correspond to median missing-momentum values $p_{\text{miss}} = 0.35, 0.45$ and 0.55 GeV/c, respectively, covering the $p_{\text{miss}}$ range of 300 – 600 MeV/c.

A large-acceptance spectrometer, BigBite, was used to detect recoiling protons in $^{12}\text{C}(e,e'pp)$ events. The BigBite spectrometer consists of a large-acceptance, non-focusing dipole magnet [42] and a custom detector package. For this measurement, the magnet was located at an angle of 99° and 1.1 m from the target with a resulting angular acceptance of about 96 msr and a nominal momentum acceptance from 0.25 GeV/c to 0.9 GeV/c. Located immediately behind BigBite was a large neutron array matched to BigBite’s acceptance. This made it possible to
Figure 4. Illustration showing the \((e, e'pN)\) reaction. The incident electron couples to a nucleon-nucleon pair via a virtual photon. In the final state, the scattered electron and struck nucleon are detected along with the correlated nucleon that is ejected from the nucleus. Illustration courtesy of Joanna Griffin and inspired by Anna Shneor.

simultaneously detect the \(^{12}\text{C}(e, e'pp)\) and \(^{12}\text{C}(e, e'pn)\) reactions.

Figure 5 shows the cosine of the angle, \(\gamma\), between the missing momentum \(\vec{p}_{\text{miss}}\) and the recoiling proton detected in BigBite \((\vec{p}_{\text{rec}})\) for the highest \(p_{\text{miss}}\) setting of 550 MeV/c [43]. Also shown in Fig. 5 is the angular correlation for the random background as defined by a time window offset from the coincidence peak. The back-to-back peak of the real triple coincidence events is demonstrated clearly. The curve is a result of a simulation of the scattering off a moving pair having a center-of-mass momentum width of 0.136 GeV/c. That width was extracted from the data and is consistent with the width measured in the \((p, ppn)\) experiment at Brookhaven National Lab [44] and well as with a theoretical calculation based on the convolution of two independent single particle momentum distributions [45].

The measured ratio of \(^{12}\text{C}(e, e'pp)\) to \(^{12}\text{C}(e, e'p)\) events is given by the ratio of events in the background-subtracted time-of-flight peak to those in the \(^{12}\text{C}(e, e'p)\) spectra. The measured ratios are limited by the finite acceptance of BigBite. The center of mass momentum distribution obtained from the measured angular correlation is used to account for this finite acceptance; the resulting extrapolated ratios are shown in Fig. 6.

To compare the \((e, e'pm)\) to \((e, e'p)\) yields, a similar procedure as above was followed. With neutrons, momentum determination was done with time-of-flight and the neutron detection
Figure 5. For the $^{12}\text{C}(e,e'\text{pp})$ reaction at $Q^2 > 1$ (GeV/c)$^2$, the distribution of the cosine of the opening angle between the $\vec{p}_{\text{miss}}$ and $\vec{p}_{\text{rec}}$ for a $p_{\text{miss}} = 0.55$ GeV/c. The histogram shows the distribution of random events. The curve is a simulation of the scattering off a moving pair with a width of 0.136 GeV/c for the pair center of mass momentum. Reprinted with permission from R. Shneor et al., Phys. Rev. Lett. 99, 072501 (2007). Copyright 2007 by the American Physical Society.

Efficiency was only about 40%. This results in a poorer signal to background ratio than the $(e,e'\text{pp})$ measurement and also a larger uncertainty. Taking into account the finite acceptance of the neutron detector and the neutron detection efficiency, it was found that 96 ± 22% of the $(e,e'p)$ events with a missing momentum above 300 MeV/c had a recoiling neutron. This result agrees with the hadron beam measurement of the $(p,2\text{pn})/(p,2p)$ reaction in which 92 ± 18% of the $(p,2p)$ events with a missing momentum above the Fermi momentum of 275 MeV/c were found to have a single recoiling neutron carrying the momentum [46].

Since the recoiling proton $^{12}\text{C}(e,e'\text{pp})$ and neutron $^{12}\text{C}(e,e'\text{pm})$ data were collected simultaneously with detection systems covering nearly identical solid angles, the ratio of $^{12}\text{C}(e,e'\text{pm})/^{12}\text{C}(e,e'\text{pp})$ could be directly determined with many of the systematic factors needed to compare the rates of the $^{12}\text{C}(e,e'\text{pp})$ and $^{12}\text{C}(e,e'\text{pm})$ reactions canceling out. Correcting only for detector efficiencies, a ratio of 8.1 ± 2.2 was determined. To estimate the effect of final-state interactions (i.e., reactions that happen after the initial scattering), the attenuation of the recoiling protons and neutrons was assumed to be almost equal. In this case, the only correction related to final-state interactions of the measured $^{12}\text{C}(e,e'\text{pm})$ to $^{12}\text{C}(e,e'\text{pp})$ ratio is due to single charge exchange. For the experiment, the neutron to proton single charge exchange dominates proton to neutron single charge exchange since the $(e,e'p)$ rate is about an order of magnitude larger than the $(e,e'pp)$ rate and thus decreases the measured $^{12}\text{C}(e,e'\text{pm})/^{12}\text{C}(e,e'\text{pp})$ ratio. Using Glauber approximation [47], it was estimated this effect was 11%. Taking this into account, the corrected experimental ratio for $^{12}\text{C}(e,e'\text{pm})/^{12}\text{C}(e,e'\text{pp})$ is 9.0 ± 2.5.

To deduce the ratio of $\text{pn}$ to $\text{pp}$ correlated pairs in the ground state of $^{12}\text{C}$, the measured $^{12}\text{C}(e,e'\text{pm})$ to $^{12}\text{C}(e,e'\text{pp})$ ratio was used. Since the experiment triggered only on forward $(e,e'p)$ events, the probability of detecting $\text{pp}$ pairs was twice that of $\text{pn}$ pairs; thus, we conclude that the ratio of $\text{pn}/\text{pp}$ pairs in the $^{12}\text{C}$ ground state is 18 ± 5 as shown in Fig. 7. This result
Figure 6. The measured and extrapolated ratios of yields for the $^{12}$C($e, e'pp$) and the $^{12}$C($e, e'p$) reactions. The shaded area represents a band of ±2σ uncertainty in the width of the center-of-mass momentum of the pair. Reprinted with permission from R. Shneor et al., Phys. Rev. Lett. 99, 072501 (2007). Copyright 2007 by the American Physical Society.

is consistent with the ($p, 2pn$) data [46]. Since both the probe and the kinematics of these two experiment were very different, it furthers the interpretation of the process as being due to scattering off a correlated pair of nucleons [48].

The small ratio of $pp,np$ has been explained by several theoretical groups [50, 51, 52]. These calculations clearly show that the measured $pp,np$ ratio is expected and is a clear indication of the nucleon-nucleon tensor force at the probed distances and relative momenta of the nucleons in a short-range two-nucleon correlation.

Instead of directly knocking out one nucleon of the correlated pair, it is also possible in the three-body system to knock out the third nucleon and observe the decay of the spectator correlated pair. This was done in the $^3$He($e, e'pp)n$ using 2.2 and 4.4 GeV electron beams and detecting the scattered electron and ejected protons in CLAS over a wide kinematic range [53]. When all three final state nucleons have momenta greater than 250 MeV/c, the reaction is dominated by events where two nucleons each have less than 20% of the transferred energy and
the third ‘leading’ nucleon has the remainder. Final state interactions of the leading nucleon are suppressed by requiring that it has perpendicular momentum with respect to $\vec{q}$ of less than 300 MeV/c. In these cases the two other nucleons (the $pn$ or $pp$ pair) are predominantly back-to-back and have very little total momentum in the momentum transfer direction. The relative pair momentum is also mostly isotropic. This indicates that the nucleon-nucleon pair is correlated and is a spectator to the virtual photon absorption. This means that the measured relative and total pair momenta, $\vec{p}_{rel} = (\vec{p}_1 - \vec{p}_2)/2$ and $\vec{p}_{tot} = \vec{p}_1 + \vec{p}_2$ are closely related to the initial momenta of the correlated pair. As shown in Fig. 8, the pair relative momentum peaks at about 300–400 MeV/c and the pair total momentum peaks at about 300 MeV/c. The $pp$ and $pn$ momentum distributions are very similar. The advantage of this approach is that there is no contribution from meson-exchange currents or isobar configurations since the virtual photon does not interact with the correlated pair. However, because the continuum interaction of the correlated pair is very strong and reduces the calculated cross section by a factor of about ten, this reaction is very difficult to calculate precisely. Diagrammatic calculations by Laget are in qualitative agreement with the measured momentum distributions, but only after including the effects of the continuum interaction.

5. Short range correlations and the EMC effect

One of the outstanding questions in nuclear physics is whether free nucleons and bound nucleons have the same quark structure. The first significant evidence that they differ is that the per nucleon deep-inelastic electron-scattering cross section ratio of heavy to light nuclei is not equal to one. This phenomenon, discovered by the European Muon Collaboration, became known as the EMC effect. It has generated considerable experimental and theoretical interest over the
Figure 8. Figure a) shows lab frame cross section versus $pn$ pair relative momentum. Points show the data, solid histogram shows the PWIA calculation times $\frac{1}{5}$, dashed histogram shows Laget’s one-body calculation [54, 55, 56], dotted histogram shows Laget’s full calculation; b) the same for total momentum; c), d) the same for $pp$ pairs. Reprinted with permission from R. A. Niyazov et al., Phys. Rev. Lett. 92, 052303 (2004). Copyright 2004 by the American Physical Society.

years, though there no generally excepted explanation for the effect [57, 58]. In general, short-range correlation and the EMC effect were considered completely different phenomena; yet why shouldn’t the quark distributions in two nucleons that are close together be affected or modified in some way?

Quantitatively comparing the magnitude of the EMC effect and the SRC probabilities in different nuclei shows that the two effects are remarkably correlated [59] (see Fig. 9). This strongly supports the idea that nuclear short-range correlations and the deep inelastic EMC effect are related phenomena. While theorists have debated the EMC effect for decades, this phenomenological observation is the first experimental clue of the cause of the EMC effect. In addition, this result allows experimentalists for the first time to extract the quark structure of a free neutron from proton and deuteron data without a theoretical model and should create
renewed interest in understanding the short-range part of the nuclear wave-function.

![Figure 9](image)

**Figure 9.** The absolute value of the slope of the EMC effect for Bjorken $x_B$ values from 0.3 to 0.7 is plotted versus the relative magnitude of the short-range correlation strength as compared to deuterium (i.e., the height of the plateau in the ratio of cross sections of nucleus $A$ to deuterium for $1.5 < x_B < 2$).

This phenomenological linking of the EMC effect and short-range correlations should greatly increase our understanding of the EMC effect, nucleon modification in nuclei (if any), and the quark structure of free neutrons. It also has implications for the physics of neutron stars and for the search for new physics.

6. Summary and outlook

From these new results, one can get a good general picture of two-nucleon correlations that take place within the nucleus. From $(e, e')$ we learn the probability of correlations in various nuclear systems. From $(e, e'p)$ we learn the probability of independent single particle knock-out and about the high-momentum tail in the extracted momentum distributions. From $^3\text{He}(e, e'pp)n$ we learn the about shape of the distorted correlated pair momentum distributions and from $^{12}\text{C}(e, e'pN)$ we learn the relative importance of $pp$, $pn$ and $nn$. Putting this all together, we learn that in $^{12}\text{C}$, 60–70% of the nucleons within the nucleus act like independent particles, while approximately 20% have a short-range correlation with another nucleus and that these partner nucleons almost always have the opposite isospin due to short-range tensor correlations. The remaining fraction of nucleons within the nucleus are thought to be in long-range correlations.

The association of the small $(e, e'pp)/(e, e'pn)$ ratio with the dominance of the nucleon-nucleon short-range tensor force leads naturally to the quest to increase the missing momentum and to look for pairs which are even closer to each other, at distances that are dominated by the repulsive core. In particular, the observed dominance of $np$ to $pp$ correlations is predicted to decrease as missing momentum is increased and the nucleon-nucleon short-range tensor force gives way to the short range repulsive force [50, 51, 52, 60]. This momentum dependence is
also expected to be more pronounced in light nuclei, motivating an upcoming Hall A triple coincidence experiment, similar to the $^{12}\text{C}(e,e'pN)$ measurement, which will map out the $np$ to $pp$ ratio over the range $400 < p_{\text{miss}} < 850$ MeV/c using $^4\text{He}$.

Further ($e,e'$) $x_B > 1$ inclusive measurements are also planned. In the near term, Hall A will make a comparison of symmetric and neutron rich isotopes of Calcium to probe the isospin onset of scaling due to $^3\text{N}$ correlations will be made from the ratio over the range 400 $pp$ sections.

After the 12 GeV upgrade, Hall C will measure the $(e,e')$ reaction in $x_B > 1$ kinematics and in the deep inelastic scattering region of $W > 2$ GeV. This will allow an investigation of quarks which are being shared by more than one nucleon [61, 62].

Beyond the approved experiments, future facility upgrades could include a large acceptance detector to detect backward recoil particles in coincidence with forward angle spectrometers. Such a detector system would allow broader studies of $(e,e'pN)$ reactions and the detection of the products of $3N$ or $N\Delta$ correlations.

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