High-Momentum components of the nuclear wave function: short range correlations, EMC effect, and the tensor parts of the N-N Interaction

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Abstract. The combination of inclusive and exclusive electron scattering data from JLab in kinematic regimes that were not reachable before, together with the analysis and interpretation of older data from hadronic reactions at BNL is finally revealing the details of short-range nucleon-nucleon correlations in nuclei. The most significant result is the demonstration of the dominance of correlated np pairs over pp and nn pairs. I will review these results, discuss them in terms of short-range tensor-force dominance and also discuss the connection to the EMC effect.

1. Short Range Correlation (SRC) in nuclei

The average distance between nucleons in the center of nuclei is typically around 1.7 femtometer (fm). However, the nucleons moving in the attractive mean nuclear field are sometimes closer than the average distance. If the separation distance between two nucleon centers is approximately one femtometer (fm) or smaller we consider them to be a Short Range Correlation (SRC) pair. In momentum space, a SRC pair is characterized by a large relative momentum and a small center-of-mass (cm) momentum, where large and small are relative to the Fermi momentum, \( k_F \).

Studies of SRCs in nuclei are important for understanding the nature of the short range NN interaction and the contributions of high momentum nucleons to the nuclear ground- and excited-state wave functions. They also have far-reaching implications for modeling and understanding cold dense nuclear matter such as neutron stars. We will also point to a recently observed phenomenological correlation between SRC and the EMC effect and discuss its possible consequences.

The description of the nucleus as being comprised of independent nucleons in a mean field requires corrections due to both long-range and short-range correlations between the nucleons. However, for many years, experimental studies of the microscopic structure of SRCs were very much restricted due to the difficulty in resolving SRCs when only moderate momentum-transfer kinematics using low and medium energy probes were available. Recently, several high-energy, large-momentum-transfer (hard) measurements, along with companion theoretical studies, have made progress in identifying SRC pairs in nuclei and understanding their dynamics.

I start with the high momentum transfer inclusive \( A(e,e') \) data from SLAC [1], Hall B Large Acceptance Spectrometer (CLAS) [2,3], and Hall C [4,5] at kinematics where \( x_B>1 \) (\( x_B = Q^2 / 2m\omega \)). \( Q^2 , \omega \) are the four-momentum and energy transfers, \( m \) is the nucleon mass). The latter two are at the U.S. Dept. of Energy’s Jefferson Laboratory (JLab). The data from CLAS are presented in figure 1 as the ratio of the inclusive cross section off heavy nuclei to \(^3\)He at sufficiently large \( Q^2 \) and \( x_B \). In this regime where scattering off slow nucleons in the nucleus does not contribute due to kinematics constrains (see details in Ref. [2,3]). The predicted signal for dominance of SRC pairs is the scaling of the ratios - a weak dependence on \( x_B, Q^2 \) for \( 1< x_B <2 \) - which is clearly observed in the data. These results reflect dominance of two-nucleon SRC (2N-SRC) in the high momentum component of the nucleus. The values of the scaled ratios for any nucleus to deuterium

\[
a_{2N}(A/d) = \frac{\sigma_A(e,e')/A}{\sigma_d(e,e')/2}
\]

indicates that such correlations involve about 20-25% of the nucleons in medium and heavy nuclei at any given instant. A second scaling region is observed for \( x_B>2 \) due to
three nucleon correlations. The contribution of three nucleon SRC at this kinematical conditions is about an order of magnitude smaller than that of two nucleon SRC. More nuclei, extensive kinematical coverage and better statistics are available from recent measurements at Hall C [4,5].

While the inclusive data suggest strong local correlations, it has taken exclusive data to confirm that the inclusive scaling is due to 2N-SRC and to directly measure what fraction of nucleon pair types are involved. A high-momentum probe can knock a non-correlated proton out of the nucleus, leaving the residual nucleus largely unaffected. If, on the other hand, the proton being struck is member of an SRC pair, the high relative momentum in the pair causes the correlated nucleon to recoil and be ejected with high-momentum almost equal in size and opposite in direction to that of the struck proton [6,7]. Figure 2 shows schematically such measurements with high-energy electron beam as were done at JLab [8,12]. Similar measurement preceded the JLab measurement using high-momentum proton probes at the U.S. Dept. of Energy’s Brookhaven National Laboratory (BNL) [13-15].
The triple coincidence $^{12}$C(p,ppn) measurement at beam momenta between 6 and 9 GeV/c at Brookhaven National Laboratory [13-15] identified np-SRC pairs and demonstrated that $92^{+18}_{-18}\%$ of the protons in $^{12}$C with momenta above 275 MeV/c are partners in np-SRC pairs [15]. The JLab, experiment show that nearly all nucleons in $^{12}$C with momentum in the range 300-600 MeV/c have a correlated nucleon partners with roughly equal and opposite momentum [8,9]. By comparing neutron-proton (np) to proton-proton (pp) yields it was also found that most SRCs are np-SRCs [14,9]. SRC np pairs in $^{12}$C outnumber the proton-proton (pp) pairs by a factor of 18 ± 5 [9]. Considering isospin symmetry, one may assume that the number of nn SRC pairs is equal to the number of pp SRC pairs in $^{12}$C.

To get a comprehensive picture of the structure of $^{12}$C, we can combine the results from the triple coincidence measurements with the inclusive $^{12}$C(e,e') measurements from JLab Hall B[3], which showed that 20±5% of the nucleons in $^{12}$C are members of SRCs. The results displayed in Fig. 3 show that 80±5% of $^{12}$C nucleons are low-momentum independent or long-range correlated nucleons, 18±5% are np-SRC pairs, while pp-SRCs and nn-SRCs are each 1±0.3%.

Fig. 3: Pie chart showing the average fraction of nucleons in the various ground state configurations of $^{12}$C.

- The small observed ratio of pp-SRC/np-SRC stimulated work by three theoretical groups [16-18] that show clearly that the measured ratio is expected and is an indication of dominance of NN tensor force at the probed distances and relative momentum of the nucleons in the SRC.

To summarize we have learned a large amount about these correlated pairs in the last decade from experiments at Jefferson Lab [8-12] and BNL [13-15] and their relation to high momentum nucleons in nuclei. The highlights are listed below:

- The probability for a nucleon to belong to a SRC pair ranges from 5% in deuterium to about 25% in nuclei such as carbon and iron;

- The threshold momentum of nucleons in SRC pairs is $p_{\text{thresh}} \approx k_F = 275 \pm 25$ MeV/c;
The momentum distribution for \( p > p_{\text{thresh}} \) is the same for all nuclei, only the magnitude varies. This magnitude is expressed as a scale factor, \( a_{2N} \);

Almost all nucleons with momenta greater than \( p_{\text{thresh}} \) are part of NN-SRC (92\% 81\%);

These SRC pairs move inside the nucleus with cm motion of about 140 MeV/c;

The NN-SRC consists of about 90\% np pairs, and 5\% each pp and nn pairs;

The tensor force dominates NN-SRC for pair relative momenta in the range of \( 300 < p_{\text{rel}} < 500 \) MeV/c

80\% of the kinetic energy (momentum) of all the nucleons in the nucleus is carried by members of the NN-SRC, which are only 20\% of the nucleons.

The association of the large measured \( ^{12}\text{C}(e,e'pn)/^{12}\text{C}(e,e'pp) \) ratio with the NN SRC tensor force [16-18] lead naturally to the quest to look for pairs where the nucleons are even closer to each other by probing pairs with larger relative momenta. This can probe distance scales that are dominated by the nucleon-nucleon repulsive hard core. JLab Experiment E07-006 [12] extends the 2N-SRC study to larger momenta in order to further explore the repulsive core of the NN interactions. Data up to relative momentum of 850 MeV/c were taken in 2011 and are currently being analyzed.

2. The EMC effect

One of the outstanding questions in nuclear physics is whether the quark structure of nucleons is modified in the nuclear medium. Evidence for nucleon modification can only come from the failure of hadronic models, which incorporate unmodified nucleons and mesons as their fundamental degrees of freedom. While the vast majority of nuclear physics experiments can be explained using hadronic models, deep inelastic scattering (DIS) measurements, of the ratio of per-nucleon cross sections of nucleus A to deuterium, cannot. These experiments typically measure a ratio of about 1 at \( x = 0.3 \), decreasing linearly to a minimum at around \( x = 0.7 \) [19–25]. This minimum depends on \( A \) and varies from about 0.94 for \( ^{4}\text{He} \) to about 0.83 for \( ^{197}\text{Au} \). This observation is known as the EMC effect. A comprehensive review of the EMC effect can be found in [26, 27] and references therein.

While the EMC and other modifications have been observed, there is no generally accepted explanation of their origin. In general, two classes of explanations have been proposed: 1) the internal structure of the nucleon is modified by the influence of the nuclear medium or 2) there are effects stemming from the many body nuclear medium itself, such as two-body currents, binding, etc. A recent publication suggests that the Coulomb field of the nucleus also plays an important role [28].

Recent published measurements of the EMC effect on light nuclei at JLab [25] show that the EMC effect does not depend directly on the atomic mass \( A \) or the average nuclear density, as
had been previously assumed by some models. Beryllium is the most significant outlier. The authors claim, “The data … suggest that the nuclear dependence of the quark distributions may depend on the local nuclear environment”. These data suggest that the EMC effect increases with local rather than the average nuclear density. It can also mean that the nuclear in-medium modification depends on the nucleon virtuality $v = (p^μ)^2 - m^2$. This implies that we should attempt to compare the EMC effect to other nuclear phenomena that are related to local density or high nucleon momenta such as short-range correlations.

Another recent JLab measurement also seems to indicate that the medium modification of the proton electromagnetic form factor increases with nucleon virtuality [29]. Proton recoil polarization was measured in the quasielastic $^4$He($\vec{e},e'\vec{p}$)$^3$H reaction at $Q^2 = 0.8$ GeV$^2$ and 1.3 GeV$^2$. The polarization-transfer coefficients were found to differ from those of the $H(\vec{e},e'\vec{p})$ reaction as the virtuality of the proton in $^4$He increases. Note that this experiment only explored relatively small values of nucleon virtuality, since the proton momenta were significantly below the Fermi momentum.

3. SRC and the EMC effect

A recent paper [30] found that the size of the EMC effect in a given nucleus is closely correlated with the probability for a nucleon in that nucleus to belong to an NN-SRC pair (see Figs. 4,5). In these figures the strength of the EMC effect for nucleus $A$ is characterized by the slope of the ratio of the deep inelastic electron scattering cross sections relative to deuterium, $dR_{EMC}/dx$, in the region $0.3 \leq x_B \leq 0.7$. The SRC strength is given by the scaling factor $a_{SN}(A/d)$ as discussed above.

![Fig 4: The EMC slopes (empty squares) [24] versus the scaling factor (full dots) for the inclusive SRC ratios [2,3].](image-url)
Last but not least I would like to speculate as to the physical reason for the observed phenomenological relation presented above. Assuming that the EMC effect is due to a difference in the quark distributions in bound and free nucleons, two approaches exist that lead to very different answers as to how the EMC strength is distributed between the SRC nucleons (20% of the nucleons that carries 80% of the kinetic energy of nucleons in nuclei) and the mean field nucleons in nuclei (80% of the nucleons with only 20% of the kinetic energy of nucleons in nuclei).

One hypothesis is that the EMC effect is caused by modification of the quark distributions by the mean field of the nucleus. The dominant scalar part of the $NN$ potential is maximal at distances typical of those between mean field nucleons in nuclei. Thus, at these distances the changes in the quark distributions should also be maximal.

A second hypothesis is that the EMC effect is mainly associated with nucleons from the SRC pairs. Those nucleons have large momentum, large virtuality, and a much denser local environment than that of the other nucleons in the nucleus. Therefore, they should exhibit the largest changes in their internal structure.

The linear correlation between the strength of the EMC and the SRC in nuclei, as seen in Fig. 5, strongly supports the second hypothesis. This calls for more theoretical and experimental study and understanding.

Since almost all high momentum nucleons in nuclei belong to SRC nucleon pairs, we suggest that measuring the EMC effect while selecting experimentally SRC pairs should enhance the EMC effect observation. In other words, we can select the nucleons on which we observe the EMC effect by detecting their SRC partners, which recoil backwards, in coincidence with the scattered electrons. A new experiment to look for EMC effect in deuterons in cases where the DIS is tagged by high momentum recoil nucleon was just approved at JLab to be performed with the upgraded 12 GeV beam [12].
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