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# Measurement of 2- and 3-Nucleon Short Range Correlation Probabilities in Nuclei

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The ratios of inclusive electron scattering cross sections of $^4$He, $^{12}$C and $^{56}$Fe to $^3$He have been measured at $1 < x_B < 3$. At $Q^2 > 1.4$ GeV$^2$, the ratios exhibit two separate plateaus, at $1.5 < x_B < 2$ and at $x_B > 2.25$. This pattern is predicted by models that include 2- and 3-nucleon short-range correlations (SRC). Relative to $A = 3$, the per-nucleon probabilities of 3-nucleon SRC are 2.3, 3.2, and 4.6 times larger for $A = 4, 12$ and 56. This is the first measurement of 3-nucleon SRC probabilities in nuclei.

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Understanding short-range correlations (SRC) in nuclei has been one of the persistent though rather elusive goals of nuclear physics for decades. Calculations of nuclear wave functions using realistic $NN$ interactions suggest a substantial probability for a nucleon in a heavy nucleus to have a momentum above the Fermi momentum $k_F$. The dominant mechanism for generating high momenta is the two nucleon interaction at distances less than the average inter-nucleon distance, corresponding to nuclear densities comparable to neutron star core densities. It involves both tensor forces and short-range repulsive forces, which share two important features, locality and large strength. The SRC produced by these forces result in the universal shape of the nuclear wave function for all nuclei at $k > k_F$ (see, *e.g.*, Refs. [1, 2]).

A characteristic feature of these dynamics is that the momentum $k$ of a high-momentum nucleon is balanced, not by the rest of the nucleus, but by the other nucleons in the correlation. Therefore, for a 2-nucleon ($NN$) SRC, the removal of a nucleon with large momentum, $k$, is associated with a large excitation energy $\sim k^2/2m_N$ corresponding to the kinetic energy of the second nucleon. The relatively large energy scale ($\geq 100$ MeV) involved in the interaction of the nucleons in the correlation makes it very difficult to resolve correlations in intermediate energy processes. The use of high energy electron-nucleus scattering measurements offers a promising alternative to improve our understanding of these dynamics.

The simplest of such processes is inclusive electron scattering, $A(e, e')$, at four-momentum transfer $Q^2 \geq 1.5$ GeV$^2$ and $x_B = Q^2/2m_N\nu > 1$ where $\nu$ is the energy transfer. We suppress scattering off the mean field nucleons by requiring $x_B \geq 1.3$ and we can resolve SRC by transferring energies and momenta much larger than the SRC scale.

Ignoring corrections due to the center of mass (cm) motion of the SRC in the nuclear mean field, we can decompose the nuclear cross section at high nucleon momentum into pieces due to electrons scattering from nucleons in 2-, 3- and more-nucleon SRC [3, 4]:

$$\sigma_A(Q^2, x_B) = \sum_{j=2}^{A} A\frac{a_j(A)}{j}\sigma_j(Q^2, x_B), \tag{1}$$

where $\sigma_A(Q^2, x_B)$ and $\sigma_j(Q^2, x_B)$ are the cross sections of electron-nucleus and electron-$j$-nucleon-correlation interactions respectively, and $a_j(A)$ is the ratio of the probabilities for a given nucleon to belong to correlation $j$ in nucleus $A$ and to belong to a nucleus consisting of $j$ nucleons.

Since the probabilities of $j$-nucleon SRC should drop rapidly with $j$ (since the nucleus is a dilute bound system of nucleons) one expects that scattering from $j$-nucleon SRC will dominate at $j < x_B < j + 1$. Therefore the cross section ratios of heavy and light nuclei should be independent of $x_B$ and $Q^2$ (*i.e.*, scale) and have discrete values for different $j$: $\frac{\sigma(A)}{\sigma(A')} = \frac{A'}{A} \cdot \frac{a_j(A)}{a_j(A')}$. This 'scaling' of the ratio will be strong evidence for the dominance of scattering from a $j$-nucleon SRC.

Moreover, the relative probabilities of $j$-nucleon SRC, $a_j(A)$, should grow with the $j^{th}$ power of the density $< \rho_A^j(r) >$ and, thus, with $A$ (for $A \geq 12$)[3]. Thus, these steps in the ratio $\frac{\sigma(A)}{\sigma(A')}$ should increase with $j$ and $A$. Observation of such steps (*i.e.*, scaling) would be a crucial test of the dominance of SRC in inclusive electron scattering. It would demonstrate the presence of 3-nucleon ($3N$) SRC and confirm the previous observation of $NN$ SRC.

Note that: (i) Refs. [5, 6] argue that the c.m. motion of the $NN$ SRC may change the value of $a_2$ (by up to 20% for $^{56}$Fe) but not the scaling at $x_B < 2$. For 3N SRC there are no estimates for the effects of cm motion. (ii) Final state interactions (FSI) are dominated by the interaction of the struck nucleon with the other nucleons in the SRC [7, 8]. Hence the FSI can modify $\sigma(j)$ but not $a_j(A)$ (ratios) in the decomposition of Eq. (1).

In our previous work [6] we measured the ratios $R(A,{}^3\mathrm{He}) = \frac{3\sigma_A(Q^2,x_B)}{A\sigma_{^3\mathrm{He}}(Q^2,x_B)}$ and showed that they scale (with both $Q^2$ and $x_B$) for $1.5 < x_B < 2$ and $1.4 < Q^2 < 2.6$ (GeV)$^2$, confirming findings [7] which reported scaling based on the comparison of the data for $A \geq 3$ [9, 10, 11] and $A = 2$ [12] obtained in somewhat different kinematic conditions. Here we repeat our previous measurement with higher statistics.

We also search for the even more elusive $3N$ SRC, correlations which originate from both short-range $NN$ interactions and three-nucleon forces, using the ratio $R(A,{}^3\mathrm{He})$ at $2 < x_B \leq 3$.

Two sets of measurements were performed at the Thomas Jefferson National Accelerator Facility in 1999 and 2002. The 1999 measurements used 4.461 GeV electrons incident on liquid $^3$He, $^4$He and solid $^{12}$C targets. The 2002 measurements used 4.471 GeV electrons incident on a solid $^{56}$Fe target and 4.703 GeV electrons incident on a liquid $^3$He target.

Scattered electrons were detected in the CLAS spectrometer [13]. The lead-scintillator electromagnetic calorimeter provided the electron trigger and was used to identify electrons in the analysis. Vertex cuts were used to eliminate the target walls. The estimated remaining contribution from the two Al 15 $\mu$m target cell windows is less than 0.1%. Software fiducial cuts were used to exclude regions of non-uniform detector response. Kinematic corrections were applied to compensate for drift chamber misalignments and magnetic field uncertainties.

We used the GEANT-based CLAS simulation, GSIM, to determine the electron acceptance correction factors, taking into account "bad" or "dead" hardware channels in various components of CLAS. The measured acceptance-corrected, normalized inclusive electron yields on $^3$He, $^4$He, $^{12}$C and $^{56}$Fe at $1 < x_B < 2$ agree with Sargsian's radiated cross sections [14] that were tuned on SLAC data [15] and describe reasonably well the Jefferson Lab Hall C [16] data.

We calculated the radiative correction factors for the reaction $A(e,e')$ at $x_B < 2$ using Sargsian's cross sections [17] and the formalism of Mo and Tsai [18]. These factors are almost independent of $x_B$ for $1 < x_B < 2$ for all nuclei used. Since there are no theoretical cross section calculations for $x_B > 2$, we used the $1 < x_B < 2$ correction factors for $1 < x_B < 3$.

We constructed the ratios of inclusive cross sections as a function of $Q^2$ and $x_B$, with corrections for the CLAS acceptance and for the elementary electron-nucleon cross sections:

$$r(A,{}^3\mathrm{He}) = \frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}\frac{3\mathcal{Y}(A)}{A\mathcal{Y}(^3\mathrm{He})}C^A_{\mathrm{rad}}, \qquad (2)$$

where $Z$ and $N$ are the number of protons and neutrons in nucleus $A$, $\sigma_{eN}$ is the electron-nucleon cross section, $\mathcal{Y}$ is the normalized yield in a given ($Q^2$,$x_B$) bin [30] and $C^A_{\mathrm{rad}}$ is the ratio of the radiative correction factors for $A$ and $^3$He ($C^A_{\mathrm{rad}} = 0.95$ and 0.92 for $^{12}$C and $^{56}$Fe respectively). In our $Q^2$ range, the elementary cross section correction factor $\frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}$ is $1.14 \pm 0.02$ for C and $^4$He and $1.18 \pm 0.02$ for $^{56}$Fe. Fig. 1 shows the resulting ratios integrated over $1.4 < Q^2 < 2.6$ GeV$^2$.

These cross section ratios a) scale initially for $1.5 < x_B < 2$, which indicates that $NN$ SRCs dominate in this region, b) increase with $x_B$ for $2 < x_B < 2.25$, which can be explained by scattering off nucleons involved in moving $NN$ SRCs, and c) scale a second time at $x_B > 2.25$, which indicates that $3N$ SRCs dominate in this region. In both $x_B$-scaling regions, the ratios are also independent of $Q^2$ for $1.4 < Q^2 < 2.6$ GeV$^2$ [8].

The ratio of the per-nucleon SRC probabilities in nucleus $A$ relative to $^3$He, $a_2(A/{}^3\mathrm{He})$ and $a_3(A/{}^3\mathrm{He})$, are just the values of the ratio $r$ in the appropriate scaling region. $a_2(A/{}^3\mathrm{He})$ is evaluated at $1.5 < x_B < 2$ and $a_3(A/{}^3\mathrm{He})$ is evaluated at $x_B > 2.25$ corresponding to the dashed lines in Fig. 1. Thus, the chances for each nucleon to be involved in a $NN$ SRC in $^4$He, $^{12}$C and $^{56}$Fe are 1.93, 2.49 and 2.98 times higher than in $^3$He. The chances for each nucleon to be involved in a $3N$ SRC are, respectively, 2.3, 3.2 and 4.6 times higher than in $^3$He. See Table I.

The systematic uncertainty in the relative per-nucleon SRC probabilities are discussed in Ref. [6]. For the $^4$He/$^3$He ratio, all uncertainties except those of the beam current and target density cancel, giving a total systematic uncertainty of 0.7%. For the solid-target to $^3$He ratios the total systematic uncertainty is 6%. For the $^{56}$Fe/$^3$He ratio there is also a $\leq 6\%$ systematic uncertainties from the electron-nucleus Coulomb interaction [19, 20] and possible effect from the pair c.m. motion which can reduce the ratio up to 20%.

To obtain the absolute values of the per-nucleon probabilities of SRCs, $a_{2N}(A)$ and $a_{3N}(A)$, from the measured ratios, $a_2(A/{}^3\mathrm{He}) = \frac{a_{2N}(A)}{a_{2N}(^3He)}$ and $a_3(A/{}^3\mathrm{He}) = \frac{a_{3N}(A)}{a_{3N}(^3He)}$, we need to know the absolute per-nucleon SRC probabilities for $^3$He, $a_{2N}(^3\mathrm{He})$ and $a_{3N}(^3\mathrm{He})$. The probability of $NN$ SRC in $^3$He is the product of the probability of $NN$ SRC in deuterium and the relative probability of $NN$ SRC in $^3$He and $d$, $a_2(^3\mathrm{He}/d)$. We define the probability of $NN$ SRC in deuterium as the probability that a nucleon in deuterium has a momentum $k > k_{min}$, where $k_{min}$ is the minimum recoil momentum corresponding to the onset of scaling at $Q^2 = 1.4$ GeV$^2$ and $x_B = 1.5$. Note that this experiment is the first to measure the ($Q^2$, $x_B$) onset, and to calculate $k_{min}$ =275±25 MeV [8]. The integral of the wave function for $k > k_{min}$ gives

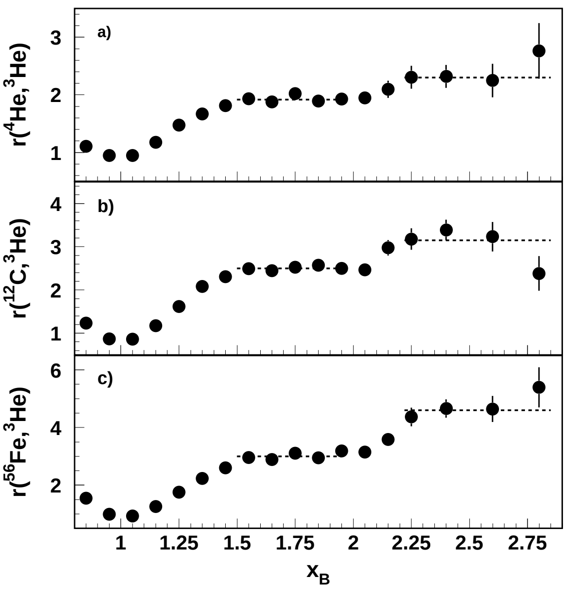


FIG. 1: Weighted cross section ratios of (a) $^4$He, (b) $^{12}$C and (c) $^{56}$Fe to $^3$He as a function of $x_B$ for $Q^2 > 1.4$ GeV$^2$. The horizontal dashed lines indicate the $NN$ and $3N$ scaling regions used to calculate the per-nucleon probabilities for 2- and $3N$ SRCs in nucleus $A$ relative to $^3$He.

$0.041 \pm 0.008$ [8] where the uncertainty is due to the uncertainty of $k_{min}$. The second factor, $a_2(^3\text{He}/d) = 1.97 \pm 0.1$, [6] comes from the weighted average of the experimental ($1.7 \pm 0.3$ [7]) and theoretical ($2.0 \pm 0.1$ values [14, 21]). Thus, $a_{2N}(^3\text{He}) = 0.08 \pm 0.016$.

TABLE I: $a_2(A/^3\text{He})$ and $a_3(A/^3\text{He})$ are the per-nucleon probabilities of 2- and $3N$ SRC in nucleus $A$ relative to $^3$He. $a_{2N}(A)$ and $a_{3N}(A)$ are the absolute value of the same probabilities in nucleus $A$ (in %). Errors shown are statistical and systematic for $a_2$ and $a_3$ and are combined (but systematic dominated) for $a_{2N}$ and $a_{3N}$. The systematic uncertainties of $^{56}$Fe/$^3$He ratio <6% (Coulomb interaction) and <20% (SRC c.m. motion) are not included.

| | $a_2(A/^3\text{He})$ | $a_{2N}(A)(\%)$ | $a_3(A/^3\text{He})$ | $a_{3N}(A)(\%)$ |
|---|---|---|---|---|
| $^3$He | 1 | 8.0±1.6 | 1 | 0.18±0.06 |
| $^4$He | 1.93±0.01± 0.03 | 15.4±3.2 | 2.33±0.12±0.04 | 0.42±0.14 |
| $^{12}$C | 2.49±0.01± 0.15 | 19.8±4.4 | 3.18±0.14±0.19 | 0.56±0.21 |
| $^{56}$Fe | 2.98±0.01± 0.18 | 23.9±5.3 | 4.63±0.19±0.27 | 0.83±0.27 |

Thus, the absolute per-nucleon probabilities for $NN$ SRC are 0.154, 0.198 and 0.239 for $^4$He, $^{12}$C and $^{56}$F respectively (see Table I). In other words, at any moment, the numbers of $NN$ SRC (which is $\frac{A}{2}a_{2N}(A)$) are 0.12, 0.3, 1.2, and 6.7 for $^3$He, $^4$He, $^{12}$C, and $^{56}$Fe, respectively.

Similarly, to obtain the absolute probability of $3N$ SRC we need the probability that the three nucleons in $^3$He are in a $3N$ SRC. The start of the second scaling region at $Q^2 = 1.4$ GeV$^2$ and $x_B = 2.25$ corresponds to $p_{min} \approx 500$ MeV. In addition, since this momentum must be balanced by the momenta of the other two nucleons [22], we require that $p_1 \geq 500$ MeV and $p_2, p_3 \geq 250$ MeV. This integral over the Bochum group's [23] $^3$He wave function ranges from 0.12% to 0.24% for various combinations of the CD Bonn [24] and Urbanna [25] $NN$ potentials and the Tucson-Melbourne [26] and Urbanna-IX [27] $3N$ forces. We use the average value, $a_{3N}(^3\text{He}) = 0.18 \pm 0.06\%$, to calculate the absolute values of $a_{3N}(A)$ shown in the fifth column of Table I. The per-nucleon probabilities of $3N$ SRC in all nuclei are smaller than the $NN$ SRC probabilities by more than one order of magnitude.

We compared the $NN$ SRC probabilities to various models. The SRC model predicts [4] the relative probabilities $a_2(^4\text{He}/^3\text{He}) = 2.03$, $a_2(^{12}\text{C}/^3\text{He}) = 2.53$, and $a_2(^{56}\text{Fe}/^3\text{He})/a_2(^{12}\text{C}/^3\text{He}) = 1.26$. These are remarkably close to the experimental values of $1.93 \pm 0.01 \pm 0.03$, $2.49 \pm 0.01 \pm 0.15$, and $1.20 \pm 0.02$ respectively.

Levinger's quasideuteron model [28] predicts 1.1 ($pn$)-pairs for all nuclei. These clearly disagree with experiment, probably because the quasideuterons include low momentum pairs and do not include ($pp$) and ($nn$) pairs.

Forest [21] calculates the ratios of the pair density distributions for nuclei relative to deuterium and gets 2.0, 4.7 and 18.8 for $^3$He, $^4$He and $^{16}$O respectively. This would correspond to $a_2(^4\text{He}/^3\text{He}) = 1.76$ and $a_2(^{16}\text{O}/^3\text{He}) = 1.76$ compared to experimental values of 1.96 for $^4$He and 2.51 for $^{12}$C (assuming that $^{12}$C and $^{16}$O are similar). This agrees for $^4$He, but not for $^{16}$O.

The Iowa University group calculates 6- and 9-quark-cluster probabilities for many nuclei [29]. If these clusters are identical to 2- and $3N$ SRC, respectively, than the calculated probabilities of 6-quark-clusters for $^4$He, $^{12}$C and $^{56}$Fe are within about a factor of two of the measured $NN$ SRC probabilities. The ratios $a_2(^{56}\text{Fe})/a_2(^{12}\text{C}) = 1.16$ is also close to the experimental value of $1.20 \pm 0.02$.

We also compared the $3N$ SRC probabilities to the SRC and quark-cluster models. The SRC model predicts the $A$-dependence of $a_3(A)$ based on the nuclear density but not the specific values. The SRC prediction of $a_3(^{56}\text{Fe})/a_3(^{12}\text{C}) = 1.40$ is remarkably close to the experimental value of $1.46 \pm 0.12$. The quark-cluster model predicts values of $a_3(A)$ that are larger than the data by about a factor of 10.

In summary, the $A(e, e')$ inclusive electron scattering cross section ratios of $^4$He, $^{12}$C, and $^{56}$Fe to $^3$He have been measured at $1 < x_B < 3$ for the first time. (1) These ratios at $Q^2 > 1.4$ GeV$^2$ scale in two intervals of $x_B$: (a) in the $NN$ short range correlation (SRC) region at $1.5 < x_B < 2$, and (b) in the $3N$ SRC region at $x_B > 2.25$; (2) For $A \geq 12$, the change in the ratios in both scaling regions is consistent with the second and third powers, respectively, of the nuclear density; (3) These features are consistent with the theoretical expectations that $NN$

SRC dominate the nuclear wave function at $p_m \gtrsim 300$ MeV and $3N$ SRC dominate at $p_m \gtrsim 500$ MeV; (4) The chances for each nucleon to be involved in a $NN$ SRC in $^4$He, $^{12}$C and $^{56}$Fe nuclei are 1.93, 2.49 and 2.98 times higher than in $^3$He, while the same chances for $3N$ SRC are, respectively, 2.3, 3.2 and 4.6 times higher; (5) In $^4$He, $^{12}$C, and $^{56}$Fe, the absolute per-nucleon probabilities of 2- and 3-nucleon SRC are 15–25% and 0.4–0.8%, respectively. This is the first measurement of $3N$ SRC probabilities in nuclei.

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