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Measurement of Two- and Three-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, 3.1, and 4.4 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 nucleon-nucleon (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 NN interaction at distances less than the average internucleon 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 (≥ 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 $Q^2 \gtrsim 1.4$ GeV^2. We suppress scattering off the mean field nucleons by requiring $x_B = Q^2/2m_N\nu \gtrsim 1.3$ (where ν is the energy transfer) and we can resolve SRC by transferring energies and momenta much larger than the SRC scale.

Ignoring the SRC center of mass (c.m.) motion effects, for the above mentioned Q^2 and x_B we can decompose the nuclear cross section into pieces due to electrons scattering from nucleons in 2-, 3-, and more-nucleon SRC [3,4]:

$$\sigma_A(Q^2, x_B) = A \sum_{j=2}^{A} (a_j(A)/j)\sigma_j(Q^2, x_B)\theta(j - x_B), \quad (1)$$

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 correlation j in a nucleus 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 $j - 1 < x_B < j$. 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 jth power of the density $\langle\rho_A^j(r)\rangle$, 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 of the effects of c.m. 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 σ_j, while such modification of $a_j(A)$ are small since the pp, pn, and nn cross sections at $Q^2 > 1$ GeV^2 are similar in magnitudes.

In our previous work [6] we showed that the ratios $R(A, {}^3\mathrm{He}) = \frac{3\sigma_A(Q^2,x_B)}{A\sigma_{^3\mathrm{He}}(Q^2,x_B)}$ scale for $1.5 < x_B < 2$ and $1.4 < Q^2 < 2.6$ GeV^2, confirming findings in Ref. [7]. Here we repeat our previous measurement with higher statistics which allows us to estimate the absolute per-nucleon probabilities of NN SRC.

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 [9]. 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 μm target cell windows is less than 0.1%. Software fiducial cuts were used to exclude regions of nonuniform 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 [10] that were tuned on SLAC data [11] and describe reasonably well the Jefferson Lab Hall C [12] data.

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:

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

where Z and N are the number of protons and neutrons in nucleus A, σ_{eN} is the electron-nucleon cross section, $\mathcal{Y}$ is the normalized yield in a given (Q^2, x_B) bin, and R^A_{rad} is the ratio of the radiative correction factors for ^{3}He and nucleus A [see Ref. [8]]. 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 ± 0.02 for C and ^{4}He and 1.18 ± 0.02 for ^{56}Fe. Note that the ^{3}He yield in Eq. (2) is also corrected for the beam energy difference by the difference in the Mott cross sections. The corrected ^{3}He cross sections at the two energies agree within $\leq 3.5\%$ [8].

We calculated the radiative correction factors for the reaction $A(e, e')$ at $x_B < 2$ using Sargsian's upgraded code of Ref. [13] and the formalism of Mo and Tsai [14]. These factors change 10%–15% with x_B for $1 < x_B < 2$. However, their ratios, R^A_{rad}, for ^{3}He to the other nuclei are almost constant (within 2%–3%) for $x_B > 1.4$. We applied R^A_{rad} in Eq. (2) event by event for $0.8 < x_B < 2$. Since there are no theoretical cross section calculations at $x_B > 2$, we applied the value of R^A_{rad} averaged over $1.4 < x_B < 2$ to the entire $2 < x_B < 3$ range. Since the x_B dependence of R^A_{rad} for ^{4}He and ^{12}C are very small, this should not affect the ratio r of Eq. (2). For ^{56}Fe, due to the observed small slope of R^A_{rad} with x_B, $r(A, {}^3\mathrm{He})$ can increase up to 4% at $x_B = 2.55$. This was included in the systematic errors.

Figure 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

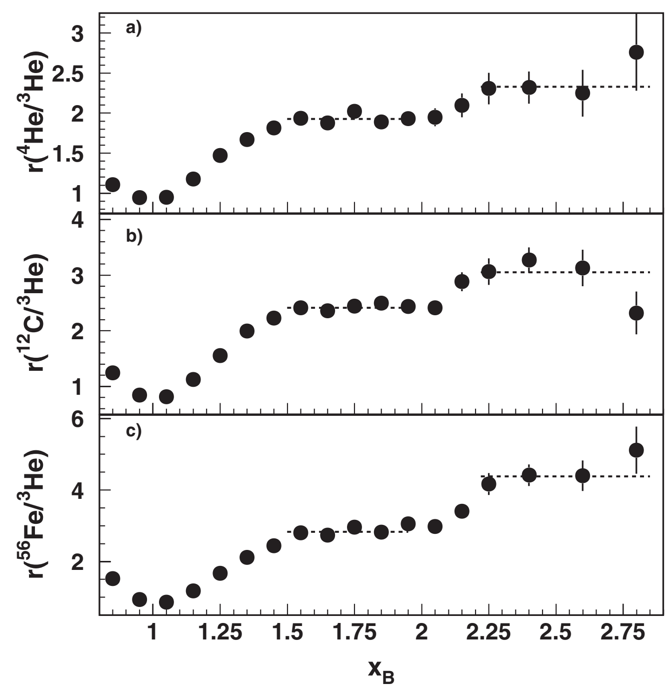

FIG. 1. Weighted cross section ratios [see Eq. (2)] of (a) ^{4}He, (b) ^{12}C, and (c) ^{56}Fe to ^{3}He as a function of x_B for $Q^2 > 1.4$ GeV^2. The horizontal dashed lines indicate the NN ($1.5 < x_B < 2$) and $3N$ ($x_B > 2.25$) scaling regions.

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 $x_B > 2.25$ [for $\frac{^4\mathrm{He}}{^3\mathrm{He}}$ ratio see also Ref. [4], Fig. 8.3a], indicating that $3N$ SRCs dominate in this region. The experimental ratios clearly show the onset of new scaling at $x_B > 2$, which, because of its small A dependence, must be a distinctly local nuclear phenomenon. Note that in the first x_B-scaling region, the ratios are also independent of Q^2 for $1.4 < Q^2 < 2.6\ \mathrm{GeV}^2$ [6,8]. In the second x_B-scaling region the ratios also appear to be independent, but with some fluctuations and large statistical uncertainties [see Fig. 19 of Ref. [8]].

We will analyze the observed scaling within the framework of the SRC model which unambiguously predicted the onset of scaling and related them to the probabilities of NN and $3N$ correlations in nuclei. The ratios of the per-nucleon SRC probabilities (neglecting c.m. motion and Coulomb interaction effects) 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 1.9, 2.4, and 2.8 times higher than in ^{3}He. The chances for each nucleon to be involved in a $3N$ SRC are, respectively, 2.3, 3.1, and 4.4 times higher than in ^{3}He. See Table I.

To obtain the absolute values of the per-nucleon probabilities of SRCs, $a_{2N}(A)$ and $a_{3N}(A)$, from the measured ratios, $a_2(A/^3\mathrm{He}) = a_{2N}(A)/a_{2N}(^3\mathrm{He})$ and $a_3(A/^3\mathrm{He}) = a_{3N}(A)/a_{3N}(^3\mathrm{He})$ 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. Since at $Q^2 = 1.4\ \mathrm{GeV}^2$, scaling begins at $x_B = 1.5 \pm 0.05$, we obtain $k_{\min} = 275 \pm 25$ MeV [8]. The integral of the momentum distribution for $k > k_{\min}$ gives $a_{2N}(d) = 0.041 \pm 0.008$ [8], where the uncertainty is due to the uncertainty of $k_{\min}$. The second factor, $a_2(^3\mathrm{He}/d) = 1.97 \pm 0.1$ [6], comes from the weighted average of the experimental value 1.7 ± 0.3 [7] and theoretical value 2.0 ± 0.1, calculated [10] with the available ^{2}H and ^{3}He wave functions [2,15] [for this ratio value, see also [16]]. Thus, $a_{2N}(^3\mathrm{He}) = 0.08 \pm 0.016$.

Thus, the absolute per-nucleon probabilities for NN SRC are 0.15, 0.19, and 0.23 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 6.4 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 $Q^2 = 1.4\ \mathrm{GeV}^2$ and $x_B = 2.25 \pm 0.1$ corresponds to $k_{\min} \approx 500 \pm 20$ MeV. In addition, since this momentum must be balanced by the momenta of the other two nucleons [17], we require that $k_1 \geq 500$ MeV and $k_2, k_3 \geq 250$ MeV. This integral over the Bochum group's [15] ^{3}He wave function ranges from 0.12% to 0.24% for various combinations of the CD Bonn [18] and Urbanna [19] NN potentials and the Tucson-Melbourne [20] and Urbanna-IX [21] $3N$ forces. We use the average value, $a_{3N}(^3\mathrm{He}) = 0.18 \pm 0.06\%$, 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 a factor of 10. Note that these results contain considerable theoretical uncertainties; however, it gives the estimate of the abundance of $3N$ versus $2N$ SRC.

The systematic uncertainties are discussed in detail in Ref. [8]. For the relative per-nucleon SRC probabilities the main sources of these uncertainties are: radiative and acceptance correction factors, corrections due to the difference of (ep) and (en) scattering cross sections and measurements at separate beam energies, liquid ^{3}He and ^{4}He targets effective length determination. The total systematic uncertainties are: (i) in the $a_2(A/^3\mathrm{He})$ probabilities—7.2%, 7.1%, and 6.3% for $A = 4$, 12, and 56, respectively; (ii) in the $a_3(A/^3\mathrm{He})$ probabilities—8.1%, 7.1%, and 7.4% for the same nuclei, respectively. For the

TABLE I. $a_j(A/^3\mathrm{He})$ and $a_{jN}(A)$ $(j = 2, 3)$ are the per nucleon relative (to ^{3}He) and absolute probabilities of (jN) SRC, respectively. Errors shown are statistical and systematic for a_j and are combined (but systematic dominated) for a_{jN}. The systematic uncertainties due to the Coulomb interaction and SRC c.m. motion are not included. For the $^{56}\mathrm{Fe}/^3\mathrm{He}$ ratio they are expected to be <2%–6% and <20%, respectively, and are somewhat smaller for $^{12}\mathrm{C}/^3\mathrm{He}$ and smaller still for $^4\mathrm{He}/^3\mathrm{He}$ ratios.

	$a_2(A/^3\mathrm{He})$	$a_{2N}(A)$ (%)	$a_3(A/^3\mathrm{He})$	$a_{3N}(A)$ (%)
^{3}He	1	8.0 ± 1.6	1	0.18 ± 0.06
^{4}He	$1.93 \pm 0.02 \pm 0.14$	15.4 ± 3.3	$2.33 \pm 0.12 \pm 0.19$	0.42 ± 0.14
^{12}C	$2.41 \pm 0.02 \pm 0.17$	19.3 ± 4.1	$3.05 \pm 0.14 \pm 0.21$	0.55 ± 0.17
^{56}Fe	$2.83 \pm 0.03 \pm 0.18$	22.7 ± 4.7	$4.38 \pm 0.19 \pm 0.33$	0.79 ± 0.25

absolute per-nucleon SRC probabilities there are additional uncertainties from determining the momentum onset of scaling and from the deuterium and ^{3}He wave functions: $\approx 20\%$ for 2-nucleon and $\approx 30\%$ for 3-nucleon SRC probabilities. For the ^{56}Fe/^{3}He ratio there is also a 2%–6% uncertainty from the electron-nucleus Coulomb interaction [22,23] for both 2- and 3-nucleon SRC. In addition, there is a possible pair c.m. motion effect which can reduce the ratio up to 20% for 2-nucleon SRC. For 3-nucleon SRC this effect is not estimated yet. Since there is no exact estimate of the last two uncertainties, we do not include them in the systematic errors of our data (see Table I) [24].

We compared the NN SRC probabilities to various models. The SRC model predicts [4] the relative to deuterium probabilities of NN SRC in ^{4}He (~ 4) and ^{12}C (5 ± 0.1), based on an analysis of hadro-production data. Using the above discussed value of $a_2(^3\text{He}/d) = 1.97 \pm 0.1$ we can find the predictions for the relative to ^{3}He probabilities $a_2(^4\text{He}/^3\text{He}) = 2.03 \pm 0.1$, and $a_2(^{12}\text{C}/^3\text{He}) = 2.53 \pm 0.5$. The SRC model also predicts the ratio $a_2(^{56}\text{Fe}/^3\text{He})/a_2(^{12}\text{C}/^3\text{He}) = 1.26$ based on Fermi liquid theory. These are remarkably close to the experimental values of $1.93 \pm 0.02 \pm 0.14$, $2.41 \pm 0.03 \pm 0.17$, and $1.17 \pm 0.04 \pm 0.11$, respectively. For $3N$ SRC probabilities the SRC model predicts [4] $a_3(^{56}\text{Fe}/^3\text{He})/a_3(^{12}\text{C}/^3\text{He}) = 1.40$ which is also remarkably close to the experimental value of $1.43 \pm 0.09 \pm 0.15$.

Levinger's quasideuteron model [25] predicts 1.1 (pn) pairs for all nuclei, which disagree with experiment, probably because it includes low momentum (pn) pairs only.

Forest [16] 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. If one assumes that this corresponds to $a_2(A, d)$, then $a_2(^4\text{He}/^3\text{He}) = a_2(^{16}\text{O}/^3\text{He}) = 1.76$ compared to experimental values of 1.96 for ^{4}He and 2.41 for ^{12}C.

The Iowa State University/University of Arizona group calculates 6- and 9-quark-cluster probabilities for many nuclei [26]. If these clusters are identical to 2 and $3N$ SRC, respectively, then the calculated probabilities of 6-quark clusters for ^{4}He, ^{12}C, and ^{56}Fe are within about a factor of 2 of the measured NN SRC probabilities. The ratio $a_2(^{56}\text{Fe}/^3\text{He})/a_2(^{12}\text{C}/^3\text{He}) = 1.16$ agrees with the experimental value of $1.17 \pm 0.04 \pm 0.11$. However, the predicted probabilities of 9-quark clusters are larger than the our $a_{3N}(A)$ value 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 of the nuclear density, respectively; (3) these features are consistent with the theoretical expectations that NN SRC dominate the nuclear wave function at $k_{\min} \gtrsim 300$ MeV and $3N$ SRC dominate at $k_{\min} \gtrsim 500$ MeV; (4) the chances for each nucleon to be involved in a NN SRC in ^{4}He, ^{12}C, and ^{56}Fe nuclei are 1.9, 2.4, and 2.8 times higher than in ^{3}He, while the same chances for $3N$ SRC are, respectively, 2.3, 3.1, and 4.4 times higher; (5) in ^{4}He, ^{12}C, and ^{56}Fe, the absolute per-nucleon probabilities of 2- and 3-nucleon SRC are 15%–23% and 0.4%–0.8%, respectively. This is the first measurement of $3N$ SRC probabilities in nuclei.

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