Evidence for Strong Dominance of Proton-Neutron Correlations in Nuclei

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We analyze recent data from high-momentum-transfer (p, pp) and (p, ppn) reactions on carbon. For this analysis, the two-nucleon short-range correlation (NN-SRC) model for backward nucleon emission is extended to include the motion of the NN pair in the mean field. The model is found to describe major characteristics of the data. Our analysis demonstrates that the removal of a proton from the nucleus with initial momentum 275–550 MeV$/c$ is $92^{+8}_{-18}\%$ of the time accompanied by the emission of a correlated neutron that carries momentum roughly equal and opposite to the initial proton momentum. This indicates that the probabilities of pp or nn SRCs in the nucleus are at least a factor of 6 smaller than that of pn SRCs. Our result is the first estimate of the isospin structure of NN-SRCs in nuclei, and may have important implication for modeling the equation of state of asymmetric nuclear matter.

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Studies of short-range nucleon correlations (SRCs) in nuclei are important for understanding the short-distance and large-momentum properties of nuclear ground state wave functions. The relevant distances in two-nucleon (NN)-SRCs are expected to be comparable to that in neutron stars corresponding to 4–10 times the central density of nuclei [1]. Thus SRC studies are essential in understanding the structure of cold dense nuclear matter. In this context the isospin content of SRCs (i.e., pn versus pp and nn pairs) is important for understanding the structure of nuclear matter made of either protons or neutrons. Studies of SRCs also give the best hope of understanding the nature of the short-range NN repulsion.

SRCs in nuclei have been actively investigated for over three decades (see, e.g., [2]). However, experimental studies of the microscopic structure of SRCs were largely restricted due to moderate momentum-transfer kinematics in which it is difficult to resolve SRCs. Recently, several experiments [3–7] made noticeable progress in understanding dynamical aspects of SRCs. For $Q^2 > 1$ GeV^2, Refs. [4,5] observed Bjorken x_B scaling for ratios of inclusive (e, e') cross sections of nuclei A to the ^{3}He nucleus when $x_B \geq 1.4$. This confirms the earlier observation of scaling for nucleus-to-deuteron cross section ratios [8,9], and indicates directly that the electrons probe high-momentum bound nucleons coming from local sources in nuclei (i.e., SRCs) with properties generally independent of the noncorrelated residual nucleus.

Based on the NN-SRC picture, which is expected to dominate the internal momentum range of $\sim$250–600 MeV$/c$, one predicts a strong directional (back-to-back) correlation between the struck nucleon and its spectator in the SRC. Experiments [3,6,7] measured triple-coincidence events for the $^3\mathrm{He}(e, e'pp)X$ and $^{12}\mathrm{C}(p, ppn)X$ reactions, and clearly demonstrated the existence of such directional correlations. They also revealed a noticeable momentum distribution of the center of mass (c.m.) of the NN-SRCs.

In this work we extend the NN-SRC model used in the analyses of $A(p, pp)X$ data [10], to incorporate the effects of the c.m. motion of SRCs. This allows us to estimate the probability for correlated neutron emission following removal of a fast proton from the nucleus in (p, ppn) reactions. Based on this model we extract from the data an upper limit to the relative probabilities of pp and nn versus pn SRCs in ^{12}C.

The measurements of $^{12}\mathrm{C}(p, ppn)X$ reactions [6,7] were performed with the EVA spectrometer at the AGS accelerator at Brookhaven National Laboratory [11,12]. EVA consists of a 0.8 T superconducting solenoid, 3.3 m long and 2 m in diameter. The 5.9–9.0 GeV$/c$ proton beam was incident along the central axis. Coincident pairs of high transverse-momentum protons were detected with four concentric cylinders of straw tube chambers. The experimental kinematics are discussed in more detail later. Neutrons were detected in coincidence with the quasielastic knockout of protons from ^{12}C. The large-momentum transfers $-t \geq 6$ GeV^2 in these processes greatly improve the resolving power of the probe and validate the instantaneous approximation for description of the removal of fast bound proton in the $pp \to pp$ subprocess. For each (p, pp) event, the momentum of the struck proton $\vec{p}_2$ before the reaction was reconstructed and compared (event by event) with the measured coincident neutron momentum $\vec{p}_n$. Because of the $\sim s^{-10}$ dependence of the underlying hard $pp \to pp$ cross section, the scattering takes place preferentially off a bound proton with large $|p_2|$ in the direction of the beam (minimizing s) [13], and hence should lead to a significant rate of emission of backward correlated nucleons due to scattering off NN-SRCs. Data confirming these characteristics of $A(p, ppn)X$ reactions are shown in Fig. 1 for ^{12}C. The data show no directional correlation for neutrons with $|p_n|$ below the Fermi sea level ($k_F = 220$ MeV$/c$). Above k_F a strong back-to-back directional correlation between $\vec{p}_2$ and $\vec{p}_n$ is evident.

In Ref. [7] the large value of the following ratio

$$F = \frac{\text{Number of } (p, ppn) \text{ events}(p_2, p_n > k_F)}{\text{Number of } (p, pp) \text{ events}(p_2 > k_F)} \quad (1)$$

was extracted, which indicates that in the 250–550 MeV$/c$ region NN-SRCs must be the major source of nucleons in nuclei. Within the SRC model, the numerator of F is due to scattering off the pn-SRC while the denominator is due to scattering off any possible configuration "pX" which contains a proton with $|p_2| \sim 250$–550 MeV$/c$. All configurations such as pn- and pp-SRCs, the high-momentum tail of the mean-field proton distribution, three and more nucleon SRCs, as well as SRCs containing non-nucleonic degrees of freedom could contribute to "pX". We define $P_{pn/pX}$ as the relative probability of finding a pn-SRC in the "pX" configuration. In this work, using a theoretical description of the $A(p, pp)X$ and $A(p, ppn)X$ reactions, we evaluate $P_{pn/pX}$ from the above measured ratio F.

Our theoretical description of the $A(p, ppn)X$ reaction, in which the hard $pp \to pp$ subprocess is accompanied by the emission of a recoil ($k_F < p_n < 550$ MeV$/c$) neutron, is based on the light-cone distorted-wave impulse approximation (LC-DWIA). This is an appropriate approximation for high-momentum-transfer reactions aimed at studies of the ground state properties of nuclei since in this case the LC momentum fraction α (defined below) of the nuclear constituents is approximately conserved without much distortion due to soft initial and final state interactions in the reaction [14,15]. This validates the factorization of the hard $pp \to pp$ scattering from the soft reinteractions, allowing to express the $A(p, ppn)X$ cross section through the product of the $pp \to pp$ scattering cross section off the bound proton, $d\sigma/dt$, and the nuclear decay function, D^{pn}:

$$\sigma^{p,ppn} = \sum_Z K \frac{d\sigma^{pp}}{dt}(s, t) \frac{2D^{pn}(\alpha, \vec{p}_t, \alpha_n, \vec{p}_{tn}, P_{R+})}{\alpha} T_{ppn}, \quad (2)$$

where $\sigma^{p,ppn} \equiv d^9\sigma / \frac{d^3p_3}{E_3} \frac{d^3p_4}{E_4} \frac{d\alpha_n}{\alpha_n} d^2p_{tn}$ and $K = \frac{2}{\pi} \times \sqrt{s^2 - 4m^2 s}$. Here p_1, p_3, and p_4 are incoming, scattered, and knocked out proton four momenta and $p_2 = p_3 + p_4 - p_1$. Also, $s = (p_3 + p_4)^2$ and $t = (p_1 - p_3)^2$. The function D^{pn} represents the joint probability of finding a proton in the nucleus with $\alpha = A \frac{E_2 - p_2^z}{E_A - P_A^z}$ and transverse momentum $\vec{p}_t$, and a recoil neutron in the residual $A - 1$ nucleus with α_n and $\vec{p}_{tn}$. $P_{R+} = E_R - p_2^z$ is the LC "plus" component of the $A - 1$ residual nuclear state. Here, $z \parallel \vec{p}_1$. T_{ppn} is the nuclear transparency for the yield of two fast protons and recoil neutron. Equation (2) correctly reproduced the angular correlation of Fig. 1 as well as average values of $\langle \alpha_n \rangle$ and $\langle \cos(\gamma) \rangle$ [6,7].

Within the LC-DWIA, the $A(p, pp)X$ reaction is expressed through the spectral function, S^p, as follows [10]:

$$\sigma^{p,pp} = \sum_Z K \frac{d\sigma^{pp}}{dt}(s, t) \frac{2S^p(\alpha, \vec{p}_t, P_{R+})}{\alpha} T_{pp}, \quad (3)$$

where $\sigma^{p,pp} \equiv d^6\sigma / \frac{d^3p_3}{E_3} \frac{d^3p_4}{E_4}$, and T_{pp} represents the nuclear transparency for the yield of two fast protons from the nucleus. For SRCs we have

$$S^p(\alpha, \vec{p}_t, P_{R+}) = \sum_s \int D^{ps}(\alpha, \vec{p}_t, \alpha_s, \vec{p}_{ts}, P_{R+}) \frac{d\alpha_s}{\alpha_s} d^2p_{ts}, \quad (4)$$

where the summation is over the possible types of the recoil particles s from the SRC. The spectral function S^p together with the mean-field contribution to the spectral function is normalized to unity. At small internal momenta, the LC-DWIA reduces smoothly to its nonrelativistic counterpart. Reasonable agreement is observed [10] in an extensive comparison of calculations based on Eq. (3) with measured α and p_t spectra [6].

The ratio F defined in Eq. (1) now can be written as

$$F = \frac{\int_{\alpha^{\min}}^{\alpha^{\max}} \int_{p_t^{\min}}^{p_t^{\max}} \int_{\alpha_n^{\min}}^{\alpha_n^{\max}} \int_{p_{tn}^{\min}}^{p_{tn}^{\max}} \sigma^{p,ppn} \frac{d\alpha}{\alpha} d^2p_t \frac{d\alpha_n}{\alpha_n} d^2p_{tn} dP_{R+}}{\int_{\alpha^{\min}}^{\alpha^{\max}} \int_{p_t^{\min}}^{p_t^{\max}} \sigma^{p,pp} \frac{d\alpha}{\alpha} d^2p_t dP_{R+}}, \quad (5)$$

where the limits for integration are defined by the experimental conditions. The kinematics of the experiment [6,7] lead to the integration by P_{R+} that covers all the range relevant to quasielastic scattering.

Using Eq. (5) and relations (2)–(4), one can relate the above defined $P_{pn/pX}$ averaged over the measured range of $\vec{p}_2$, $\vec{p}_n$, and P_{R+} to the ratio F as follows:

$$P_{pn/pX} = F/(T_n R)\cdot \quad (6)$$

Here T_n accounts for the attenuation of the neutron and

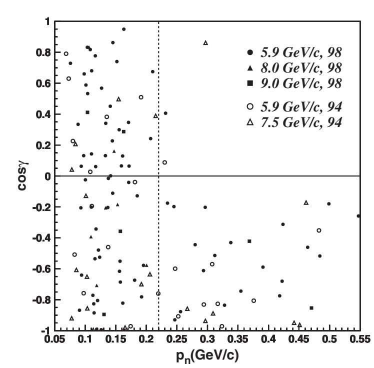

FIG. 1. The correlation between p_n and its direction γ relative to $\vec{p}_2$. Data labeled by 94 and 98 are from Refs. [6,7], respectively. The momenta are the beam momenta. The dotted vertical line corresponds to $k_F = 220$ MeV$/c$.

$$R \equiv \frac{\int_{\alpha^{\min}}^{\alpha^{\max}} \int_{p_t^{\min}}^{p_t^{\max}} \int_{\alpha_n^{\min}}^{\alpha_n^{\max}} \int_{p_{tn}^{\min}}^{p_{tn}^{\max}} D^{pn} \frac{d\alpha}{\alpha} d^2 p_t \frac{d\alpha_n}{\alpha_n} d^2 p_{tn} dP_{R+}}{\int_{\alpha^{\min}}^{\alpha^{\max}} \int_{p_t^{\min}}^{p_t^{\max}} S^{pn} \frac{d\alpha}{\alpha} d^2 p_t dP_{R+}}, \tag{7}$$

where S^{pn} is the part of the spectral function S^p related to pn-SRCs only. In the derivation of Eq. (6) we used $T_{ppn} \approx T_{pp}T_n$, which is justified for kinematics in which two energetic, >3 GeV/c protons are produced in the projectile fragmentation region while the neutron is detected with $|p_n| \leq 550$ MeV/c in the backward direction. The accuracy of this approximation is proportional to the relative yield of recoil neutrons due to rescattering of the energetic protons off uncorrelated neutrons in the nucleus, which amounts ~5% for the considered kinematics.

Note that Eq. (6) gives a well-defined upper limit for $P_{pn/pX}$; namely, if the nucleus is transparent to the recoil neutron ($T_n = 1$), all the strength of the SRC is due to pn-SRCs, and if the kinematic cuts cover all the domain relevant to NN-SRC ($F = R = 1$) then $P_{pn/pX} = 1$.

The function R can be estimated in the NN-SRC model in which the decay function, D^{pn} is a convolution of two density matrices representing the relative (ρ^{pn}_{SRC}) and c.m. ($\rho^{pn}_{\mathrm{c.m.}}$) momentum distributions of the pn-SRC:

$$D^{pn} = \rho^{pn}_{\mathrm{SRC}}(\alpha_{\mathrm{rel}}, \vec{p}_{t,\mathrm{rel}})\rho^{pn}_{\mathrm{c.m.}}(\alpha_{\mathrm{c.m.}}, \vec{p}_{t,\mathrm{c.m.}})\frac{\alpha_n}{\alpha_{\mathrm{c.m.}}} \times \delta\left(P_{R+} - \frac{m^2 + p_{t,n}^2}{m\alpha_n} - \frac{M_{A-2}^2 + p_{t,\mathrm{c.m.}}^2}{m(A - \alpha_{\mathrm{c.m.}})}\right), \tag{8}$$

where $\alpha_{\mathrm{rel}} = \frac{\alpha - \alpha_n}{\alpha_{\mathrm{c.m.}}}$, $p_{t,\mathrm{rel}} = p_t - \frac{\alpha}{\alpha_{\mathrm{c.m.}}} p_{tn}$, $\alpha_{\mathrm{c.m.}} = \alpha + \alpha_n$, and $p_{t,\mathrm{c.m.}} = p_t + p_{tn}$. Within the SRC model [8], ρ^{pn}_{SRC} is related to the LC density matrix of the deuteron as

$$\rho_{\mathrm{SRC}}(\alpha, p_t) = a_{pn}(A)\frac{\Psi_D^2(k)}{2 - \alpha}\sqrt{m^2 + k^2}, \tag{9}$$

where $\Psi_D(k)$ is the deuteron wave function, and $k = \sqrt{\frac{m^2 + p_t^2}{\alpha(2-\alpha)} - m^2}$ $(0 < \alpha < 2)$. The parameter $a_{pn}(A)$ is the probability (relative to the deuteron) of having a pn SRC pair in nucleus A. Note that it cancels out in R, while $P_{pn/pX}$ contains information on a_{pn}/a_{NN}, with a_{NN} related to the probability of NN-SRCs.

The c.m. motion of the SRC relative to the $(A - 2)$ spectator system is described by a Gaussian ansatz similar to Refs. [16,17] with σ being a parameter. This distribution can be expressed through the LC momentum of the c.m. of the SRC as follows:

$$\rho_{\mathrm{c.m.}}(\alpha, p_t) = 2m\left(\frac{1}{2\pi\sigma^2}\right)^{3/2} e^{-\{[m^2(2-\alpha)^2 + p_t^2]/2\sigma^2]}. \tag{10}$$

It is normalized as $\int \rho_{\mathrm{c.m.}}(\alpha, p_t)\frac{d\alpha}{\alpha} d^2 p_t = 1$.

The factorization of Eq. (8) is specific to the NN-SRC model, in which it is assumed that the singular character of the NN potential at short distances defines the main structure of the nucleon momentum distribution, and that it is weakly affected by the interaction of the NN-SRC with the $A - 2$ nuclear system. This approach gives a good description of the spectral function of ^{3}He [17], as well as medium nuclei [16], with fitted values of total probabilities for NN-SRC which are up to 20% less than the values extracted in Ref. [4,5,9].

Figure 2 shows R as a function of σ, calculated within the above approach, as a dashed line. Here we used the same $0.6 < \alpha < 1.1$ and $k_F < p_t < 0.55$ GeV/c cuts in both (p, pp) and (p, ppn) reactions. It can be seen from Fig. 2 that R approaches unity at $\sigma \to 0$ which is consistent with the prediction of the SRC model with the c.m. at rest. Figure 2 shows a large sensitivity of R to the width of the c.m. momentum distribution.

To extract $P_{pn/pX}$ from the data of Refs. [6,7] using Eq. (6) one needs estimates of R, T_n, and F, for the kinematic cuts of the experiment, which are

$$\begin{aligned} &\text{struck proton:} \quad 0.6 < \alpha < 1.1; \qquad p_2 > p^{\min} \\ &\text{recoil neutron:} \quad 0.9 < \alpha_n < 1.4; \\ &\qquad p^{\min} < p_n < 0.5572^0 < \theta_n < 132^0. \end{aligned} \tag{11}$$

Here we follow Ref. [5] and set $p^{\min} = 0.275$ GeV/c to suppress mean-field contribution to $\leq 1\%$. R: the solid curve in Fig. 2 represents R calculated for the experimental cuts of Eq. (11). It is different from unity even for $\sigma \to 0$ due to the different integration ranges for p_2 and p_n; Eq. (11) places no restriction on $p_{2t} \equiv p_t$, while $p_{nt} \geq 204$ MeV/c. T_n: we used $T_n = 0.85$ obtained from the simulation based on Eq. (2) using the experimental limits of Eq. (11). T_n includes Pauli Blocking effects according to Ref. [18] as well as a small correction due to neutrons from the rescattering of the fast incoming and outgoing protons calculated in the eikonal approximation [19,20]. F: the ratio F is taken from Ref. [7], where it is quoted as $F = 0.49 \pm 0.13$ for $p^{\min} = 0.22$ GeV/c. For $p^{\min} = 0.275$ GeV/c our analysis of the same data gives $F = 0.43^{+0.11}_{-0.07}$. The uncertainty is dominated by the low statistics. Since the lower limit of the extracted $P_{pn/pX}$ is sensi-

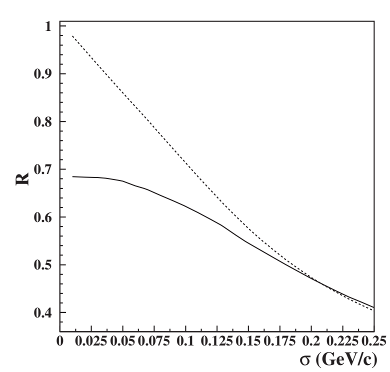

FIG. 2. R as a function of σ. The dashed line is for the same cuts applied to both the (p, pp) and (p, ppn) reactions; the solid line is for the cuts of the EVA experiment.

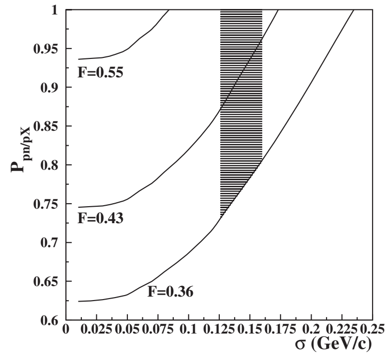

FIG. 3. $P_{pn/pX}$ as a function of σ. The shaded area corresponds to the $P_{pn/pX}$ values at $\sigma_{\rm exp} = 143 \pm 17$ MeV/c.

tive to the lower limit on F [Eq. (6)] we choose for F the best 1 standard deviation low limit allowed by the data.

Using the above values of R, T_n, and F, we estimate $P_{pn/pX}$ from Eq. (6). Figure 3 shows the σ dependence of $P_{pn/pX}$ for $F = 0.36$, 0.43, and 0.55, respectively. Since $P_{pn/pX} \leq 1$, there is an interesting correlation between σ and $P_{pn/pX}$, which allows us to put a constraint on σ. For example for $F = 0.43$, σ cannot exceed 174 MeV/c. To evaluate $P_{pn/pX}$ we use the magnitude of $\sigma^{\rm exp} = 143 \pm 17$ MeV/c extracted from the same data set [7]. This value is in excellent agreement with the theoretical expectation of 139 MeV/c of Ref. [16]. Note that $\sigma^{\rm exp}$ dictates the range of possible values for $P_{pn/pX}$. From the central (0.43) and minimal (0.36) values of F we obtain

$$P_{pn/pX} = 0.92^{+0.08}_{-0.18}. \tag{12}$$

This result indicates that at least 74% of the time the removal of a fast proton is accompanied by the emission of a fast recoil neutron. It allows us also to estimate an upper limit of the ratio of absolute probabilities of pp- to pn-SRCs [21]:

$$\frac{P_{pp}}{P_{pn}} \leq \frac{1}{2}(1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04}. \tag{13}$$

This result can be used to estimate separately the absolute probabilities of pn, pp, and nn SRCs in the nuclear wave function. For this we use the total probability of NN-SRCs [$P_{NN}(^{12}\mathrm{C}) = 0.20 \pm 0.042$] obtained by combining the results of large Q^2 and x_B inclusive $A(e, e')X$ data from Refs. [4,5,9]. The value of P_{NN} is practically independent of whether or not we account for the c.m. motion of the SRC. Using P_{NN} and Eq. (13) we obtain $P_{pn}(^{12}\mathrm{C}) = 0.184 \pm 0.045$ and $P_{pp}(^{12}\mathrm{C}) = P_{nn}(^{12}C) \leq 0.03$.

Summarizing, from Eqs. (12) and (13) we conclude that our analysis of (p, pp) and (p, ppn) reactions indicates that if a nucleon with momentum between 275–550 MeV/c is removed from the nucleus using a high momentum and energy transfer probe, at least 74% of the time it will originate from pn-SRCs. The data also show significantly smaller (a factor of 6 at least) probabilities for pp and nn NN-SRCs as compared to pn NN-SRCs in carbon. This result may indicate the dominance of the tensor forces in NN-SRCs and have important implications for modeling the equation of state of asymmetric nuclear matter. It indicates that the equation of state of neutron stars could be affected by the large suppression of the number of neutrons above the Fermi sea. Future experiments involving high-Q^2 $(e, e'pp)$ and $(e, e'pn$ reactions off medium-to-heavy nuclei (e.g., Ref. [22]), as well as theoretical studies based upon realistic treatments of SRCs and final-state-interaction effects (see, e.g., Ref. [23–25]), will allow one to verify and significantly improve the accuracy of the present results.

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