n-p Short-Range Correlations from $(p, 2p + n)$ Measurements

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We studied the ^{12}C$(p, 2p + n)$ reaction at beam momenta of 5.9, 8.0, and 9.0 GeV/c. For quasielastic $(p, 2p)$ events $\mathbf{p}_f$, the momentum of the knocked-out proton before the reaction, was compared (event by event) with $\mathbf{p}_n$, the coincident neutron momentum. For $|p_n| > k_F = 0.220$ GeV/c (the Fermi momentum) a strong back-to-back directional correlation between $\mathbf{p}_f$ and $\mathbf{p}_n$ was observed, indicative of short-range n-p correlations. From $\mathbf{p}_n$ and $\mathbf{p}_f$ we constructed the distributions of c.m. and relative motion in the longitudinal direction for correlated pairs. We also determined that 49 ± 13% of events with $|p_f| > k_F$ had directionally correlated neutrons with $|p_n| > k_F$.

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For the past half century, the dominant model for the structure of nuclei, especially light nuclei, has been the nuclear shell model. In the shell model, the long-range (~ 2 fm) part of the NN interaction, in combination with the Pauli principle, produces an average potential in which the nucleons undergo nearly independent motion, and the residual interactions can be treated by perturbation theory. However, the NN interaction is also highly repulsive at short range (~ 0.4 fm). This short-range repulsion is responsible for the saturation density of nuclei, e.g., the nearly constant density in the interior of all stable nuclei heavier than ^{4}He. The effect of this two-nucleon short-range (2N-SRC) repulsion should also manifest itself in the motions of the nucleons in the nucleus. In 1998, Mardor *et al.* [1] showed that for high-energy $(p, 2p)$ reactions at high-momentum transfer, quasielastic scattering can be identified. They also showed, assuming the validity of the plane-wave impulse approximation (PWIA), that high-momentum transfer $(p, 2p)$ yields the same momentum distributions as $(e, e'p)$. Building on this result, Aclander *et al.* [2] described a new technique for observing 2N-SRC with a high-momentum-transfer proton reaction, based on a proposal by Frankfurt and Strikman [3]. In this Letter we demonstrate that 2N-SRC can be observed directly and that their contribution to quasielastic scattering is sizable at high initial momentum. We also present the first results of the c.m. momentum of the correlated NN pair as well as the relative momentum of the two nucleons in their c.m. frame.

For quasielastic knockout of protons from nuclei, e.g., ^{12}C$(p, 2p)$ in [1,2] and for this work, we can reconstruct (event by event) the three momentum $\mathbf{p}_f$ that the struck target proton had before the reaction:

$$\mathbf{p}_f = \mathbf{p}_1 + \mathbf{p}_2 - \mathbf{p}_0, \tag{1}$$

where $\mathbf{p}_0$ is the momentum of the incident proton and $\mathbf{p}_1$ and $\mathbf{p}_2$ are the momenta of the two detected protons. Note that our analysis is based on the assumption that the PWIA is valid, an assumption verified at the level of a few percent for our experimental conditions [1].

For p-p elastic scattering near 90°, the cross section $\frac{d\sigma}{dt}$ falls as s^{-10}, where s and t are the standard Mandelstam variables. From this strong dependence on s we expect p-p quasielastic scattering to occur preferentially with nuclear protons that have the longitudinal component of $\mathbf{p}_f$ in the beam direction, because this reduces s and increases $\frac{d\sigma}{dt}$ [4]. When two nucleons in a nucleus interact at short range, they must have large, nearly equal, momenta in opposite directions (because of their strong repulsion at short range) [5]. If the pair is broken by a quasielastic interaction one of the nucleons may emerge from the nucleus, with relatively large momentum, in a direction opposite the original momentum of its partner. Our experiment then consists of measuring the two protons of the quasielastic scattering in coincidence with the emerging correlated neutron. Since $\mathbf{p}_f$ is roughly parallel to the beam, we placed 36 neutron detectors primarily in the backward hemisphere, to search for neutrons with $\mathbf{p}_n \approx -\mathbf{p}_f$. See [6] for experimental details.

The measurements reported here (and in [2]) were taken with the EVA spectrometer [6,7] at Brookhaven National Laboratory. EVA consists of a 0.8 T superconducting solenoid, 3.3 m long and 2 m in diameter, with the beam incident along the central axis. Coincident pairs of high transverse-momentum ($\mathbf{p}_t$) protons are detected with four concentric cylinders of strawtube drift chambers.

For all of the results discussed below we applied the five following cuts to the data: (i) The projectile should be a proton, as determined by Čerenkov detectors in the beam. (ii) There should be two (and only two) high-$\mathbf{p}_t$ (> 0.6 GeV/c) positive-charge tracks. (iii) The missing energy, E_{miss}, should be appropriate for quasielastic scattering and was defined by the resolution at each energy [1]. (iv) The neutron momentum should be in the range $0.05 < p_n < 0.55$ GeV/c. (v) The laboratory azimuthal angles for the two detected protons must lie within $\pm 45°$ of the plane through EVA parallel to the face of the active neutron detector. Cut (v) was implemented so that we could combine our results with those in [2], which were also taken with EVA but with more limited acceptance.

Our primary objective was to identify short-range correlated n-p pairs in ^{12}C nuclei. The signature of such pairs is that the momentum of the detected neutron $\mathbf{p}_n \approx -\mathbf{p}_f$. We note, however, that the motion of the c.m. of such an n-p pair in the nucleus will keep this from being a perfect equality. The simplest directional correlation we can construct is "up-down." The neutron detectors were all placed below the midplane of EVA, so the neutrons were all detected in the "downward" direction. We can then compare this with the "upward" component of $\mathbf{p}_f$.

Figure 1 is a scatter plot for $(p, 2p + n)$ events of p_f^{up} vs the neutron momentum p_n, where p_f^{up} is the projection of $\mathbf{p}_f$ on an axis normal to the faces of the neutron detectors. The vertical dashed line in Fig. 1 is at $k_F = 0.22$ GeV/c, the Fermi momentum for ^{12}C [8]. Similar to [1], the uncertainties in Fig. 1 are derived from resolutions measured for p-p elastic scattering. In Fig. 1 there is a striking difference in the distribution of p_f^{up} for $p_n < k_F$ and $p_n \geq k_F$. For $p_n < k_F$ the events are distributed nearly equally between those with $p_f^{\text{up}} > 0$ ("up") and $p_f^{\text{up}} < 0$ ("down"). By contrast, for $p_n \geq k_F$, a large fraction of the events have $p_f^{\text{up}} > 0$. Thus $\mathbf{p}_f$ is predominantly up when $\mathbf{p}_n$ is (by definition) down for $p_n \geq k_F$. This is a strong confirmation of what was reported in [2].

We now construct the full directional correlation between $\mathbf{p}_f$ and $\mathbf{p}_n$ as

$$\cos\gamma = \frac{\mathbf{p}_f \cdot \mathbf{p}_n}{|\mathbf{p}_f||\mathbf{p}_n|}, \tag{2}$$

where γ is the angle between $\mathbf{p}_f$ and $\mathbf{p}_n$.

In Figs. 2(a) and 2(b) we plot $\cos\gamma$ for $p_n \geq k_F = 0.22$ GeV/c and $p_n < k_F$, respectively. As in Fig. 1 there is a pronounced difference between these distributions.

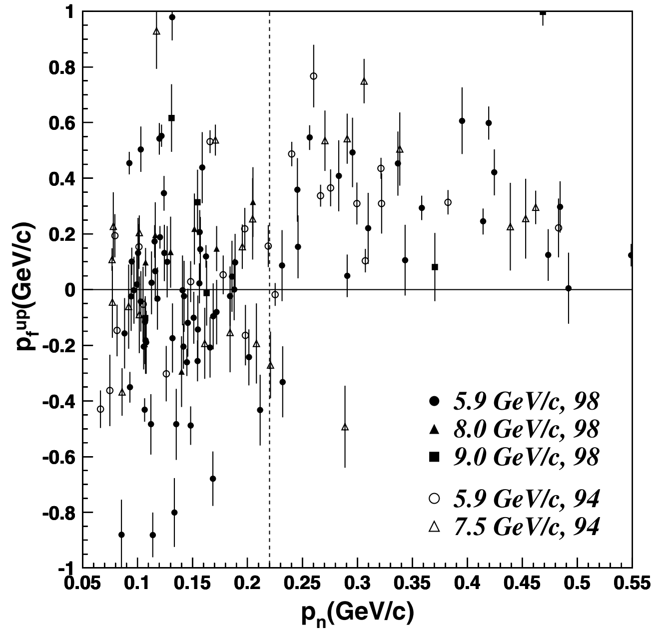

FIG. 1. Scatter plot of p_f^{up} vs p_n with cuts (i), (ii), (iii), (iv), and (v) (see text) for ^{12}C$(p, 2p + n)$ events. Data labeled "98" (solid symbols) are for this work. Data labeled "94" are from Aclander *et al.* [2]. The vertical dashed line at 0.22 GeV/c corresponds to k_F, the Fermi momentum for ^{12}C.

Figure 2(a) shows a strong "back-to-back" directional correlation with the distribution peaking at $\cos\gamma = -1$; only three events have $\cos\gamma > 0$. By contrast, in Fig. 2(b), the distribution is nearly uniform in $\cos\gamma$, and the numbers of events for $\cos\gamma < 0$ and $\cos\gamma > 0$ are the same within statistics (51 and 43, respectively). For Fig. 2(a) ($p_n > k_F$), the probability that 38 uncorrelated events could be distributed 35 to 3 is vanishingly small ($\sim 10^{-8}$). To check the results in Fig. 2, we generated background spectra of events with two high p_t tracks plus one soft track in EVA. The resulting spectra for both $p_n > k_F$ and $p_n < k_F$ were small and flat, indicating that the peak at $\cos\gamma = -1$ in Fig. 2(a) is not an instrumental artifact and that backgrounds are small.

The effects of initial-state and final-state interactions (ISIs and FSIs) are expected to be larger in the transverse than in the longitudinal direction [9]. Therefore, in extracting the relative and c.m. motion for correlated n-p pairs we focus on the longitudinal (z) components of $\mathbf{p}_n$ and $\mathbf{p}_f$. For beams of high-energy protons, the natural variables for representing the motion of a nucleon in the nucleus are the light-cone variables $\mathbf{p}_t$ and $\alpha = (E - p_z)/m$. Note that $\alpha \approx 1$ for $p_z = 0$; therefore, we would expect $\alpha_p + \alpha_n \approx 2$ for a correlated pair with $\mathbf{p}_n \approx -\mathbf{p}_f$. [$\alpha_p = (E - p_{fz})/m$; $\alpha_n = (E - p_{nz})/m$.]

As noted earlier, the p-p cross section, $\frac{d\sigma}{dt}$, near 90° c.m. is proportional to s^{-10}. We therefore need to correct for this "reaction bias" when looking at longitudinal variables. The differential cross section as a function of the solid angle is $d\sigma/d\Omega = (s - 4m^2)(4\pi)^{-1} d\sigma/dt$. Thus $\frac{d\sigma}{d\Omega} \sim s^{-9}$, and this strong s dependence enhances

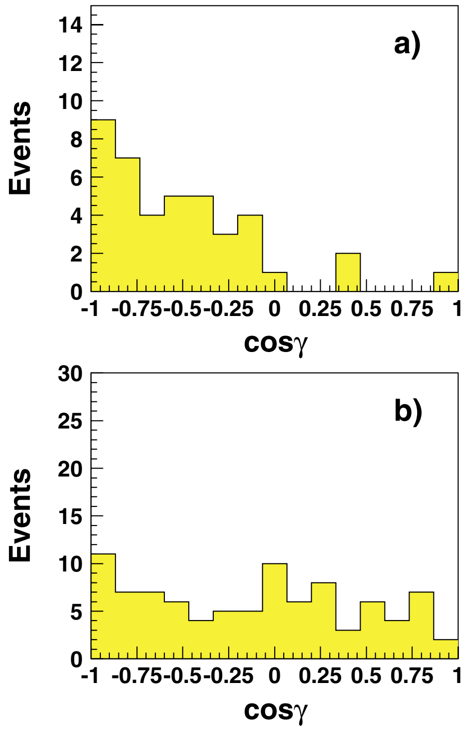

FIG. 2 (color online). Plots of $\cos\gamma$, where γ is the angle between $\mathbf{p}_n$ and $\mathbf{p}_f$, for $^{12}C(p, 2p + n)$ events. Panel (a) is for events with $p_n > 0.22$ GeV/c, and panel (b) is for events with $p_n < 0.22$ GeV/c; 0.22 GeV/$c = k_F$, the Fermi momentum for ^{12}C.

quasielastic reactions with low s for the p-p collisions. Protons in the nucleus with longitudinal momentum in the same direction as the beam are thus more likely to be knocked out. We therefore weighted each event by a correction factor equal to $(s/s_0)^9$ to obtain the nuclear distributions without the reaction bias, where s_0 is the total c.m. energy for $pp \to pp$ at each beam momentum, and s is calculated for each event from $\mathbf{p}_f$ for that event.

In Fig. 3 we show plots of α_p, α_n, and $\alpha_p + \alpha_n$ (all with s-weighting) for events with $p_n > k_F$. We note for Fig. 3 that α_p is generally <1 and $\alpha_n > 1$. Of course, our placement of the neutron detectors primarily in the backward hemisphere forces α_n to be largely > 1. In Fig. 3, the spread of $\alpha_n + \alpha_p$ about 2 should be due to the c.m. motion of the pair. Ciofi degli Atti *et al.* [10] emphasized the importance of the c.m. motion of correlated pairs for explaining nucleon spectral functions at large momenta and removal energies.

In the longitudinal direction,

$$p_z^{\rm cm} = p_{nz} + p_{fz}. \tag{3}$$

By approximating $E_p \approx E_n \approx m$, we obtain

$$\alpha_p + \alpha_n = \left(1 - \frac{p_{fz}}{m}\right) + \left(1 - \frac{p_{nz}}{m}\right), \tag{4}$$

which leads to

$$p_z^{\rm cm} = 2m\left(1 - \frac{\alpha_p + \alpha_n}{2}\right). \tag{5}$$

The longitudinal momentum of the particles in their c.m. frame can be extracted from the difference of the α variables. Approximating $E_p \approx E_n \approx m$, we obtain

$$\alpha_p - \alpha_n = \left(1 - \frac{p_{fz}}{m}\right) - \left(1 - \frac{p_{nz}}{m}\right) = \left(\frac{p_{nz} - p_{fz}}{m}\right), \tag{6}$$

which leads to

$$p_z^{\rm rel} = m|\alpha_p - \alpha_n|. \tag{7}$$

Figures 4(a) and 4(b) are plots of $p_z^{\rm cm}$ and $p_z^{\rm rel}$. For $p_z^{\rm cm}$ in Fig. 4(a), the centroid is -0.013 ± 0.027 GeV/c. The spread in the distribution is $\sigma = 0.143 \pm 0.017$ GeV/c. For $p_z^{\rm rel}$ in Fig. 4(b), the centroid is 0.289 ± 0.017 GeV/c, and $\sigma = 0.097 \pm 0.007$ GeV/c.

An interesting number which can be extracted from our data is the fraction of $^{12}C(p, 2p)$ events which have correlated neutrons with $\mathbf{p}_n \approx -\mathbf{p}_f$ when $p_n, p_f \geq k_F$. To extract this number, we need to correct the measured neutron flux for neutron detection efficiency and flux attenuation, and for solid-angle coverage. Our neutron detectors were placed almost entirely in the backward hemisphere, so we calculate the fraction of 2π sr for the backward hemisphere covered by our detectors.

What we then calculated was

$$F = \frac{\text{corrected No. of}(p, 2p + n)\text{ events}}{\text{No. of}(p, 2p)\text{ events}} = \frac{A}{B} \tag{8}$$

for the same data sample. B was obtained by applying cuts (i), (ii), (iii), and (v) to events with $p_f \geq k_F$ for our 5.9 GeV runs excluding the data reported in [2]. The quantity $B = 2205$ then was all events satisfying the

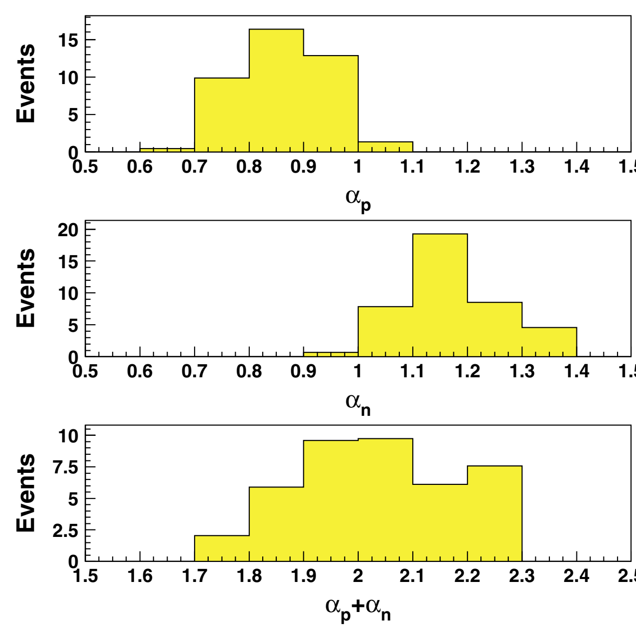

FIG. 3 (color online). Plots of the light-cone variables α_p, α_n, and their sum $\alpha_p + \alpha_n$ for events with $p_n > k_F = 0.22$ GeV/c. Data are for $^{12}C(p, 2p + n)$ events. Each event has been "s-weighted," as described in the text.

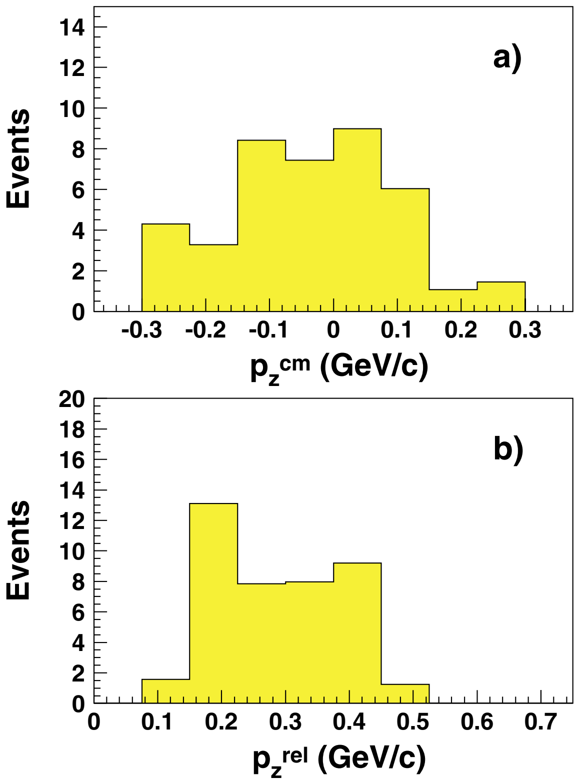

FIG. 4 (color online). Plots of (a) $p_z^{\rm cm}$ and (b) $p_z^{\rm rel}$ for correlated n-p pairs in ^{12}C, for ^{12}C$(p, 2p + n)$ events. Each event has been s-weighted, as described in the text.

above cuts and data selection. The quantity A was obtained from the sample of all 18 $(p, 2p + n)$ events in the sample B with $p_n \geq k_F$, where a correction for flux attenuation (t) [11] and for detection efficiency (ϵ) [12] was applied event by event. The resulting quantity was then corrected for the solid-angle coverage to obtain A:

$$A = \frac{2\pi}{\Delta\Omega} \sum_{i=1}^{18} \frac{1}{\epsilon_i} \frac{1}{t_i} = 1090. \quad (9)$$

The average value of $\epsilon_i^{-1} t_i^{-1}$ was 8.2 ± 0.82 and $2\pi/\Delta\Omega = 7.42$. We then obtain

$$F = \frac{A}{B} = 0.49 \pm 0.13. \quad (10)$$

The sample of 18 measured $(p, 2p + n)$ events is clearly small, and the uncertainty in F is determined largely by this sample size. The result is still compelling: roughly half of the measured quasielastic $(p, 2p)$ events with $p_f > k_F$ have a neutron emitted in the backward hemisphere with $p_n > k_F$. We note that this result is similar to that reported in [6] for hard inclusive $(p, 2p + n)$.

In summary, for quasielastic $(p, 2p)$ events we reconstructed $\mathbf{p}_f$, the momentum of the struck proton in ^{12}C before the reaction. Then, for neutrons with $p_n > 0.220$ GeV/c (which is k_F, the Fermi momentum for ^{12}C), we found a strong directional correlation for $\mathbf{p}_f$ and $\mathbf{p}_n$, namely, $\mathbf{p}_n \approx -\mathbf{p}_f$. By contrast, for $p_n < k_F$ we found no correlation. This was evident in the one-dimensional up-down and longitudinal correlations and the full three-dimensional correlation. For the longitudinal direction, where ISI and FSI effects should be small, we extracted the distributions of c.m. and relative motion for n-p pairs.

We conclude, therefore, that neutrons emitted into the backward hemisphere with $p_n > k_F$ come from n-p SRC, since SRC is a natural mechanism to explain such momentum-correlated pairs. An analysis of the events for 5.9 GeV/c beam momentum with $p_f > k_F$, indicates that $49 \pm 13\%$ of these events have a correlated neutron with $p_n > k_F$. Because this measured fraction includes only n-p and not p-p SRC, the total correlated fraction must be even larger. Therefore we conclude that 2N-SRC must be a major source of high-momentum nucleons in nuclei. We also measured the longitudinal components of the c.m. momentum of the correlated pn pair and the relative momentum of the pn pair in its c.m. system. Further applications of this technique are planned [13] at the Thomas Jefferson National Accelerator Facility.

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[1] Y. Mardor *et al.*, Phys. Lett. B **437**, 257 (1998).
[2] J. Aclander *et al.*, Phys. Lett. B **453**, 211 (1999).
[3] L. L. Frankfurt and M. I. Strikman, Phys. Rep. **76**, 215 (1981); **160**, 235 (1988).
[4] G. R. Farrar *et al.*, Phys. Rev. Lett. **62**, 1095 (1989).
[5] A. De Shalit and H. Feshbach, *Theoretical Nuclear Physics* (Wiley, New York, 1974).
[6] A. Malki *et al.*, Phys. Rev. C **65**, 015207 (2002).
[7] J. Y. Wu *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **349**, 183 (1994).
[8] E. J. Moniz *et al.*, Phys. Rev. Lett. **26**, 445 (1971).
[9] L. L. Frankfurt *et al.*, Phys. Rev. C **56**, 1124 (1997).
[10] C. Ciofi degli Atti *et al.*, Phys. Rev. C **44**, R7 (1991).
[11] D. J. Hughes and R. B. Schwartz, BNL Report No. 325, 1958.
[12] R. A. Cecil *et al.*, Nucl. Instrum. Methods **161**, 439 (1979).
[13] TJNAF experiment E01-015, E. Piasetzky, W. Bertozzi, J. W. Watson, and S. Wood, spokespersons, 2001.