Approaching the nucleon-nucleon short-range repulsive core via the $^4\text{He}(e,e'pN)$ triple-coincidence reaction.

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The experiment was performed in Hall A of Jefferson Laboratory (JLab) using a 4 μA electron beam with energy of 4.454 GeV incident on a high pressure (13 atm) 4He gas target at 20 K. The 20-cm long gas target had a density of 0.033 g/cm³, and was contained in an aluminum cylinder with a 4-cm radius.

The two Hall A high resolution spectrometers (HRS) [11] were used to identify 4He(e, e′p) events. Scattered electrons were detected in the left HRS (L-HRS) at a central scattering angle of 20.3° and momentum of 3.602 GeV/c. This setup corresponds to the quasi-free knockout of a single proton with transferred three-momentum |q| ≈ 1.64 GeV/c, transferred energy ω ≈ 0.86 GeV, the negative four-momentum transfer squared Q² = 2 (GeV/c)², and x_B = Q² / 2m_pω = 1.2, where m_p is the proton mass. Knocked-out protons were detected using the right HRS (R-HRS) which was set at 3 different central angles and momenta: (33.5°, 1.38 GeV/c), (29°, 1.3 GeV/c), and (24.5°, 1.19 GeV/c). These kinematical settings correspond to (e, e′p) central missing momenta (p_{miss} = p_p - q) values of 500 MeV/c, 625 MeV/c, and 750 MeV/c, respectively, and covering a missing-momentum range of 400 – 830 MeV/c, with overlap between the three different settings. The angle between q̂ and the recoil nucleus was 40 – 50°.

For highly correlated pairs, the missing momentum of the A(e, e′p) reaction is expected to be balanced almost entirely by a single recoiling nucleon. A large acceptance spectrometer (BigBite) followed by a neutron detector (HAND) with matching solid angles were used to detect correlated recoiling protons or neutrons. The layout of the experimental setup is schematically presented in Fig. [1].
reconstructed vertex from the two HRSs ensured that, for every event, both the electron and the proton emerged from the same place in the $^4$He target. A cut on the two-dimensional distribution of the $y$-scaling variable versus $\omega$ and a missing-mass cut were applied to remove the contribution from $\Delta(1232)$ excitation [14] (see appendix). With all these cuts applied, a data set of $^4$He($e,e'p$) events was generated, each with a measured missing momentum.

The recoiling protons were identified in BigBite using the measured energy loss in the $\Delta E$ - $E$ scintillator detectors, the measured time-of-flight (TOF), and the momentum reconstructed using the trajectory in the magnetic field. The momentum resolution of BigBite, determined from elastic electron-proton scattering, was $\Delta p/p = 1.5\%$. The overall proton detection efficiency was $73 \pm 1\%$, primarily due to the gaps between the scintillators and the tracking inefficiency of the wire chambers.

The pattern of hits in sequential layers of HAND was used to identify neutrons [15]. The momentum of the neutrons was determined using the measured TOF between the target and HAND. A time resolution of 1.5 ns allowed determination of the neutron momentum with an accuracy that varied from 2.5\% (at 400 MeV/$c$) to 5\% (at 830 MeV/$c$). The neutron detection efficiency was 40\%\textpm{}1.4\% for 400–830 MeV/$c$ neutrons. This determination is based on the efficiency measured up to 450 MeV/$c$ using the $d(e,e'p\gamma)$ reaction, and extrapolated using a simulation that reproduces well the measured efficiency at lower momenta [16].

Figure 2 shows the distribution of the cosine of the angle between the missing momentum and the recoiling neutrons ($\gamma$). We also show the angular correlation for the random background as defined by a time window off the coincidence peak. The back-to-back peak of the real triple coincidence events is demonstrated clearly. The curve is a result of a simulation of the scattering of a moving pair having a center-of-mass (CM) momentum width of 100 MeV/$c$ as discussed below. Similar back-to-back correlations were observed for the recoiling protons detected in BigBite. The timing peak shown in the insert of Fig. 2 is due to real triple coincidences and the flat background is due to random coincidences between the $^4$He($e,e'p$) reaction and neutrons in HAND. The signal to background ratio at the three kinematics setups were $1:2-2.5$.

Figure 3 shows the missing mass and energy for the $^4$He($e,e'pp$) reaction corresponding to a two-neutron residual system (see appendix for definitions). Taking into account the binding energy of the two protons, the excitation energy and the CM kinetic energy of the residual two-neutron system is relatively low, supporting the picture that they are essentially spectators in a reaction that breaks up a $pp$-SRC pair. Similar missing-energy and -mass distributions were obtained for the
FIG. 2. The distribution of the cosine of the opening angle $\gamma$ between the $p_{\text{miss}}$ and $p_{\text{recoil}}$ for the $p_{\text{miss}} = 625$ and 750 MeV/c kinematics combined. The histogram (dashed dotted, red online) shows the distribution of random events. The solid curve is a simulation of scattering off a moving pair with a CM momentum having a width of 100 MeV/c. The insert is the TOF spectrum for neutrons detected in HAND in coincidence with the $4\text{He}(e,e')$ reaction in the highest missing-momentum kinematics. The random background is shown as a dashed line.

FIG. 3. The background-subtracted missing-mass distribution for $4\text{He}(e,e'p)$ events. The insert represents the background-subtracted missing energy for the $4\text{He}(e,e'p)$ events. Note that subtracting the binding energy of the two protons leaves the two neutrons residual system with a low excitation energy.

$4\text{He}(e,e'p)$ reaction but with inferior resolution due to the lower momentum resolution for neutrons.

Software cuts were applied to both BigBite and HAND that limited their acceptances to $\pm14^\circ$ in the vertical direction, $\pm4^\circ$ in the horizontal direction, and $300 - 900$ MeV/c in momentum. We used a simulation based on the measurements to correct the yield of the $4\text{He}(e,e'pN)$ events for the finite acceptances of the recoiling protons and neutrons in Bigbite and HAND. Following Ref. [11], the simulations assume that an electron scatters off a moving SRC pair with a CM momentum relative to the $A - 2$ spectator system described by a Gaussian distribution as in [17]. We assumed an isotropic 3-dimensional motion of the pair and varied the width of the Gaussian motion equally in each direction until the best agreement with the data was obtained. The nine measured distributions (three components in each of the three kinematic settings for $np$ pairs) yield, within the uncertainties, the same width with a weighted average of $100 \pm 20$ MeV/c. This is in good agreement with the CM momentum distribution calculated in Ref. [11]. Figure 2 compares the simulated and the measured distributions of the opening angle between the knocked-out and recoiling nucleons. The fraction of events detected within the finite acceptance was used to correct the measured yield. The uncertainty in this correction was typically 15%, which dominates the systematic uncertainties of the $4\text{He}(e,e'pN)$ yield.

The measured $\frac{4\text{He}(e,e'pN)}{4\text{He}(e,e')}$ ratios are given by the number of events in the background-subtracted triple-coincidence TOF peak (as shown in the insert of Fig. 2) corrected for the finite acceptance and detection efficiency of the recoiling nucleons, divided by the number of random-subtracted double coincidence $4\text{He}(e,e'p)$ events. These ratios, as a function of $p_{\text{miss}}$ in the $4\text{He}(e,e'p)$ reaction, are displayed as full symbols in the two upper panels of Fig. 4. Because the electron can scatter from either proton of a $pp$ pair (but only from the single proton of an $np$ pair), we divided the $4\text{He}(e,e'p)$ yield by two. Also displayed in Fig. 4, as empty symbols with dashed bars, similar ratios for $^{12}\text{C}$ obtained from previous electron scattering [11, 12] and proton scattering [4] measurements. In comparing the $^{12}\text{C}$ and $4\text{He}$ data notice that there is a difference in the naive counting ratio of $Z(Z-1)$ between the two cases. The horizontal bars show the overlapping momentum acceptance ranges of the various kinematic settings. The vertical bars are the uncertainties, which are predominantly statistical.

Because we obtained the $4\text{He}(e,e'pp)$ and $4\text{He}(e,e'pn)$ data simultaneously and with the same solid angles and momentum acceptances, we could also directly determine the ratio of $4\text{He}(e,e'pp)$ to $4\text{He}(e,e'pn)$. In this ratio, many of the systematic factors needed to compare the triple-coincidence yields cancel out, and we need to correct only for the detector efficiencies. This ratio as a function of the missing momentum is displayed in the lower panel of Fig. 4, together with the previously measured ratio for $^{12}\text{C}$ [2].

To correct for final-state interactions (FSI), we calculated the attenuations of the leading and recoiling nucleons as well as the probability for single charge exchange (SCX) using the Glauber approximation [18]. To a good approximation the correction to the ratios due to the leading-proton attenuation is small. The attenuation of the recoiling nucleon decreases the measured
The number of Monte-Carlo wave functions derived from a realistic calculation for the ground states of the one standard deviation bands shown in Fig. 4. 

ident and combined by simulation to create the width of and the calculated corrections were treated as independent and systematic uncertainties of the measurements Fig. 4 as bands (see appendix for details). The statistical fluctuations is marked by white strips. Ratios for $^{12}$C are shown as empty symbols with dashed bars. The empty star in the upper panel is the BNL result [4] for $^{12}$C(p, 2p)/$^{12}$C(p, p). See text for a comment on the $^{12}$C/ $^4$He naive counting ratios.

The Glauber corrections ($T_L = 0.75$ and $T_R = 0.66 - 0.73$), with $T_L$ and $T_R$ the leading and recoil transparencies, were calculated by the Ghent group [18]. We assumed the uncertainties to be $\pm 20\%$ of these values. The probability for SCX ($P_{SCX}$) was assumed to be $1.5 \pm 1.5\%$ based on the SCX total cross section of $1.1 \pm 0.2$ mb [19]. The pair fraction extracted from the measured ratios with the FSI calculated corrections are shown in Fig. 4 as bands (see appendix for details). The statistical and systematic uncertainties of the measurements and the calculated corrections were treated as independent and combined by simulation to create the width of the one standard deviation bands shown in Fig. 4.

The two-nucleon momentum distributions were calculated for the ground states of $^4$He using variational Monte-Carlo wave functions derived from a realistic Hamiltonian with two- and three-nucleon potentials [10]. The number of pp-SRC pairs is much smaller than np-SRC pairs for values of the relative nucleon momentum $K_{rel} \approx 400$ MeV/c. This is because the correlations induced by the tensor force are strongly suppressed in the case of the pp pairs, which are mostly in a $^1S_0$ state [8–10, 20]. As the relative momenta increase, the tensor force becomes less dominant, the role played by the short-range repulsive force increases and with it the ratio of pp/np pairs. The solid (black) curve in Fig. 4 was obtained using the weighted average of the calculations [10] with arbitrary angles between $\vec{K}_{rel}$ and $\vec{K}_{CM}$, the CM momentum or the pair. The calculation with $K_{CM} = 0$, which agrees quantitatively with the Perugia group calculation [20], is very little different from the average shown in the figure. To compare the calculations to the data in Fig. 4 we assumed that the virtual photon hits the leading proton and $p_{miss} = K_{rel}$ (PWIA).

To summarize, measurements reported here facilitate the isospin decomposition of the 2N-SRC in the high-momentum tail of the nucleon momentum distribution. The small, relatively constant measured $^4$He($e, e'pp$)/$^4$He($e, e'p$) ratio reflects a small contribution from pp-SRC pairs, most probably dominated by the repulsive short-range force. The large $^4$He($e, e'pn$)/$^4$He($e, e'p$) ratio clearly shows np-SRC dominance. The observed reduction in the fraction of measured 2N-SRC contribution to the total ($e, e'p$) re-
moval strength as a function of the missing momentum can be due to increasing FSI and/or the onset of 3N-SRC [5]. A definitive conclusion on the relative contribution of these effects requires a more detailed theoretical study.

The missing-momentum dependence of the $^4\text{He}(e,e'p)/^4\text{He}(e,e'n)$ ratio, and the $^4\text{He}(e,e'pp)/^4\text{He}(e,e'pn)$ ratio, which agree well with the calculated ratio of $pp$-SRC / $np$-SRC pairs in the ground state, reflect the transition from tensor force dominance to the repulsive force domain as the nucleon’s momenta increase. Comprehensive calculations, which take into account the full reaction mechanism in a relativistic treatment, as well as additional data with better statistics will allow a more detailed determination of the role played by the elusive repulsive short-range nucleon-nucleon interaction.

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Appendix

To extract the SRC pair ratios $\#pp/\#np$, $\#pp/\#p$, and $\#np/\#p$ from the measured cross-section ratios $(R = \frac{^4\text{He}(e,e'p)/^4\text{He}(e,e'p)}{^4\text{He}(e,e'n)/^4\text{He}(e,e'n)})$, $R1 = \frac{^4\text{He}(e,e'p)/^4\text{He}(e,e'p)}{^4\text{He}(e,e'e'p)/^4\text{He}(e,e'e'p)}$, $R2 = \frac{^4\text{He}(e,e'p)/^4\text{He}(e,e'n)}{^4\text{He}(e,e'e'p)/^4\text{He}(e,e'e'p)}$ we assumed factorization and used the equations A.1-A.3 listed below:

$$\frac{\#pp}{\#np} = \frac{T_L \cdot R - P_{SCX} \cdot \sigma_{en}}{2 \cdot T_L - 2 \cdot P_{SCX} \cdot \sigma_{en} \cdot R}$$

$$\frac{\#pp}{\#p} = \frac{R_1 \cdot \sigma_{en} / T_L \cdot P_{SCX} \cdot T_R - R_2 \cdot T_R}{2 \cdot (\sigma_{en} / T_L \cdot P_{SCX} \cdot T_R)^2 - 2 \cdot T_R^2}$$

$$\frac{\#np}{\#p} = \frac{R_2 - 2 \cdot \#pp / \#p \cdot T_R}{\sigma_{en} / T_L \cdot P_{SCX} \cdot T_R},$$

where $\sigma_{en}$ is the cross section for electron scattering off the proton (neutron) [21].

The expression for missing mass is:

$$M_{miss} = \sqrt{(\omega + M_A - E_f - E_{rec})^2 - (p - p_f - p_{rec})^2}.$$  \hspace{1cm} (A.4)

$M_A$ is the mass of $^4\text{He}$ and the mass of the deuteron when applying the $\Delta(1232)$ cut. $E_f$ and $p_f$ ($E_{rec}$ and $p_{rec}$) are the energy and momentum of the knocked-out proton (recoil nucleon). The missing energy is given by:

$$E_{miss} = \omega - T_p - T_{rec} - T_B,$$ \hspace{1cm} (A.5)

where $T_p$, $T_{rec}$, and $T_B$ are the kinetic energy of the knocked-out proton, recoil partner and remaining $A - 2$ system, respectively.

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