Two-Nucleon Momentum Distributions Measured in $^3\text{He}(e,e'pp)n$

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We have measured the $^3\text{He}(e,e'pp)n$ reaction at 2.2 GeV over a wide kinematic range. The kinetic energy distribution for ‘fast’ nucleons ($p > 250$ MeV/c) peaks where two nucleons each have 20% or less, and the third nucleon has most of the transferred energy. These fast $pp$ and $pn$ pairs are back-to-back with little momentum along the three-momentum transfer, indicating that they are spectators. Experimental and theoretical evidence indicates that we have measured distorted two-nucleon momentum distributions by striking the third nucleon and detecting the spectator correlated pair.

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The independent particle mean-field model of the nuclear wave function is a surprisingly good approximation. Among other successes, it describes the shapes of the single-nucleon momentum distributions in nuclei as measured by $(e,e'p)$ nucleon knockout reactions. However, discrepancies between the measured and calculated magnitudes suggest that two-nucleon knockout processes, especially those involving two-nucleon $(NN)$ short range correlations, are important. These short distance nucleon pairs are primarily responsible for the high momentum components of the nuclear wave function.

In addition, recent $A(e,e')$ measurements and theoretical calculations indicate about a five times higher probability per-nucleon to find an $NN$ pair with large relative momentum and small total momentum (i.e.: in a short range correlation) in nuclei ($A \geq 12$) than in deuterium. We also know that nucleons in nuclei overlap each other a significant fraction of the time. Taken together, these imply that we now need to understand correlated $NN$ pairs, the next term in the mean-field expansion of the nuclear wave function.

Unfortunately, measuring the momentum distribution of these $NN$ correlations directly is very difficult because their signals are frequently obscured by effects such as final state interactions (FSI) and two body currents, which include meson exchange currents (MEC) and isobar configurations (IC). To date, there have been only a few measurements of $(e,e'pp)$ or $(e,e'np)$ two nucleon knockout from nuclei. The effects of correlations can only be inferred from these experiments by comparing them to detailed calculations which include both $NN$ correlations and two body currents. However, ‘exact’ ($e.g.$: Faddeev) calculations are only possible for light nuclei at low energies.

The published definitions of Short Range Correlations (SRC) vary, frequently referring to the difference between a mean field wave function and an exact wave function. This paper will use an experimental definition of an SRC as an $NN$ pair with large relative momentum and small total momentum.

This paper reports new $^3\text{He}(e,e'pp)n$ results that provide a cleaner measurement of two-nucleon momentum distributions. Measuring these momentum distributions will greatly aid our understanding of Short Range Correlations.

We measured 2.261 GeV electron scattering from $^3\text{He}$, using a 100% duty factor beam at currents between 5 and 10 nA incident on a 4.1-cm long liquid $^3\text{He}$ target. We detected almost all outgoing charged particles in the Jefferson Lab CLAS (CEBAF Large Acceptance Spectrometer), a nearly $4\pi$ magnetic spectrometer. These measurements were part of the ‘e2’ run group that took data in Spring 1999.

The CLAS uses a toroidal magnetic field and six independent sets of drift chambers and time-of-flight scintillation counters for charged particle identification and trajectory reconstruction. Momentum coverage extends down to 0.25 GeV/c for protons over a polar angular range of $8^\circ < \theta < 140^\circ$ while spanning nearly 80% of the azimuth. Electron triggers are formed from the coincidence of a gas threshold Čerenkov counter and a sampling electromagnetic calorimeter (EC). Software fiducial cuts exclude regions of non-uniform detector response, while acceptance and tracking efficiencies are estimated using GSIM, the CLAS GEANT Monte-Carlo simulation.

We identified electrons using the total energy deposited...
in the EC, and protons using time-of-flight. We identified the neutron using missing mass to select $^3$He$(e,e'pp)n$ events. We used vertex cuts to eliminate the target walls. Figures 1a and b show the electron acceptance ($Q^2 = -q_\mu q^\mu = \vec{q}^2 - \omega^2$ is the square of the four-momentum transfer, $\omega$ is the energy transfer, and $\vec{q}$ is the three-momentum transfer) and undetected neutron missing mass resolution, along with the result from a $^3$He$(e,e'pp)n$ GSIM simulation that includes detector resolution but not electron radiation. For $^3$He$(e,e'pp)n$ events, the momentum transfer $Q^2$ is concentrated between 0.5 and 1 (GeV/c)$^2$. The energy transfer, $\omega$, is concentrated slightly above but close to quasielastic kinematics ($\omega = Q^2/2m_p$).

We checked the data normalization by comparing $^3$He$(e,e'p)$ cross sections measured here and in Jefferson Lab Hall A [15] at the same energy and momentum transfer ($\vec{q} = 1.5$ GeV/c and $\omega = 0.837$ GeV). The ratio of our cross sections to the Hall A cross sections was 1.00 ± 0.15, where the error bar is due primarily to kinematical uncertainties.

In order to understand the energy sharing in the reaction, we plotted the kinetic energy of the first proton divided by the energy transfer ($T_{p1}/\omega$) versus that of the second proton ($T_{p2}/\omega$) for each event (Figure 2). (Note that the assignment of protons 1 and 2 is arbitrary.) Since the threshold for proton detection is $p_p = 250$ MeV/c, we also cut on neutron momentum $p_n \geq 250$ MeV/c. There are three peaks at the three corners of the plot, corresponding to events where two nucleons each have less than 20% of the energy transfer and the third ‘leading’ nucleon has the remainder. We call the two nucleons ‘fast’ because $p > 250$ MeV/c is larger than the average nucleon bound-state momentum. We cut on these peaks, as indicated by the lines in Figure 2. The solid lines indicate the ‘leading n, fast pp pair’ cut and the dashed lines indicate the ‘leading p, fast pn pair’ cut.

Then we looked at the opening angle of the two fast nucleons. Figure 3 shows the opening angle for fast pp pairs with a leading neutron (the opening angle distribution of fast pn pairs for events with a leading proton is almost identical). Note the large peak at 180° (cos $\theta_{NN} \approx -1$). The peak is not due to the cuts, since we do not see it in a simulation which assumes three-body absorption of the virtual photon followed by phase space decay [16]. It is also not due to the CLAS acceptance since we see it for both fast pp and fast pn pairs. This back-to-back peak is a very strong indication of correlated NN pairs.

Now that we have identified correlated pairs, we want to study them. In order to reduce the effects of final
state rescattering, we cut on the perpendicular component (relative to $\vec{q}$) of the leading nucleon’s momentum, $p^+ < 0.3 \text{ GeV/c}$. The resulting fast $NN$ pair opening angle distribution is almost entirely back-to-back (see Figure 3). These fast nucleons are distributed almost isotropically in angle (after correcting for the CLAS acceptance). The pair average total momentum parallel to $\vec{q}$ ($< \vec{p}_{\text{tot}} >$) is also much smaller than the average $q$ ($< q >$) $\approx 1 \text{ GeV/c}$.

Both of these indicate that the paired nucleons are predominantly spectators and that their measured momentum distributions reflect the pair’s initial momentum distribution in the nucleus.

The resulting relative $\vec{p}_{\text{rel}} = (\vec{p}_1 - \vec{p}_2)/2$ and total $\vec{p}_{\text{tot}} = \vec{p}_1 + \vec{p}_2$ momentum distributions of the $pn$ and $pp$ pairs are shown in Figure 4. Since the $NN$ pairs are spectators, all quantities and cross sections are given in the lab frame. The cross sections are integrated over the experimental acceptance. Radiative and tracking efficiency corrections have been applied \[17\]. The overall normalization uncertainty is 15%.

The PWIA calculation reduced by a factor of 6 \[18\], thick dashed histogram shows Laget’s one-body calculation \[19\ \& \ 20\], thin dot-dashed histogram shows Laget’s full calculation; a) the same for the fast $pn$ pair. Points show the data, solid histogram shows the PWIA calculation (see Figure 5a) by Sargsian \[18\] that uses an exact $^3\text{He}$ wave function \[22\] and the De Forest ‘cc1’ single nucleon current \[23\]. We generated events in phase space, weighted them by the PWIA cross section, and applied the same cuts as with the actual data. The results are reasonably close (considering the simplicity of the model) to the data except for a scale factor. The data distributions have similar shapes, including the virtual photon distribution, the kinetic energy distributions, and the fast pair opening angles. The relative momentum distributions are similar but have a different detailed shape (see the solid histograms in Figure 4). The PWIA total momentum distribution peaks significantly below the data. These discrepancies will be discussed below.

The relative momentum distribution rises rapidly starting at about 0.25 GeV/c (limited by the minimum nucleon momenta of 0.25 GeV/c), peaks at about 0.35 GeV/c, and has a tail extending to about 0.7 GeV/c. The total momentum distribution rises rapidly from 0, peaks at about 0.25 GeV/c, and falls rapidly. The momentum distributions have an upper limit determined by the cut $T_{\text{fast}} < 0.2\omega$. Note that these distributions are very similar for both $pp$ and $pn$ pairs.

![FIG. 5: Feynman diagrams for a) Plane Wave Impulse Approximation and b) pair distortion.](image)

We also compared our data to a Plane Wave Impulse Approximation (PWIA) calculation (see Figure 5a) by Sargsian \[18\] that uses an exact $^3\text{He}$ wave function \[22\] and the De Forest ‘cc1’ single nucleon current \[23\]. We generated events in phase space, weighted them by the PWIA cross section, and applied the same cuts as with the actual data. The results are reasonably close (considering the simplicity of the model) to the data except for a scale factor. The data distributions have similar shapes, including the virtual photon distribution, the kinetic energy distributions, and the fast pair opening angles. The relative momentum distributions are similar but have a different detailed shape (see the solid histograms in Figure 4). The PWIA total momentum distribution peaks significantly below the data. These discrepancies will be discussed below.

Table I shows the integrated cross sections. The PWIA cross section is on average about five times larger than the data for both $pp$ and $pn$ pairs. Note that the ratio of $pn$ to $pp$ cross sections is approximately the same for data (3.0) and for PWIA (2.9) indicating the importance

| Cross Section (pb) | $pp$ | $pn$ |
|-------------------|------|------|
| Data              | 4.4±0.1| 13.4±0.2|
| Laget 1-body      | 3.3  | 9.9  |
| Laget Full        | 4.2  | 18.6 |
| PWIA              | 20.7 | 60.5 |
| PWIA / Data       | 4.8  | 4.5  |

TABLE I: Cross sections integrated over the CLAS acceptance. The normalization uncertainty (systematic uncertainty) of the data is 15%. The calculations are described in the text.
of single particle knockout in the reaction mechanism.

Exact calculations by W. Glöckle et al. at much lower momentum transfer and $p_{tot} = 0$ looked at the effects of different reaction mechanisms. They found that neither MEC nor rescattering of the leading nucleon had an effect, and that the continuum state interaction of the outgoing $NN$ pair (‘pair distortion’ – diagram b of Figure 5) decreased the cross section by a factor of approximately 10 relative to the PWIA result. Calculations by C. Ciofi degli Atti and L. Kaptari also found that pair distortion significantly decreased the cross section\textsuperscript{25}.

Calculations by Laget (described in detail below) also showed these effects. His calculation further showed that pair distortion reduces the PWIA cross section for $s$-wave $NN$ pairs much more than for $p$-wave pairs, effectively shifting both the $p_{rel}$ and $p_{tot}$ peaks to higher momentum. Laget’s one-body $p_{tot}$ distribution peaks at about 250 MeV/c, much larger than the PWIA $p_{tot}$ peak and in better agreement with the data (see the thick dashed curve in Figure 4b and d).

Thus, these calculations suggest that the factor of five difference between the data and the PWIA calculation (Figure 5a) is due to the continuum state interaction of the outgoing $NN$ pair (‘pair distortion’ – Figure 5b). That plus the rough similarity between the data and the PWIA calculation indicates that we may have measured two-nucleon momentum distributions by striking the third nucleon and observing the spectator correlated pair.

We also compared our data to a full calculation using a diagrammatic approach by Laget\textsuperscript{19, 20, 21}, integrated over the CLAS acceptance\textsuperscript{20}. This calculation includes one-, two- and three-body amplitudes. The one-body amplitudes include diagrams with two spectator nucleons including direct knockout (Figure 5a) plus continuum state interaction of the spectator $NN$ pair (pair distortion (Figure 5b)). The two-body amplitudes include diagrams with one spectator nucleon including FSI between the struck nucleon and one other plus two-body MEC and IC\textsuperscript{21}. The three-body amplitudes include diagrams with no spectator nucleons including three-body MEC and IC\textsuperscript{13}. The calculation uses the dominant $s$- and $p$-waves for the $T = 1$ pairs and $s$- and $d$-waves for the $T = 0$ pairs that are then coupled to the third nucleon in the bound state wave function. The model made absolute predictions and was not adjusted to fit the data.

The one-body calculations describe the $pn$ pairs well, both qualitatively and quantitatively (see Figures 6a and b). However, the full calculation overestimates the data by about 60%. The calculation describes $p_{rel}$ for $pp$ pairs badly but $p_{tot}$ well (see Figures 6a and d). The failure is due possibly to the truncation of the wave function to only the lower angular momentum states. Note that Laget predicts three-body effects to be much larger for events with a leading proton and a fast $pn$ pair than for events with a leading neutron and a fast $pp$ pair. We do not see this difference in the data.

Comparison of the results of Laget’s calculations with the data shows that (1) the continuum state interaction of the outgoing $NN$ pair decreases the cross section significantly relative to the PWIA result, and by supressing the $s$-wave, shifts the peak to larger momenta, (2) two-body currents (MEC and IC) plus rescattering of the leading nucleon contribute less than 5% of the cross section, and (3) three-body currents contribute about 20% of the $pp$ and 50% of the $pn$ cross section, but do not improve agreement with the data.

These results reinforce the conclusions we drew from the data that we are measuring the high momentum part of the distorted $NN$ momentum distribution. Note however, that since two-body currents do not contribute, the only other possible contributions are due to three-body currents, also a subject of great interest.

Detailed calculations with exact wave functions are clearly needed in order to quantitatively relate the measured distorted $NN$ momentum distributions to Short Range Correlations in the nucleus.

To summarize, we have measured the $^3$He$(e, e'pp)n$ reaction at 2.2 GeV over a wide kinematic range. The kinetic energy distribution for ‘fast’ nucleons ($p > 250$ MeV/c) peaks where two nucleons each have 20% or less and the third or ‘leading’ nucleon carries most of the transferred energy. These fast nucleon pairs (both $pp$ and $pn$) are back-to-back, almost isotropic, and carry very little momentum along $q$, indicating that they are predominantly spectators.

PWIA calculations reproduce the observed $pp$ to $pn$ cross section ratio, indicating the importance of single-nucleon knockout mechanisms. Calculations by Laget with many different diagrams and a truncated bound state wave function predict that leading-nucleon FSI and two-body exchange currents are negligible, and continuum-state interactions of the spectator pair reduce the cross section significantly. However, the predicted three-body exchange current contributions of about 20% for $pp$ pairs and 50% for $pn$ pairs do not improve agreement with the data.

Thus experimental and theoretical evidence indicates that we have measured distorted $NN$ momentum distributions in $^3$He$(e, e'pp)n$ by striking the third nucleon and detecting the spectator correlated pair.

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