Two nucleon correlations measured with $^3\text{He}(e,e'pp)n$

L.B. Weinstein and R. Niyazov, for the CLAS Collaboration
Old Dominion University, Norfolk, VA 23529, USA

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Abstract. Despite tremendous progress in recent years in measuring single nucleon momentum distributions in nuclei, two-nucleon momentum distributions remain largely unmeasured. Here we report on a measurement of $^3\text{He}(e,e'pp)n$ that is primarily sensitive to the two-nucleon momentum distribution and relatively uncontaminated by final state rescattering or by two-body currents.

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1 Introduction

Single nucleon properties in nuclei have been thoroughly studied, primarily through proton knockout from nuclei, such as $O(e,e'p)$ [1]. The valence proton momentum distributions and more deeply bound proton momentum and energy distributions have been measured by many experiments [2]. Valence knockout is well described by single nucleon knockout calculations that include the effects of final state interactions. However, the fact that a) we only see about 70% of the ‘expected’ number of nucleons and b) there is a large cross section at large excitation energies of the residual nucleus indicates that multi-nucleon processes play a significant role. While there have been many $(e,e'p)$ measurements from nuclei, there have been very few $(e,e'pp)$ measurements.

There are two general sources of two-nucleon knockout from nuclei. One source is the interaction of the virtual photon with two nucleons, typically through meson exchange currents or isobar configurations. This is referred to as a two-body current. The second one is the interaction of the virtual photon with one nucleon of a ‘correlated pair’. (Note that the distinction between correlations [in the wave function] and currents [in the operator] is blurred by the fact that unitary transformations can transform one into the other.)

A correlated pair is typically a pair of nucleons that have large relative momentum (because they are at short range) and small total momentum. Thus, one signature of correlations is finding two nucleons with large relative momentum and small total momentum in the initial state. Unfortunately, the effects of $NN$ correlations are frequently obscured by the effects of two body currents [3]. In order to disentangle these competing effects, a series of comprehensive measurements are needed.

Fig. 1. a $Q^2$ vs $\omega$ for $^3\text{He}(e,e'pp)n$ at $E_{beam} = 2.2$ GeV. Note the huge kinematic acceptance. b Missing mass for $^3\text{He}(e,e'pp)$. We cut at the indicated lines to select $(e,e'pp)n$ events.

The seven experiments took data simultaneously in Spring 1999, measuring approximately 500 million $A(e,e'X)$ events, using the CEBAF Large Acceptance Spectrometer (CLAS) at Jefferson Lab, a $4\pi$ magnetic spectrometer, with 1.16, 2.26 and 4.46 GeV polarized electrons incident on targets from $^3\text{He}$ to $^{56}\text{Fe}$ [4]. This paper reports the results from 2.2 and 4.4 GeV electrons on $^3\text{He}$.

2 Measuring $^3\text{He}(e,e'pp)n$

We studied $^3\text{He}(e,e'pp)n$ by measuring electron induced two proton knockout reactions from $^3\text{He}$ using the CLAS detector and cutting on the missing mass. Figures 1a and b show the electron acceptance and undetected neutron missing mass resolution for $E_{beam} = 2.2$ GeV. The threshold of the CLAS is approximately 250 MeV/c for protons.

Because this is the first time that $^3\text{He}(e,e'pp)n$ has been measured using an almost $4\pi$ detector, our data anal-
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**Fig. 2.** a Nucleon kinetic energy distribution for 2.2 GeV $^3\text{He}(e,e'pp)n$. The kinetic energy of proton 1 divided by $\omega (T_p^1/\omega)$ is plotted versus the same for proton 2. (Note $p_p \geq 250$ MeV/c.) Note the dominant band running from (1,0) to (0,1) corresponding to very low energy neutrons. b The cosine of the opening angle between the two protons for events with $p_n < 250$ MeV/c. Note the large peak at 90°

In order to understand the energy sharing in the reaction, we plotted the kinetic energy divided by the energy transfer of the first proton ($T_p^1/\omega$) versus that of the second proton ($T_p^2/\omega$) for each event (a lab-frame Dalitz plot). Note that the assignment of protons 1 and 2 is arbitrary. See Fig. 2a. The threshold for proton detection in CLAS is $p_p \geq 250$ MeV/c. The dominant feature of this plot is a band running from the upper left corner (proton 1 has almost all of the energy) to the lower right (proton 2 has almost all of the energy) corresponding to very low energy neutrons. When we cut on this ridge, requiring that $p_n < 250$ MeV/c, the opening angle between the two protons peaks at 90° (see Fig. 2b). As we know from teaching introductory physics, when a moving object collides elastically with an identical stationary object, the opening angle is always 90°. Thus, this peak indicates single proton knockout followed by hard $pp$ rescattering.

Further evidence for this comes from preliminary data from Zhang [6]. He analyzed the same $^3\text{He}(e,e'pp)n$ data with $p_n < 150$ MeV/c, looking at events with a fast backward proton ($\theta_{pq} > 100°$). See Fig. 3. It was conjectured that these fast backward protons could not have been affected by final state interactions (FSI). However, calculations by Laget show that the cross section is dominated by final state interactions with significant contributions from two-body currents (meson exchange currents and isobar configurations). These results are very consistent with the 90° peak in the $pp$ opening angle distribution.

Since we are looking for two-nucleon correlations, we eliminate these FSI-dominated events by setting the same threshold for neutrons as for protons: $p_n \geq 250$ MeV/c. When we look at this Dalitz plot (see Fig. 4), we see three peaks at the three corners of the plot, corresponding to events where two ‘fast’ 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 $p \gg p_{fermi}$. These peaks are much more pronounced at $E_{beam} = 4.4$ GeV (not shown). We cut on these peaks where the two fast nucleons each have less than 20% of the energy transfer.

Then we looked at the opening angle of the two fast nucleons. Figure 5-a shows the pair opening angle for fast
Points = data, histogram = PWIA decreased by a factor of 5.

Fig. 6. 2.2 GeV $^3$He(e, e'pp)n cross section vs. momentum. Points = data, histogram = PWIA decreased by a factor of 5. 

a) leading proton and a fast pn pair: pair relative momentum $p_{rel}$; b) leading proton and a fast pn pair: total momentum $p_{tot}$; c) leading neutron and a fast pp pair: $p_{rel}$; d) leading neutron and a fast pp pair: $p_{tot}$

3 Studying correlated pairs

Now consider these presumably correlated pairs. Since we believe that we have observed events where the leading nucleon absorbed the virtual photon and the two fast nucleons are emitted back to back, we cut on the perpendicular momentum of the leading nucleon to deemphasize rescattering ($p_\perp < 300$ MeV/c). This cut selects the back-to-back events very cleanly. Unfortunately, there are only 3400 fast pn and 1100 fast pp events remaining in the entire 2.2 GeV data set (and ten times fewer at 4.4 GeV).

If the fast back-to-back $NN$ pairs are really uninvolved in the photon absorption, then they should be distributed isotropically (the angular distribution of the neutrons with respect to $q$ is shown in Fig. [5]). Further evidence that the fast $NN$ pair is a spectator comes from the average momentum of the pair along $q$. This is about 0.07 GeV/c for $E_{beam} = 2.2$ GeV and about 0.1 GeV/c for $E_{beam} = 4.4$ GeV, much less than the average momentum transfers of $Q^2 = 0.7$ and $1.4$ (GeV/c)$^2$ respectively.

The 2.2 GeV fast $NN$ pair relative ($p_{rel} = \frac{1}{2}|p_1 - p_2|$) and total ($p_{total} = |p_1 + p_2|$) momentum distributions are shown in Fig. [6]. Note how similar the $pp$ and $pn$ distributions are. The 4.4 GeV distributions (not shown) are similar.

Thus, because when we select a quasifree leading nucleon, the fast $NN$ pairs are back to back, relatively isotropic and have small average momentum along $q$, we conclude that the fast $NN$ pair is a spectator.
4 Comparison to theory

Calculations by W. Glöckle [7] at lower energy strengthen this conclusion. He calculated the $^4\text{He}(e,e'\text{pp})\text{n}$ cross section where the leading nucleon has momentum $\mathbf{p}_N = \mathbf{q}$ and the other two nucleons have total momentum $p_{\text{total}} = 0$ for various values of the momentum transfer, $400 \leq |\mathbf{q}| \leq 600$ MeV/c, and relative momentum. He found that MEC did not contribute, rescattering of the leading nucleon did not contribute, and the continuum state interaction of the outgoing $NN$ pair decreased the cross section by a factor of approximately 10 relative to the PWIA result. Thus, he found that this reaction is a very clean way to measure the overlap integral between the $NN$ continuum state and the same two nucleons in the bound state.

C. Ciofi degli Atti and L. Kaptari also found that the continuum interaction of the outgoing pair significantly decreased the cross Sect. [8].

We compared our results to two other calculations, 1) a Plane Wave Impulse Approximation (PWIA) calculation by M. Sargsian [9] using Glöckle’s bound state wave function with no final state interactions, and 2) a diagrammatic calculation by J.-M. Laget [10][11][12] using a Faddeev wave function from P. Sauer and including one-, two-, and three-body mechanisms as well as rescattering terms. We averaged all of the models over the CLAS acceptance and cuts using a monte carlo.

The PWIA calculation of Sargsian has $Q^2$ vs $\omega$, $NN$ pair opening angle, $p_{\text{rel}}$, and $p_{\text{total}}$ distributions that are consistent with the data (see Fig. 10). The momentum distributions peak at smaller momentum than the data. This is probably due to a much stronger $NN$-pair continuum interaction in the $NN$ s-wave than in the p-wave. This interaction therefore reduces the s-wave strength more than the p-wave, shifting the peaks to higher momenta. The PWIA cross section is a factor of 5 larger than the data which is consistent with the expected effects of the $NN$ continuum state interaction calculated by Glöckle, by Ciofi degli Atti and by Laget. It also predicts the same ratio of $pp$ to $pn$ pairs as seen in the data.

Laget’s one-body calculation describes the $pn$ pairs well, both qualitatively and quantitatively (see Fig. 16 and b). However, the full calculation overestimates the data by about 60%. The calculation describes $p_{\text{rel}}$ for $pp$ pairs badly but $p_{\text{total}}$ well (see Fig. 7 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.

5 Summary

We have studied the $^4\text{He}(e,e'\text{pp})\text{n}$ reaction, selecting events where one nucleon has most of the kinetic energy and has less than 300 MeV/c of momentum perpendicular to $\mathbf{q}$. When we do this, we see isotropic, back-to-back, fast $NN$ pairs with small average momentum along $\mathbf{q}$. We have measured the total and relative momentum distributions of these pairs and found that they do not depend significantly on isospin ($pp$ vs $pn$ pairs) or on momentum transfer.

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, by measuring $^4\text{He}(e,e'\text{pp})\text{n}$, we appear to have directly measured $NN$ correlations without any significant contamination from other processes by striking the third nucleon and detecting the spectator correlated pair.

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References

9. M. Sargsian: Private communication