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NN correlations measured in ^{3}He(e, e′pp)n

L.B. Weinstein[a] and R. Niyazov

For the CLAS Collaboration
Physics Department, Old Dominion University, Norfolk, VA 23529, USA

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Abstract. We have measured the $^3\mathrm{He}(e,e'pp)n$ reaction in the Jefferson Lab CLAS with 2.2 and 4.4 GeV electrons. We looked at the energy distribution of events with all three nucleons at high momentum ($p > 250$ MeV/c). This distribution has peaks where two nucleons each have 20% or less of the energy transfer (*i.e.*, the third or "leading" nucleon carries most of the kinetic energy). The angular distribution of these two "fast" nucleons shows a very large back-to-back peak, indicating the effect of correlations. While there is some theoretical disagreement, experimental evidence, plus calculations at lower energy by W. Glöckle, indicates that these events are primarily sensitive to NN correlations.

PACS. 21.45.+v Few-body systems – 25.30.Dh Inelastic electron scattering to specific states

1 Introduction

The single-nucleon energy and momentum distributions in nuclei have been thoroughly measured by nucleon knockout, pickup and stripping reactions. The shapes of these distributions, although not their magnitudes, are well described by mean-field impulse approximation calculations. The discrepancies between the measured and calculated magnitudes indicate that nucleon-nucleon correlations are an important part of the nuclear wave function. To date, there have been almost no measurements of correlated NN momentum distributions in nuclei.

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, such as meson exchange currents (MEC) and isobar configurations (IC) [1]. In order to disentangle these competing effects, a series of comprehensive measurements are needed.

In order to provide this, we measured electron scattering from nuclei, $A(e,e'X)$, using the Jefferson Lab CLAS (CEBAF Large-Acceptance Spectrometer), a 4π magnetic spectrometer. The CLAS Multihadron run group comprised of seven experiments ran in Spring 1999, measuring approximately 500 million events with 1.1, 2.2 and 4.4 GeV polarized electrons incident on targets from ^{3}He to ^{56}Fe.

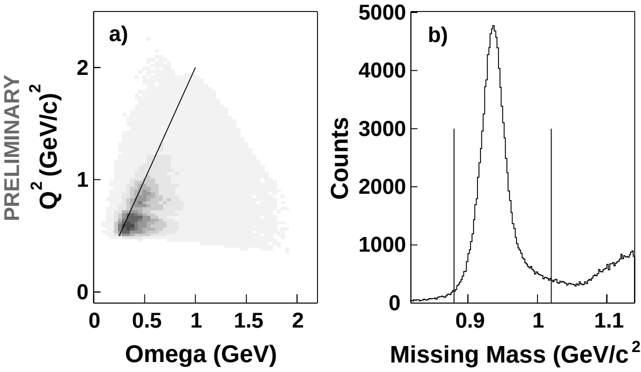

Fig. 1. a) Q^2 *vs.* ω for $^3\mathrm{He}(e,e'pp)n$ at $E_{\mathrm{beam}} = 2.2$ GeV. Note the huge kinematic acceptance. b) Missing mass for $^3\mathrm{He}(e,e'pp)$. We cut at the indicated lines to select $(e,e'pp)n$ events.

This paper will concentrate on the results from the $^3\mathrm{He}(e,e'pp)n$ reaction which exhibit a strong signature for NN correlations.

2 The ^{3}He(e, e′pp)n measurements

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

Note that all data shown here are *preliminary*.

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[a] e-mail: `weinstei@physics.odu.edu`

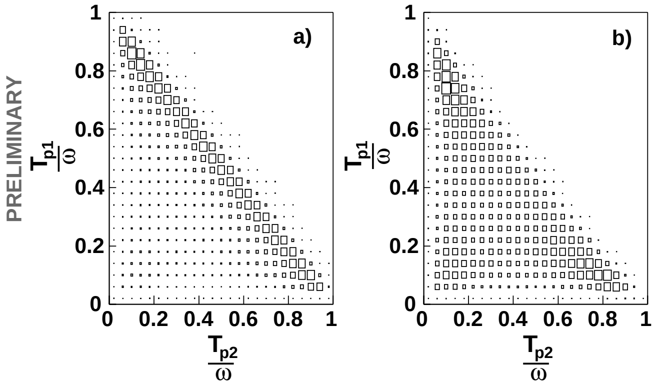

Fig. 2. Nucleon kinetic-energy distribution for 2.2 GeV $^3\mathrm{He}(e,e'pp)n$. The kinetic energy of proton 1 divided by ω is plotted against the kinetic energy of proton 2 divided by ω. The threshold for proton detection is $p \geq 250$ MeV/c. a) All events; b) events where $p_n > 250$ MeV/c. Note the peaks in the corners.

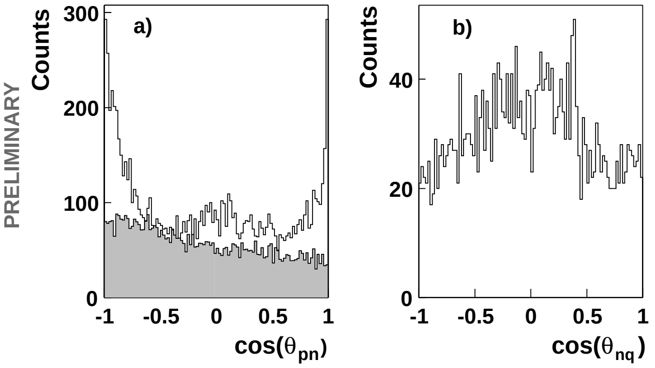

Fig. 3. a) Opening angle of the fast pn pairs for events in the upper left and lower right corners of fig. 2b. The backward-peaked histogram shows the data, the filled histogram shows the results of a fire ball phase space simulation assuming three-body absorption of the virtual photon and phase space decay (with arbitrary normalization). b) The angle between the neutron in the fast pn pair and $\mathbf{q}$, where $p_\perp < 300$ MeV/c.

Because this is the first time that $^3\mathrm{He}(e,e'pp)n$ has been measured using an almost 4π detector, our data analysis philosophy is to follow and understand the dominant features of the data.

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_{p1}/ω) *vs.* that of the second proton (T_{p2}/ω) for each event (a lab-frame Dalitz plot). When we did this, the dominant feature is a ridge running from the upper left corner (proton 1 has all the energy) to the lower left corner (proton 2 has all the energy) corresponding to events where the two protons share the energy transfer and the neutron is a low-momentum "spectator" (see fig. 2a). When we cut on this ridge, we see that the opening angle of the two protons has a large peak at 90°, indicating that it is due primarily to hard final-state rescattering (*i.e.*, photon absorption on one proton followed by billiard ball rescattering on the second proton).

Since we are not interested in final-state rescattering, we eliminated those events and focussed on events where all three nucleons have momentum greater than 250 MeV/c (fig. 2b). In this case 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 $p \gg p_{\mathrm{fermi}}$. These peaks are much more pronounced at $E_{\mathrm{beam}} = 4.4$ GeV (not shown). We cut on these peaks where the two fast nucleons each have less than 20% of the energy transfer and where all three nucleons have $p > 250$ MeV/c.

Then we looked at the opening angle of the two fast nucleons. Figure 3a shows the pair opening angle for fast pn pairs with a leading proton. Note the large peak at 180 degrees ($\cos\theta_{NN} \approx -1$). The distribution for fast pp pairs with a leading proton is identical. The peak is not due to the cuts, since we do not see it in a fire ball phase space simulation assuming three-body absorption of the virtual photon and phase space decay. It is also not due to the CLAS acceptance since we see it both for leading protons (which we detect) and leading neutrons (which we infer from missing mass). This back-to-back peak is a strong indication of correlated NN pairs.

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 de-emphasize 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. You can see this in the angular distribution of the neutrons with respect to $\mathbf{q}$ (see fig. 3b). Further evidence that the fast NN pair is uninvolved in absorbing the virtual photon comes from the average momentum of the pair along $\mathbf{q}$. This is about 0.07 GeV/c for $E_{\mathrm{beam}} = 2.2$ GeV and about 0.1 GeV/c for $E_{\mathrm{beam}} = 4.4$ GeV, much less than the average momentum transfers of $Q^2 = 0.7$ and 1.4 $(\mathrm{GeV}/c)^2$, respectively.

The fast NN pair relative ($p_{\mathrm{rel}} = \frac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$) and total ($p_{\mathrm{total}} = |\mathbf{p}_1 + \mathbf{p}_2|$) momentum distributions are shown in figs. 4a) and b) for fast pn pairs at $E_{\mathrm{beam}} = 2.2$ GeV. The distributions (not shown) are very similar for both pn and pp pairs at both $E_{\mathrm{beam}} = 2.2$ and 4.4 GeV.

Thus, because when we select a quasifree leading nucleon the fast NN pairs are:

- back to back,
- isotropic and
- have small average momentum along $\mathbf{q}$,

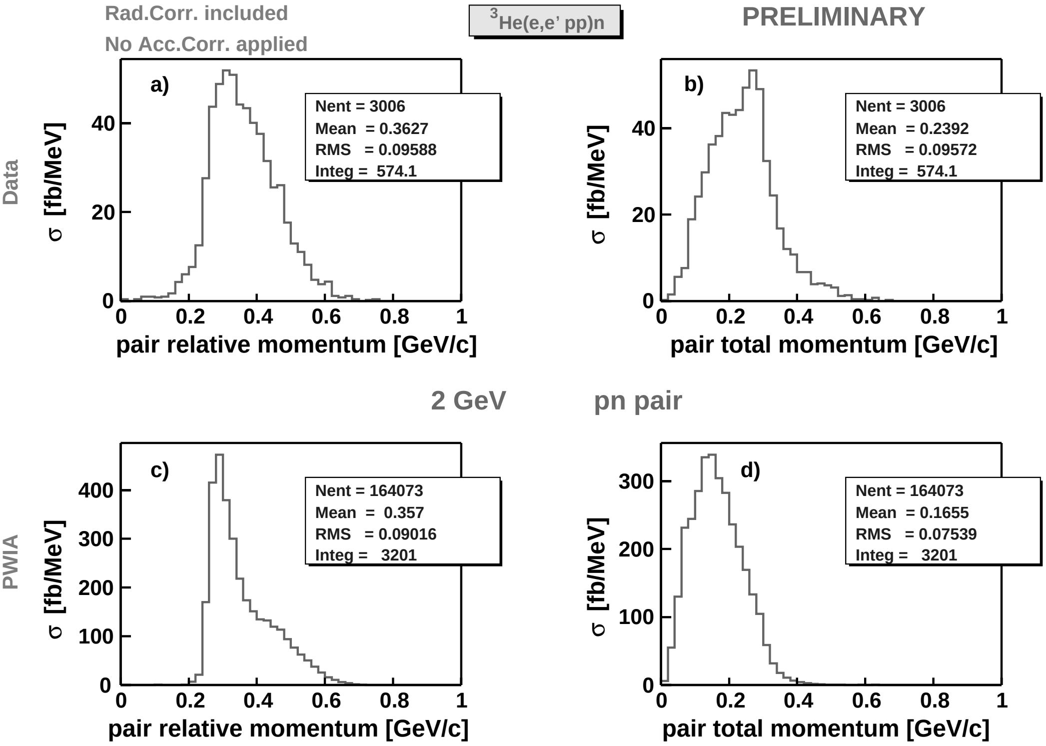

Fig. 4. Cross-section for events with a leading proton and a fast pn pair at $E_{\text{beam}} = 2.2$ GeV. a) Data: relative momentum; b) Data: total momentum; c) PWIA: relative momentum; d) PWIA: total momentum.

we conclude that the fast NN pair is not involved in absorbing the virtual photon. Because we measure similar total- and relative-momentum distributions for

- pp and pn pairs and
- $0.5 < Q^2 < 1$ ($E_{\text{beam}} = 2.2$ GeV) and $1 < Q^2 < 2$ (GeV/c)^2 ($E_{\text{beam}} = 4.4$ GeV),

we conclude that we have measured bound-state NN correlations.

We appear to have measured NN correlations in ^{3}He by striking the *third* nucleon and detecting the correlated pair. This is similar to other proposed correlation searches where you strike one nucleon of a correlated pair and detect the other nucleon leaving the nucleus. However, these other searches suffer from the weakness that their proposed signal can also be due to two-body currents (*e.g.*, photon absorption on an exchanged meson).

4 Comparison to theory

Calculations by W. Glöckle [2] at lower energy strengthen this conclusion. He calculated the ^{3}He$(e,e'pp)n$ 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

1. MEC did not contribute,
2. rescattering of the leading nucleon did not contribute, and
3. 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.

We compared our results to three other calculations, 1) a plane-wave impulse approximation (PWIA) calculation by M. Sargsian [3] using Glöckle's bound-state wave function with no final-state interactions, 2) a calculation by J.-M. Laget [4] using a Faddeev wave function from P. Sauer and including one-, two-, and three-body mechanisms as well as rescattering terms, and 3) a home-made model of pion production on the struck proton followed by pion absorption on the remaining pn pair. We averaged all of the models over the CLAS acceptances and cuts using a Monte Carlo.

The pion production and rescattering model used pion production cross-sections from the MAID parametrization [5], pion absorption on deuterium from the SAID parametrization [6], and proton initial momentum distributions in ^{3}He from $(e,e'p)$ measurements [7]. This model failed in several key respects. While it did produce a large back-to-back peak in the NN angular distribution (since a soft pion transfers a lot of energy but very little momentum), a) the average energy transfer was much larger than the data (typical of the $\Delta(1232)$), b) the relative-momentum distribution was too large (since the minimum relative energy $E_{\mathrm{rel}} = m_\pi$), and c) the ratio of the number of fast *pn* pairs to fast *pp* was much lower than the data (1 instead of 3). Thus, while this mechanism might be very important for other three-nucleon knockout experiments, it does not explain this data.

Preliminary calculations from Laget describe the kinetic-energy, relative-momentum and total-momentum distributions very well, both qualitatively and quantitatively. They indicate that one-body knockout plus rescattering cannot describe the data and that three-body mechanisms are needed. However, the virtual-photon distribution in this calculation is significantly different from the data (peaked in the delta region rather than the quasielastic), indicating a different reaction mechanism.

The PWIA calculation of Sargsian has Q^2 *vs.* ω, NN pair opening angle, and relative- and total-momentum distributions that are consistent with the data (see fig. 4c, d). It is a factor of 6 larger than the data which is consistent with the expected effects of the NN continuum state interaction calculated by Glöckle. However, it predicts 5 *pn* pairs for each *pp* pair *vs.* 3 in the data and it predicts a ratio of 4 for $\sigma(E_{\mathrm{beam}} = 2.2)/\sigma(E_{\mathrm{beam}} = 4.4)$ *vs.* 11 for the data.

More calculations are clearly needed to resolve these discrepancies.

5 Summary

We have studied the ${}^3\mathrm{He}(e, e'pp)n$ 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 many features of the data. Calculations by Glöckle at lower energy indicate that the cross-section depends primarily on the overlap integral between the continuum state and bound state of the NN pair. Neither meson exchange currents nor the final-state rescattering of the leading nucleon appear to contribute to the cross-section. However, calculations by Laget indicate that three-body mechanisms are required. More theoretical work is needed to resolve these issues.

Thus, by measuring ${}^3\mathrm{He}(e, e'pp)n$, we might 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

1. S. Janssen *et al.*, Nucl. Phys. A **672**, 285 (2000).
2. W. Glöckle, in *Proceedings of the 5th Workshop on Electromagnetically Induced Two-Hadron Emission, Lund, Sweden, 2001*, edited by P. Grabmayr (Lunds Universiteit, 2001).
3. M. Sargsian, private communication.
4. G. Audit *et al.*, Nucl. Phys. A **614**, 461 (1997); J.M. Laget, J. Phys. G **14**, 1445 (1988).
5. D. Drechsel, O. Hanstein, S.S. Kamalov, L. Tiator, Nucl. Phys. A **645**, 145 (1999); nucl-th/9807001. Available at `http://www.kph.uni-mainz.de/MAID/maid2000/maid2000.html`.
6. C.H. Oh, R.A. Arndt, I.I. Strakovsky, R.L. Workman, Phys. Rev. C **56**, 635 (1997).
7. E. Jans *et al.*, Nucl. Phys. A **475**, 687 (1987).