Short range correlations in nuclei*

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Abstract Studying nucleon-nucleon (NN) correlated pairs will teach us a great deal about the high momentum part of the nuclear wave function, the short range part of the NN interaction, and the nature of cold dense nuclear matter. These correlations are similar in all nuclei, differing only in magnitude. High momentum nucleons, $p > p_{\mathrm{fermi}}$, all have a correlated partner with approximately equal and opposite momentum.

At pair relative momenta of $300 < p_{\mathrm{rel}} < 500$ MeV/c, these correlated pairs are dominated by tensor correlations. This is shown by the dominance of pn over pp pairs at pair total momentum and by the parity of pn to pp pairs at large pair total momentum.

Key words correlations, nucleon momentum distributions, tensor correlations

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1 Introduction

Nucleon-nucleon (NN) Correlations are a crucial part of understanding the nucleus. Studying these correlated pairs will teach us a great deal about the high momentum part of the nuclear wave function, the short range part of the NN interaction, and the nature of cold dense nuclear matter. These correlated pairs are responsible for the high momentum part of the nuclear wave function.

A correlated nucleon is one where the momentum of the nucleon is balanced by the momentum of one and only one other nucleon (rather than by the total momentum of the $A-1$ other nucleons). These two nucleons form a correlated pair with small total momentum and large relative momentum.

Measurements of the ratios of electron scattering cross sections of nuclei to deuterium and ^{3}He all scale for $1.5 < x_{\mathrm{B}} < 2$ (for $Q^2 > 1.5$ GeV^2). This shows that the high momentum distribution has the same shape for all nuclei and that it is therefore due to short range correlations (which would be the same for all nuclei) and not to the mean field (which differs). The probability that a nucleon belongs to a correlated pair is at least 20% for nuclei heavier than carbon [1–3].

These measurements also saw clear evidence for the presence of 3N correlations, where the momentum of one nucleon is balanced by two other nucleons. The probability of these correlations is much smaller, at about 1%. They will not be discussed further in this talk.

Understanding correlations could also help us understand phenomena as diverse as neutron star cooling and the EMC effect.

2 Experimental results

There are two general types of measurements of correlated pair distributions in nuclei. In the first type of experiment, the probe scatters from a high momentum nucleon in the nucleus. The scattered probe and the knocked out nucleon are detected. In addition, a detector is placed to detect a possible correlated partner of the knocked out nucleon. In the second type of experiment, the probe scatters from a nucleon in ^{3}He and the experimenter studies the disintegration of the spectator correlated pair.

The two types of experiment have very different theoretical uncertainties and thus complement each other well. In the first type of experiment, it is very important to understand the final state interactions of the ejected nucleon and the possible effects of two-body currents (meson exchange currents or nucleon excitations). In the second type of experiment it is

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very important to understand the continuum interaction of the spectator nucleons.

2.1 Hitting the correlated pair

A C(p,ppn) measurement at EVA/BNL was the first experiment to show that high momentum nucleons have correlated partners and low momentum nucleons do not [4]. A high energy incident proton knocked out a proton from the nucleus and a neutron was also detected. Low momentum neutrons were emitted isotropically. High momentum ($p > 275$ MeV/c) neutrons were emitted entirely backward from the proton missing momentum (which is equal to the proton initial momentum in the absence of final state interactions). This indicates that neutrons of momentum greater than 275 MeV/c are members of correlated pairs.

Recent measurements at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) have provided much more information about these short range correlations. Experiments in Jefferson Lab Hall A measured electron scattering from carbon, detecting the scattered electron and the knocked out proton in the two High Resolution Spectrometers and looking for the associated correlated nucleon in the BigBite spectrometer and neutron wall. The experiment was performed at incident energy $E_0 = 4.6$ GeV, momentum transfer $Q^2 = 2$ GeV^2, momentum fraction $x_{\mathrm{B}} = Q^2/2m\omega = 1.2$ (where ω is the energy transfer), and proton momentum $p_{\mathrm{p}} \approx 1.4$ GeV/c. The missing momentum (the momentum transfer minus the proton momentum, $\vec{p}_{\mathrm{miss}} = \vec{q} - \vec{p}_{\mathrm{p}}$) ranged from 300 to 600 MeV/c.

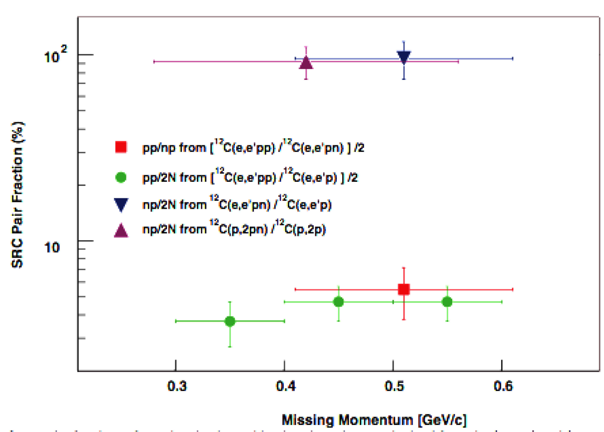

Fig. 1. (color online) The fractions of correlated pair combinations as obtained from (e, e′pp), (e, e′pn) and (p, ppn) measurements.

They measured the probability that the knocked-out proton was accompanied by a correlated nucleon, either a proton or a neutron (see Fig. 1). They found that 96% ± 23% of high-missing-momentum protons had an associated correlated neutron [5] and that 9.5%±2% of high-missing-momentum protons had an associated correlated proton [6]. The neutron probability is consistent with that measured at EVA/BNL (92% ± 18%).

These measurements show that all high-missing-momentum protons have an associated correlated nucleon, i.e., that all high momentum nucleons are members of correlated pairs. They also showed that, at relatively low correlated pair total momenta, these pairs are dominated by pn pairs (see Fig. 2).

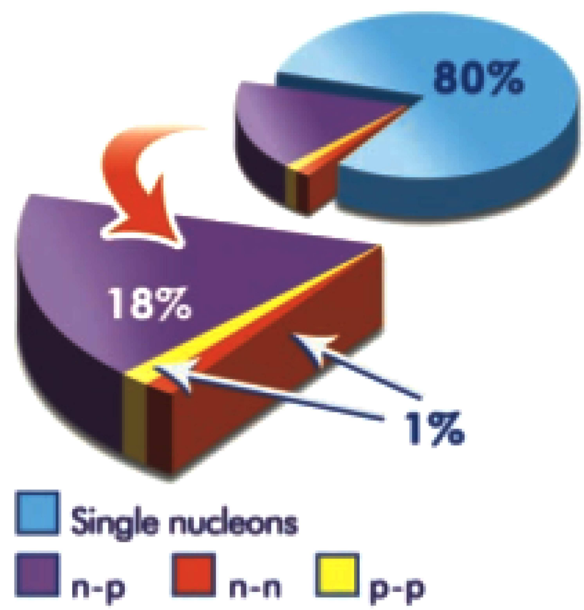

Fig. 2. (color online) The average fraction of nucleons in the various initial state configurations of ^{12}C.

Thus, this experiment lets us describe the initial state configuration of ^{12}C as roughly 80% single nucleon, 18% np pairs, and 1% each pp and pn pairs [5].

2.2 Spectator correlated pairs

Recent experiments using the CEBAF Large Acceptance Detector (CLAS) [7] in Jefferson Lab's Hall B scattered electrons from a range of nuclei, detecting almost all charged particles with momenta $p > 250$ MeV/c. Analysis has concentrated on the ^{3}He(e, e′pp)X reaction at incident electron energies of 2.2 and 4.7 GeV [8].

We identified ^{3}He(e, e′pp)n events through missing mass. Unlike the small aperture spectrometer experiments of Hall A, these measurements covered a wide range in energy and momentum transfer, with $0.5 < Q^2 < 2$ GeV^2 and $1 < Q^2 < 4$ GeV^2 at incident energies of 2.2 and 4.7 GeV respectively. The events were centered at $x_B \approx 1$, but with a large spread.

When we looked at events where all three nucleons have $p > 250$ MeV/c, we see clear peaks in the three corners of the lab-frame Dalitz plot (see Fig. 3). We cut on those three peaks to select events with a leading proton and a pn pair or with a leading neutron and a pp pair. The opening angle of the NN pair has a significant peak at $\cos\theta_{NN} = -1$ or $\theta_{NN} = 180°$ (see Fig. 4). This back-to-back peak is significant evidence for correlations.

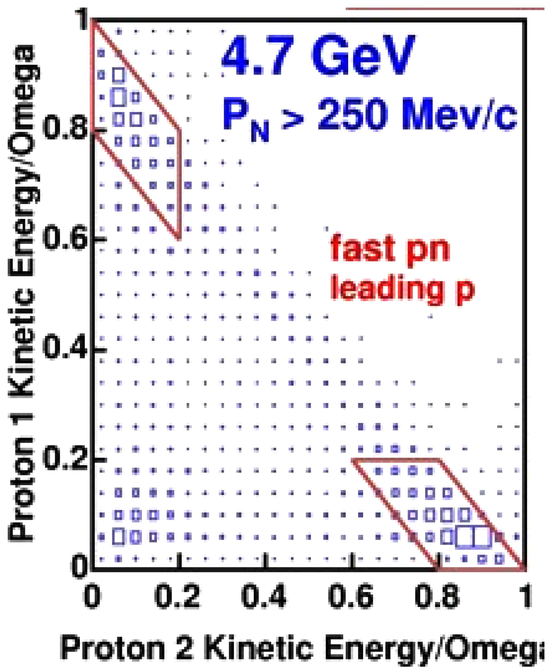

Fig. 3. (color online) Lab frame Dalitz plot for ^{3}He(e, e′pp)n at $E_0 = 4.7$ GeV. The horizontal and vertical axes show the kinetic energy of each proton divided by the energy transfer. (The assignment of protons one and two was arbitrary.) The red boxes indicate the cuts to select events with a leading proton and a pn pair.

In order to reduce the effects of rescattering of the leading nucleon we then required that the leading nucleon have momentum perpendicular to the momentum transfer, $p_{\rm perp}^{\rm leading} < 300$ MeV/c. When we do this, the resulting NN pairs are almost entirely back to back (see Fig. 4).

There are two pieces of evidence that these correlated pairs are spectators to the knockout reaction. The total momentum of the pair parallel to the momentum transfer $p_{\parallel}^{\rm tot}$ is much smaller than the momentum transfer and agrees with one-body calculations. In addition, the neutron in the correlated pair is distributed almost isotropically.

Now that we have measured spectator correlated pairs, we can construct the pair relative and total momentum distributions. The relative momentum rises at about 250 MeV/c, peaks between 350 and 400 MeV/c, and is very small at about 600 MeV/c. (Note that the minimum relative momentum is determined by the fact that $p_N > 250$ MeV/c and that the opening angle peaks at 180°.) The total momentum distribution rises from zero, peaks at about 250 to 300 MeV/c, and then drops to zero by 500 MeV/c. The momentum distributions are very similar for both pp and pn pairs and for both $E_0 = 2.2$ and 4.7 GeV. The pn to pp ration is about four, much less than the corresponding result from ^{12}C.

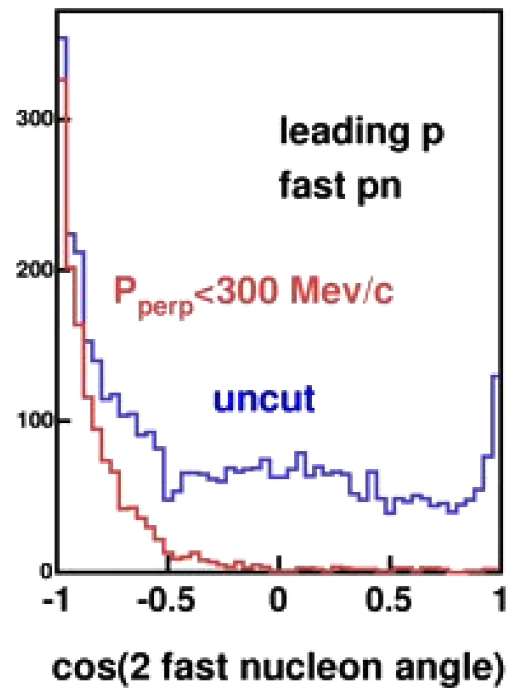

Fig. 4. (color online) The cosine of the opening angle of the pn pair for ^{3}He(e, e′pp)n events with a leading proton. The solid blue (upper) histogram shows all events, the solid red (lower) histogram shows events with $p_{\rm perp}^{\rm leading} <$ 300 MeV/c.

Calculations including free knockout of one nucleon and the continuum interaction of the spectator pair by Golak [9] and by Laget [10] show that the continuum interaction of the spectator pair significantly decreases the contribution from s-wave pairs and significantly decreases the reaction cross section. However, neither calculation describes the data more than qualitatively.

2.3 Tensor correlations

In order to develop a coherent understanding of the ^{3}He spectator correlated pair and the ^{12}C struck correlated pair data, we calculated the ratio of pp to pn pairs as a function of pair total momentum, $p_{\rm tot}$, for pairs with $300 < p_{\rm rel} < 500$ MeV/c. Note that the ratio is very small at small total momentum, consistent with the previous measurements at Hall A and BNL, and the ratio increases to the pair counting expectation (1/2) at large pair total momentum. See Fig. 5.

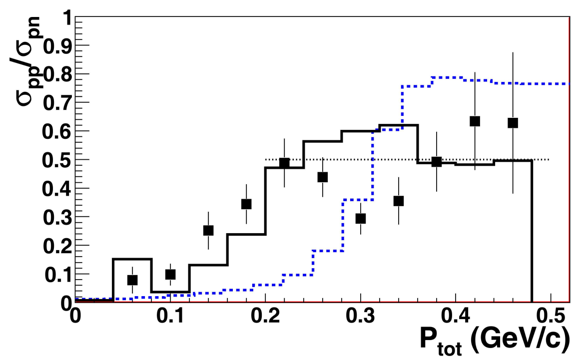

Fig. 5. (color online) The ratio of pp to pn cross sections for ^{3}He(e, e′pp)n as a function of pair total momentum, $p_{\rm tot}$, for $300 < p_{\rm rel} < 500$ MeV/c. The points are the data, the solid black histogram is the one-body calculation by Golak, averaged over the experimental acceptances, and the dashed blue histogram is the ratio of the pp to pn momentum distributions. The data have been scaled by the ratio of the electron-proton to electron-neutron elementary cross sections, to reflect the cross section for interacting with the struck nucleon.

The ratio of pp and pn cross sections from the one-body calculation by Golak averaged over the experimental acceptances agrees with data. This calculation does not include final state interactions of the knocked out nucleon or meson exchange currents. It does calculate the continuum interaction of the spectator correlated pair exactly. This is important, because that interaction decreases the cross section by approximately an order of magnitude. Note that the calculation describes the cross section ratio much better than it does the individual cross sections.

The simple ratio of the momentum distributions for pp and pn pairs in the ^{3}He ground state does not describe the data. While it is small at small $p_{\rm tot}$ and increases at large $p_{\rm tot}$, its shape is quite different from the data.

The agreement of the one-body calculation with the data ratio also gives us confidence that we are measuring spectator correlated pairs.

This is a strong signal for the dominance of tensor correlations. At small $p_{\rm tot}$, the pp wave function is predominantly s-wave. This has a minimum at $p_{\rm rel} \approx 400$ MeV/c. This minimum in the pn wave function is filled in by tensor forces [11–13], leading to a small ratio of pp to pn (or alternatively, a large ratio of pn to pp).

As the pair total momentum increases, the minimum in the pp wave function naturally fills in, increasing the ratio of pp to pn. Finally, at large $p_{\rm tot}$, the ratio of pp to pn pairs is 0.5, consistent with the number of pp and pn pairs in ^{3}He.

2.4 Neutron star cooling

Correlations can contribute significantly to neutron star cooling. A classical neutron star consists of fermi gases of electrons, protons and neutrons. It should cool predominantly by the Urca process where a neutron decays to a proton, electron and neutrino and a proton can combine with an electron to produce a neutron and a neutrino.

At low temperatures, the fermi spheres are almost filled, reducing the probability of Urca processes. However, correlations could cause larger holes in the fermi spheres, enhancing this process by large factors and speeding neutron star cooling [14].

3 Summary

We have learned a tremendous amount about short range correlations in the last few years.

1) Short Range Correlations (SRC) are universal and have the same momentum distribution for all nuclei. The probability that a nucleon is part of a SRC ranges from 5% in deuterium to 25% in iron.

2) Correlated nucleons in a pair have their momentum balanced by only one other nucleon. When a correlated nucleon is knocked out, its partner is also emitted.

3) SRCs are predominantly pn pairs at low pair total momentum (at intermediate pair relative momentum ($300 < p_{\rm rel} < 500$ MeV/c). At higher pair total momentum, pn and pp pairs contribute about the same. This shows the dominance of tensor correlations at these relative momenta.

4) We have measured pair relative and total momenta in ^{3}He by hitting the third nucleon and measuring the spectator correlated pairs.

In the near future we will extend these measurements to larger relative momenta to study central correlations and access higher densities. In the longer term, experiments at 12 GeV at Jefferson Lab will measure whether the EMC effect is due to correlated nucleons.

Improved knowledge of short range correlations will provide valuable insight into neutron stars, cold dense nuclear matter, the short distance behavior of nucleons and possibly even quark effects in nuclei.

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