Understanding Nucleons in the Nuclear Medium

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Abstract. Recent cross section (e,e’pN) short-range correlation experiments have clearly shown the strong dominance of tensor correlations for (e,e’p) missing momenta greater than the Fermi momentum; while recent ²H(e,e’p)n and ⁴He(e,e’p)t asymmetry experiments at low missing momentum have shown small changes from the free nucleon form factor. By doing asymmetry experiments as a function of missing momentum, these results can be linked together and observed as a change of sign in the measured asymmetry. This idea will be presented within the context of the recently completed Jefferson Lab Hall A quasi-elastic, polarized ³He(e,e’N) experiments (N=0,p,n,d) where the asymmetries of several reaction channels were measured with three, orthogonal target-spin directions. Together, these various experiments will help us to better understand nucleons in the nuclear medium.

Keywords: short-range correlations, tensor correlations, medium modifications
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INTRODUCTION

Early independent particle model calculations, while nicely predicting the inelastic energy levels in nuclei, dramatically over predicted the occupation density of these states as measured in (e,e’p) experiments [1, 2]. A spectroscopic factor of 60-70% was needed to bring the model and the data into agreement. The simplest explanation for the discrepancy was that something that doesn’t effect the general shell-structure was taking strength away from the predicted states. This is generally agreed to be caused by the correlations between the nucleons in the nucleus and is illustrated in Fig. 1. As is shown, since the overall strength must be a constant, the effect of these correlations is to decrease the strength at low missing momentum and increase the strength at high missing momentum relative to a independent-particle model.

Experimentally, the signature of a nucleon-nucleon correlations should be seen as knocked-out, back-to-back nucleons with relative momenta much greater then the Fermi momentum of around 250 MeV/c. Unfortunately, many reaction mechanisms such as Meson Exchange Currents (MEC) and/or Final State Interactions (FSI) have this same final-state and thus complicate trying to probe for initial-state correlations. While Jefferson Lab’s higher beam energy and high Q² was thought to be a solution to this problem, the initial Jefferson Lab knock-out reaction data from two- and few-body systems at high missing-momentum were also sensitive to these reactions mechanisms [3, 4, 5, 6], though it was also clear that corrections were a needed ingredient to explain the observed cross sections.
The solid line is an approximate momentum distribution of the nucleon in $^3$He based on the data from Benmokhtar et al. [3]. The inflection in the solid line above the Fermi momentum (approximately 250 MeV/c) is due to tensor and short-range correlations between the nucleons in the nucleons. The dashed line shows an independent-particle model distribution, which is larger at low momentum but continues to fall-off exponentially at high momentum.

**RECENT PROGRESS**

**Cross Section Measurements**

Recent pair knock-out measurements have observed a very strong dominance of proton-neutron pairs over proton-proton pairs. This was first seen at Brookhaven where a proton beam was used as the probe [7] and then at Jefferson Lab where an electron beam was used as the probe [8, 9]. Unlike most observables, the dominance of back-to-back high-momentum proton-neutron pairs can be explained neither by MEC nor FSI but instead is attributed by several theory groups to initial-state tensor correlations [10, 11, 12, 13]; thus, this observation is finally a clean signature of an initial-state correlations.

The effect of these same correlations has also become clear in inclusive scattering. This is done by making ratios of inclusive (e,e') cross section as a function $x_B$ with $x_B = Q^2/2m\omega$ where $Q^2$ is the square of the four-momentum transferred to the system, $m$ is the mass of a nucleon, and $\omega$ is the energy transfer. For $Q^2$ greater than 1 [GeV/c]$^2$, one can observe clear scaling in the $x_B > 1$ cross section ratio; a phenomenon known as...
y-scaling. This was originally reported in SLAC data [14] and later with higher precision CLAS inclusive data [15]. By taking the ratios to $^3$He instead of deuterium, the CLAS experiments were able to not only show two-nucleon correlations from a scaling in the $1 < x_B < 2$ region [15], but also possible three-nucleon correlations by showing a second scaling in the $2 < x_B < 3$ region [6].

### Asymmetry Measurements

As one considers these correlations in terms of an exactly calculable two-body system, the strong tensor correlations are associated with the d-state of the deuteron’s wavefunction. As pointed out by Friar [16], wave functions are not observables; but if one clearly defines the basis, it is possible to calculate a d-state probability for a given momentum distribution. In this spirit, it has been clearly shown within a model, such as Arenhövel et al.’s [17], one can predict the polarized beam-target asymmetry for proton knock-out from vector polarized deuterons as a function of missing momentum. Such models and experiments have shown that at low missing momentum the asymmetry is primarily due to the s-state of the nucleon-nucleon potential used in the model, whereas the high missing momentum asymmetry is primarily due to the d-state of the nucleon-nucleon potential used in the model [18]. Polarization transfer experiments done at low missing momentum on the $^4$He(e,e’p)$^3$H reaction have also not seen a large effect at low missing momentum [19].

### THREE-BODY SYSTEM

At Mainz, the $^3$He(e,e’pn)p cross section has recently been measured and again shows the dominance of the proton-nucleon reaction (tensor-correlations) in the momentum range above the Fermi momentum [20]. Interestingly, the Faddeev calculations using AV-18 or Bonn-B nucleon-nucleon potentials over-estimate the magnitude of the $^3$He(e,e’pn)p cross section at low missing momentum. While from this experiment alone it is hard to say why there is a discrepancy, it is clear that there is still more physics going on then in these very up-to-data calculations.

Complimenting this new cross section result, an extensive series of quasi-elastic polarized $^3$He measurements have been made at Jefferson Lab for a $Q^2$ of 0.2, 0.5 and 1.0 [GeV/c]$^2$ with the polarized target’s spin oriented in three orthogonal directions [21, 22, 23]. These experiments used the two Hall A High Resolution Spectrometers (HRS) [24], the BigBite magnet [25, 26] with a customized hadron detector package for identification of protons and deuterons, and the 3 m high, 0.4 m deep, and 1 m wide Hall A Neutron Detector (HAND) that was used for the $^{12}$C(e,e’pn) experiment [9]. With this combination of detectors, it was possible to measure the (e,e’), (e,e’p), (e,e’n), and (e,e’d) data simultaneously. This experiment was completed during the summer of the 2009, and analysis is now underway. By measuring so many reaction channels over a large range in $Q^2$, it is hoped that we will be able to dramatically improve our understanding of the three-body system.
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