3N Short-Range Correlations

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1 Executive Summary

The existence of 2N short-range correlations (2N-SRCs) [1] has been confirmed by a number of experiments at SLAC [2] and Jefferson Lab [3–6]. Many results have come from A/D cross section ratios of quasielastic scattering at $x > 1$ and modest Q^2 values. In these kinematics, mean field contributions are expected to be negligible, and the scattering probes two-body physics - pairs of nucleons with large, back-to-back momenta, associated with interaction via the strong, short-distance part of the NN potential. The inclusive measurements revealed this universal behavior across all nuclei as expected in kinematics dominated by SRCs [7, 8], and mapped out the contribution of 2N-SRCs in a range of light and heavy nuclei. Additional measurements demonstrated dominance of *np* pairs in these SRCs [9–12]. Additional measurements, mainly triple-coincidence A(e,e'pN) experiments [9–11], and more recently with inclusive measurements from nuclei with differing N/Z values [12, 13], have studies the isospin structure of 2N-SRCs, demonstrating significant enhancement of np-SRCs relative to nn- and pp-SRCs.

In addition to predicting the dominance of 2N-SRCs at sufficiently large x and Q^2 values, the SRC model [2] also presented the possibility that at larger x and Q^2 value, the 2N-SRC contributions may become small enough that three-nucleon (3N) SRCs may dominate. In this case, a similar universal behavior would lead to a Q^2-independent plateau in the nuclear cross section ratio somewhere above $x = 2$.

Existing searches for 3N-SRCs have yet to provide any significant evidence of the expected x and Q^2 independence of the target ratios above the region dominated by 2N-SRCs. Recent works [14, 15] make predictions for the onset of large 3N-SRC contributions, which are just beyond the reach of existing high-precision data. Nonetheless, cross sections in the region where 3N-SRCs are expected to dominate are consistent with the strength predicted in this approach, although the data precision is very limited.

We propose a measurement with a number of targets in the 3N-SRC scaling kinematics to: (1) establish Q^2 independence required by the SRC picture by observing scaling at more than one scattering angle, (2) obtain direct cross section ratios to ^{3}He for theory comparisons, and (3) perform clear tests of the isospin dependence of 3N-SRCs with ^{3}He and ^{3}H. The measurement will be performed with two target ladders, the first using a standard target ladder including the high-density helium target cells, and the second with a version of the tritium target system that was used in Hall A in 2018, which will have to be modified for use in Hall C.

2 Kinematic onset of 3N-SRCs

The presence of 2N-SRCs was established by observing universal two-body behavior in the inclusive cross section ratio for kinematics sensitive to high-momentum nucleons [8, 14, 16]. Measurements of the A/^{2}H cross section ratio for inclusive scattering for $x > 1.4$-1.5 yielded a constant value, connected to the relative contribution of 2N-SRCs in the heavy nucleus relative to the deuteron, and this was also shown to be Q^2 independent for $Q^2 > 1.4$-1.5 GeV^2. Figure 1 shows the plateau in x for several light nuclei (left panel), and the observation of Q^2 independence above 1.4 GeV^2 in the right panel.

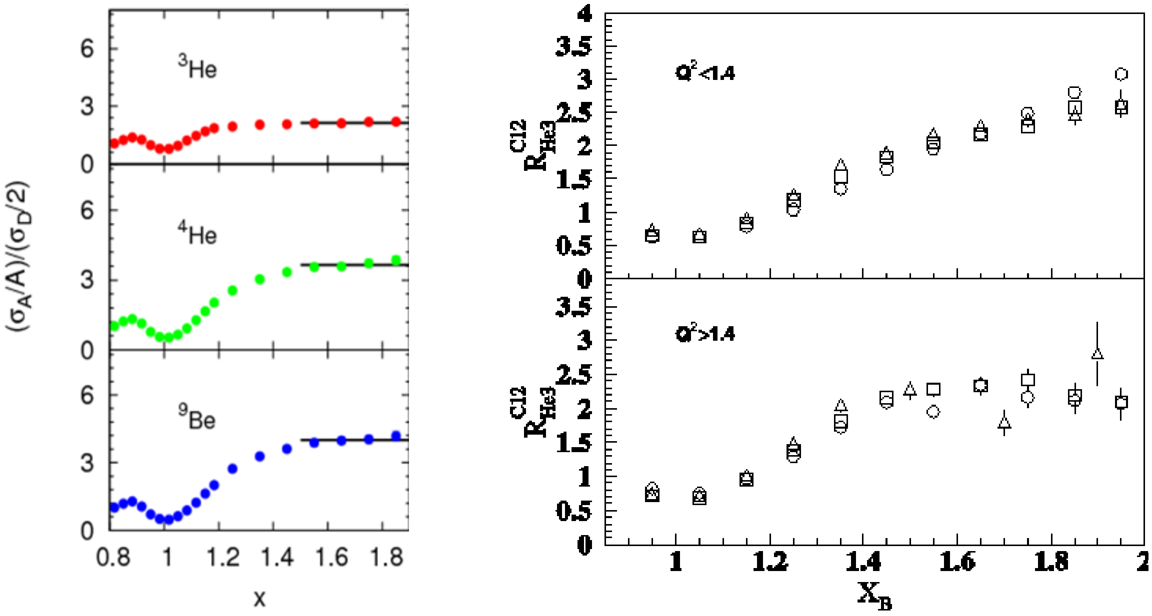

Figure 1: **Left:** A/^{2}H ratios for light nuclei from E02-109 [3], showing the 2N-SRC plateau for $x \gtrsim 1.4$. **Right:** ^{12}C/^{3}He cross-section ratios are shown for the 2N-SRC scaling region, demonstrating the onset of a 2N-SRC plateau for $Q^2 \approx 1.4$ GeV^2

It was argued [2] that for $x > 2$, the 2N-SRC contributions might drop off an 3N-SRC contributions become dominant, leading to a second plateau in measurements of the A/^{3}He inclusive cross section ratios. However, while it was relatively easy to determine where 2N-SRCs should dominate the scattering, the question of what kinematics are needed to isolate 3N-SRCs is much less clear.

There were several factors made it possible to reliably predict where 2N-SRCs would dominate the cross section:

- Inclusive scattering at large x and Q^2 (corresponding to low energy transfer, ν) suppresses inelastic contributions and isolates quasielastic e-N scattering. Quasielastic scattering at $x > 1$ imposes a kinematic threshold for scattering that requires a minimum initial nucleon momentum (which increases with x and with Q^2, as illustrated in the left panel of Figure 2).
- The simple structure of the 2N-SRC, nearly identical to the high-momentum part of the deuteron distribution, gives a reliable prediction for the falloff of the 2N-SRC contribution at large nucleon momenta.
- Most importantly, the very rapid falloff of the mean field contribution around the Fermi momentum (Fig. 2 - right panel) makes it easy to identify where the SRC contributions will dominate, even without reliable knowledge of the size and momentum-dependence of the

2N-SRC contributions

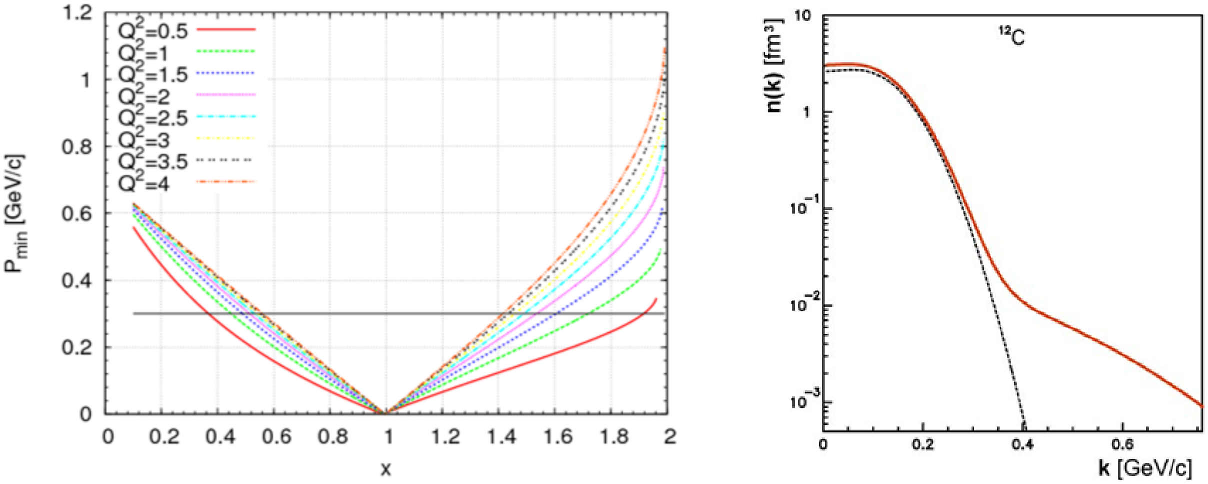

Figure 2: **Left:** The minimum momentum of the struck nucleon, P_{min} for quasielastic e-N scattering as a function of x for different values of Q^2. For x, Q^2 values above the line, $P_{min} = 300$ MeV/c and mean-field contributions should be falling rapidly. **Right:** Momentum distribution for a nucleon in carbon in a mean-field model (black dashed line) and including the impact of the short-range NN potential (red solid line).

Because of the rapid falloff of the mean-field contribution, it is clear that 2N-SRC contributions should dominate for kinematics that select scattering for nucleons above the Fermi momentum. Depending on the exact value of P_{min} required for SRCs to dominate, Fig. 1 predicts that we should expect scaling for $x \approx 1.4$ at $Q^2 \gtrsim 2$ GeV^2.

Experiments at SLAC [2] and JLab [3–6] measured ratios of several nuclei and found scaling in x for $x > 1.4$ starting at $Q^2 \approx 1.4$ GeV^2, as illustrated in Fig. 1. While this yields P_{min} slightly below the Fermi momentum, keep in mind that this is the minimum momentum kinematically allowed, and is only achieved if the nucleon momentum is exactly opposite to the photon direction. Scattering from nucleons with a longitudinal momentum larger than P_{min}, or with finite transverse momenta (not included in calculations P_{min} will also contribute to the scattering.

The situation is significantly more complicated for 3N-SRCs. First, the contribution from 2N-SRCs falls off more more slowly than the mean field contributions, and so predicting what nucleon momentum is required for the 3N-SRCs to dominate is very sensitive to the details of size and nature of the 3N-SRC contributions. On top of this, the structure of the 3N-SRC is more complicated and predictions for its contribution are highly model dependent. Momentum sharing among the three nucleons can be symmetric or highly-asymmetric, as illustrated in Fig. 3. While we can calculate P_{min} as a function of x and Q^2 for heavy nuclei, this value is dependent on the momentum distribution of the spectators in the 3N-SRC, so a more realistic estimate of relevant minimum momenta for 3N-SRCs is dependent for the symmetric and asymmetric momentum configurations.

Another complication arises due to the fact that several isospin configurations are possible for 3N-SRCs. Even if SRCs are dominated by ppn and pnn contributions, scattering from isoscalar nuclei should have identical contributions from these configurations (plus possible configurations from ppp- or nnn-SRCs). In the ratio to ^{3}He, where only the ppn configuration is possible, the ratio will be sensitive to differences in the number of protons and neutrons at the largest momenta in 3N-SRCs. In a symmetric configuration (left panel of Fig. 3, scattering from the highest momentum

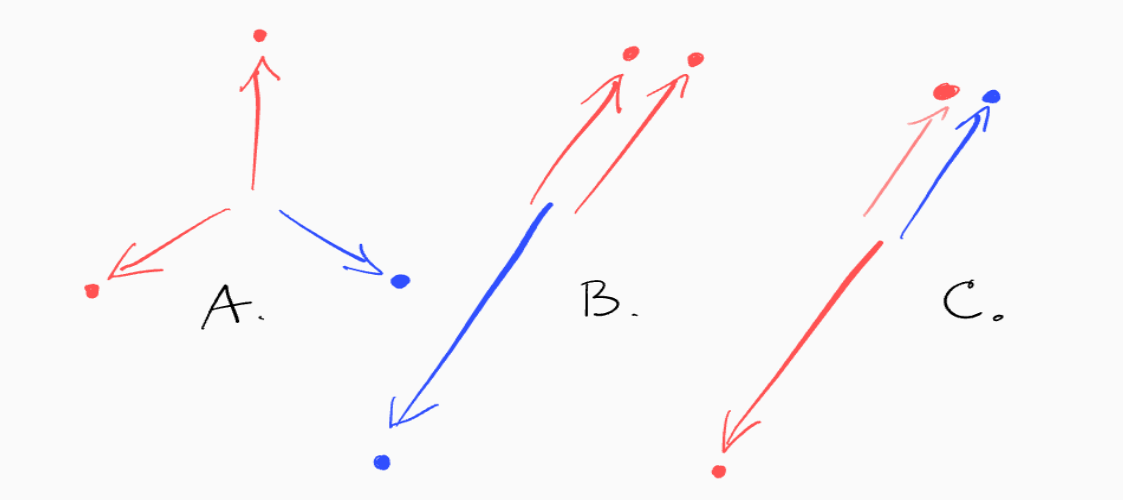

Figure 3: Different possible momentum/isospin configurations for a ppn 3N-SRCs. In (A), the momentum is distributed evenly among all three nucleons, while (B) and (C) have a highly asymmetric sharing of the momentum. When probing the highest-momentum nucleons, (A) will have contributions from two protons and one neutron, while (B) will be dominated by the single neutron and (C) will be dominated by the doubly-occurring proton.

nucleons in ^{3}He will involve both protons and the neutron. In a highly asymmetric configuration, (right panel of Fig. 3), the high-momentum part of the distribution could be dominated by the singly-occuring neutron, the double-occuring proton, or some combination. Thus, the question of whether the highest-momentum nucleons are protons, neutrons, or a mix of both, will modify the A/^{3}He ratio. If the relative contributions of protons and neutrons varies as a function of momentum, this could also distort the x dependence of the ratio.

The result of these complications is a situation where it is hard to make reliable predictions for the kinematic "onset point". Searches for 3N-SRCs had to take A/^{3}He cross sections at whatever Q^2 values were accessible and look for a clear plateau in x for x well above 2, to suppress the 2N-SRCs. As discussed in the next section, existing data do not show indications of 3N-SRCs, but are limited to lower Q^2 values or extremely low precision. Therefore, it is critical to extend the Q^2 range of such measurements as far as possible, and to find ways to alleviate the issue of corrections associated with different isospin structure in in ^{3}He when taking A/^{3}He ratios. One such option, discussed below, is examining ratios of isoscalar nuclei to ^{4}He so that we are dominantly seeing equal contributions of ppn- and pnn-SRCs. In addition, comparisons of ^{3}H and ^{3}He can provide direct information on the momentum and isospin structure of 3N-SRCs.

3 Previous Measurements

3.1 Searches for 3N-SRCs

In 2006, the CLAS collaborations claimed observation of a 3N-SRC plateau in A/^{3}He ratios [17]. This was unexpected as the data were taken for $Q^2 \approx 1.6$ GeV^2 and the plateau in x appeared earlier than expect, at $x \sim 2.2$. Prior to the measurement, the expectation was that larger Q^2 values were required, and that the 2N-SRC contributions would likely be significant well past $x = 2.2$ due to the center-of-mass momentum of the 2N-SRC.

An experiment that included a high-Q^2 search for 3N-SRCs was taking data at the time the

CLAS results were published. E02-019 aimed observe a 3N-SRC plateau in the $x > 2$ region at $Q^2 \approx 2.9$ GeV^2. Unfortunately, the ^{3}He cross section falloff at large x was faster than expected, and with the large endcap subtraction associated with the short ^{3}He target, the statistics of the A/^{3}He ratios was significantly limited by the ^{3}He data. Nonetheless, these higher-Q^2 data were in tension with the previous CLAS 3N-SRC plateau observations [17], as shown in the left panel of Figure 4. Initially, it was unclear if the results disagreed, or if the difference was related to the different Q^2 values of the two experiments.

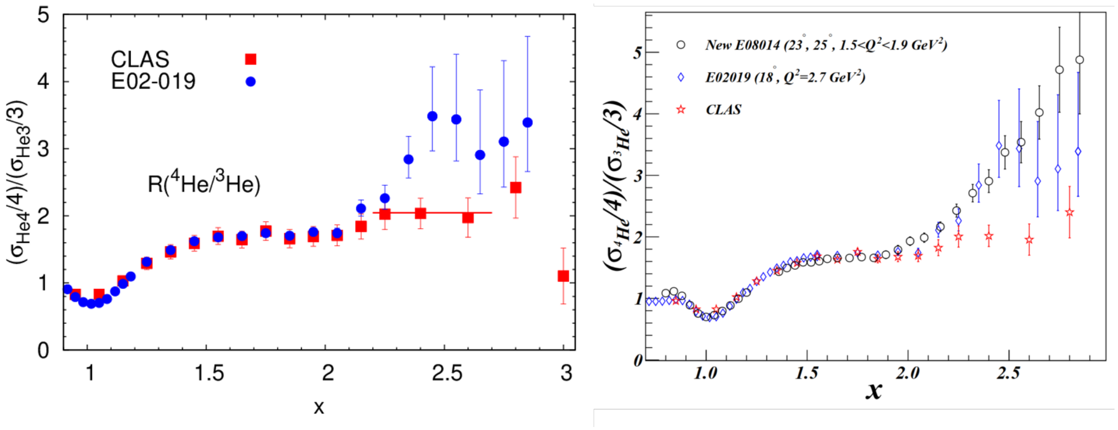

Figure 4: **Left:** A/^{3}He cross section ratios from the CLAS measurement ($Q^2 \approx 1.6$ GeV^2) and the Hall C E02-019 experiment ($Q^2 \approx 2.9$ GeV^2. **Right:** A/^{3}He ratios for the CLAS and E02-019 experiments, and for the Hall A E08-014 measurement which took data at kinematics approximating the CLAS measurement ($Q^2 \approx 1.6$ GeV^2).

In this context, JLab E08-014 was approved with the aim of focusing on the $x > 2$ region with longer cryogenic targets (for higher statistics) and kinematics that overlapped with the CLAS measurements [17]. These new data at $Q^2 \approx 1.6$ GeV^2 were consistent with the Hall C data at 2.9 GeV^2, and disagreed with the CLAS data taken at similar kinematics, as shown in the right panel of Fig. 4. It was later demonstrated to be an artifact of bin migration associated with the ∼1% momentum resolution in CLAS [18], leaving the question of 3N-SRCs unanswered.

No second plateau was observed in the Hall A data [5] as illustrated by the right-hand-side plot in Fig.4. Thus, at present, we have a measurement at $Q^2 \approx 1.6$ GeV^2 with moderate statistics that does not show a plateau and data at $Q^2 \approx 2.9$ GeV^2 which are consistent with a plateau, but with uncertainties far to large to make a claim of having observed 3N-SRCs. Note that a clean identification of 3N-SRCs requires both x and Q^2 independence of the cross section, meaning that even observing a clean plateau in x is only an indication, and multiple Q^2 values or some other supporting evidence would be required to make a strong claim.

3.2 Momentum-isospin structure of 3N-SRCs

Comparing measurements of ^{3}H and ^{3}He provides the cleanest way to study the structure of ppn and pnn configurations. As illustrated in Fig. 3, there are multiple configurations that, in the limit of large nucleon momentum, yield different contributions from protons and neutrons. In the 3N-SRC region, configuration (B) is dominated by the singly occuring neutron, so the ^{3}H/^{3}He cross section ratio will be close to the proton/neutron cross section ratio (∼2.5), while (B) will be close to the neutron/proton cross section ratios (∼0.4). For configuration (A), or an isospin-independent mix of (B) and (C), the cross section ratio will be

$$\sigma_{3H}/\sigma_{3He} \approx \frac{\sigma_p + 2\sigma_n}{2\sigma_p + \sigma_n} \approx 0.75 \quad \text{for} \quad \sigma_p/\sigma_n \approx 2.5. \tag{1}$$

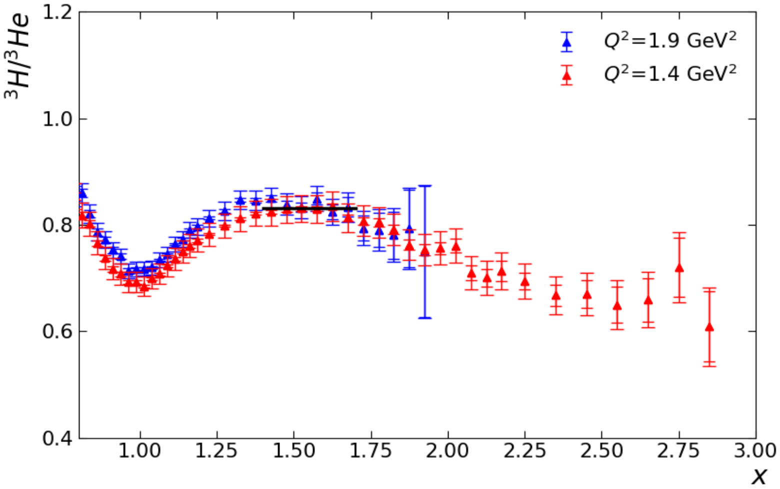

Figure 5: Preliminary ^{3}H/^{3}He ratio from E12-11-112 [13].

Figure 5 shows the preliminary results for the $x > 2$ ^{3}He/^{3}H cross section ratio. While the kinematics of the measurement are insufficient to isolate 3N-SRCs, the fact that the ratio drops from $R = 0.85$ in the 2N-SRC region (indicating a significant enhancement of the np-SRC/pp-SRC ratio) towards a value that indicates a proton-to-neutron ratio of close to 2:1. At higher Q^2 values, where contributions from 3N-SRCs are dominant, this would yield a measurement of the ratio of protons to neutrons at the largest momenta. But even at this low Q^2 value, it suggests that as contributions beyond 2N-SRCs begin to become important, we are seeing an increase in the proton contribution, pointing towards symmetric configurations or proton-dominated asymmetric configurations.

We note that E12-11-112 also observed the onset of 2N-SRC scaling behavior at significantly lower x and Q^2 than previous measurements. This is in part because of the smaller Fermi momentum for these light nuclei, and in part because scaling-violating effects at low Q^2, e.g. meson-exchange contributions and final-state interactions, are expected to be nearly identical in ^{3}H and ^{3}He. The same should be true for $x > 2$, and so we expect that the ^{3}H/^{3}He comparison will be a useful tool for studying the momentum-isospin configurations of 3N-SRCs at accessible Q^2 values, even if there is a small dilution due to contributions from 2N-SRCs.

4 Upcoming Measurement - E12-06-105

Recent theoretical work [14,15] suggests that 3N-SRCs do not begin to dominate until much higher Q^2 values than those of previous searches. Instead of looking at the onset of scaling in terms of x and Q^2, which are used to identify a minimum momentum of the struck nucleon in the target's rest frame, they use the light-cone variable α. This represents the light-cone nuclear momentum fraction carried by the struck nucleon, which more directly represents the nucleon momentum at large Q^2 values.

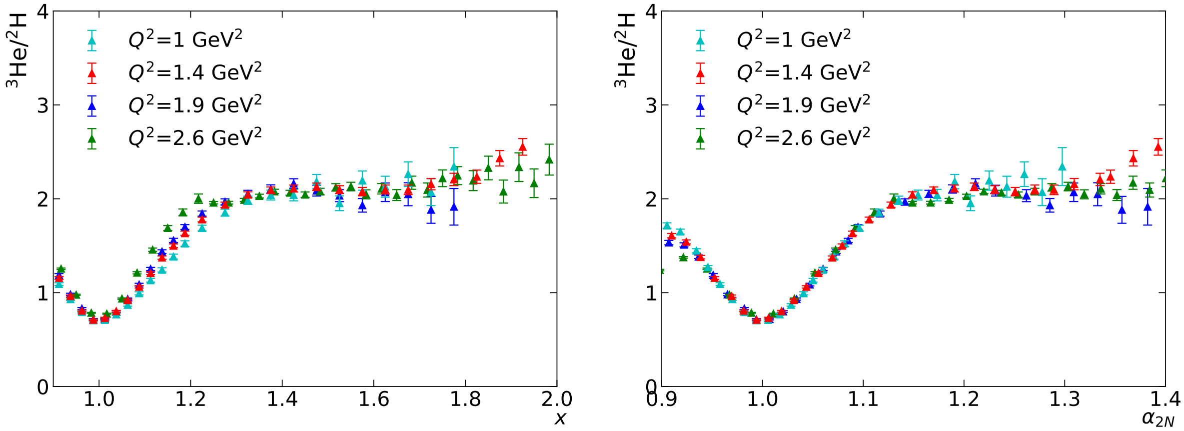

Figure 6: Preliminary ^{3}He to ^{2}H cross section ratios as a function of x and α_{2N} over a range in Q^2 from E12-11-112, along with the E02-109 data at 2.6 GeV^2 [3].

In inclusive scattering, we cannot directly measure α because it depends on the details of the spectator system. However, α can be reconstructed for QE scattering from the deuteron, and for heavier nuclei we use α_{2N}, which assumes scattering from an at-rest 2N-SRC. Figure 6 shows the cross section ratios for ^{3}He/^{2}H from E12-11-112 and E01-019 [19] as a function of x and of α_{2N}. The use of α_{2N} incorporates finite Q^2 corrections such that the onset of scaling occurs at fixed $\alpha_{2N} \approx 1.15$ rather than starting at an x value that decreases with increasing Q^2. Note that the use of α_{2N} improves scaling even for very low Q^2 values and near the QE peak, where the model dependence in estimating the light cone momentum fraction with α_{2N} is likely to be the most important. For 3N-SRCs, one can define multiple versions of α_{3N} under different assumptions for the structure of the 3N-SRCs. In this letter of intent, we take the convention of Ref. [14, 15]

The left panel of Fig. 7 shows α_{3N} for different values of Q^2 as a function of x to show the relationship between the two variables. The authors of Ref. [14, 15] suggest that a minimum of $\alpha_{3N} = 1.6$–1.8 is needed to experimentally isolate the second (3N) scaling plateau. The right panel of Fig. 7 illustrates why this is the case by showing calculated contributions from the mean field as well as 2N-SRCs, which dominate below $\alpha_{3N} = 1.6$, but are very small compared to the 3N-SRC contributions by $\alpha_{3N} = 1.8$–1.9.

The model of Refs. [14, 15] also makes a prediction for the probability of finding a nucleon in a 3N-SRC, $a_3(A)$, relative to 2N-SRCs, $a_2(A)$. Because 3N-SRCs come dominantly from two hard NN interactions, they find that $a_3(A) \propto a_2(A)^2$, assuming that 3N-SRCs are predominantly in *ppn* or *nnp* configurations. The authors of Ref [15] go on to test this hypothesis by assuming scaling in this (α_{3N}=1.6 - 1.8) region for the E02-019 data and verifying that $a_3 \propto a_2^2$ for these data. This offers additional support that the E02-019 data were consistent with a 3N-SRC scaling plateau, but the result is again limited by the poor statistics of the ^{3}He data.

The upcoming Hall C experiment [20] will improve both the Q^2 coverage and precision compared to existing searches. Precision data for several nuclear targets will be taken at 8°, corresponding to Q^2=2.1 GeV^2 at $x = 2.5$. This will be a significant increase in Q^2 compared to the Hall A measurement [5], with improved statistics over both previous measurements. However, the Q^2 value is well below what the calculations of Ref. [14, 15] suggest are necessary to isolate 3N-SRCs. E12-06-105 will also take data at a larger angle (9-10 degrees), corresponding to $Q^2 \approx$3 GeV^2 at $x = 2.5$), with full statistics only for ^{4}He and ^{12}C. This will provide a first look at the region where

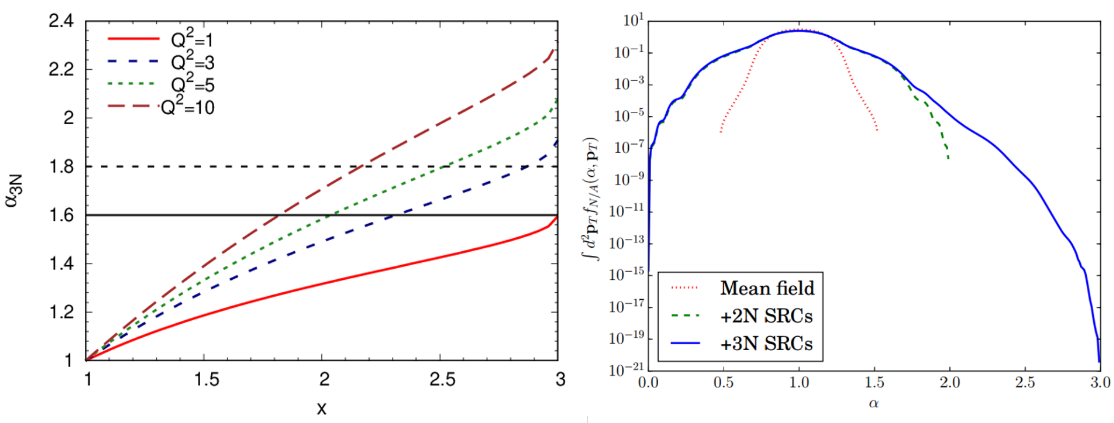

Figure 7: **Left:** α_{3N} as a function of x calculated for several values of Q^2. **Right:** The total contribution to the cross section, along with the cross section excluding 3N-SRCs and excluding all SRCs. [14]

models suggest 3N-SRCs may dominate the scattering cross section. While taking ^{12}C/^{4}He ratios will yield a smaller signal in ^{12}C/^{3}He, comparing isoscalar nuclei avoids complications associated with the comparison to ^{3}He, which has only ppn configurations.

5 Proposed Measurement

Having examined all previous data in this region into account and taking guidance from theoretical predictions, we believe it most likely that scaling will not be observed at 8°, but may be observed at 10°. We propose this follow-up measurement to: (1) Establish Q^2 independence required by the SRC picture, (2) Obtain direct ratios to ^{3}He for theory comparisons, and (3) perform clear tests of the isospin dependence.

In the unlikely event that $Q^2 \approx 2.1$ GeV^2 measurements of experiment E12-06-105 show clear indications of 3N-SRC dominance, the measurements from ^{3}H and ^{3}He outlined here will allow for a comparison of scattering from a heavy nucleus to (^{3}H+^{3}He)/2, providing an effective "isoscalar" A=3 nucleus. This avoids the uncertainties associated with comparing ppn and pnn contributions in the heavy isoscalar nucleus to the ppn-only contribution in ^{3}He. In addition, the direct comparison of ^{3}H to ^{3}He will allow us to better understand the momentum and isospin configurations of 3N-SRCs.

If 3N-SRCs are not cleanly isolated at $Q^2 = 2.1$ GeV^2, the tritium to ^{3}H/^{3}He comparison provides the same information mentioned above, but we can also significantly improve the studies of 3N-SRCs in $A > 4$ nuclei by expanding on the measurements taken in E12-06-105, guided by what we learn about the onset of scaling in those measurements. Note that E12-06-105 typically has 1-2 hours of data taking for each target at 8 degrees ($Q^2 = 2.1$ GeV^2), and roughly one day each for ^{4}He and ^{12}C at the higher angle ($Q^2 \approx 3$ GeV^2). With approximately 2-3 weeks of beamtime, and a better understanding of the cross sections for $x > 2$ at modest-to-large Q^2 values, we can take data on ^{12}C and ^{4}He at a larger Q^2 value, add ^{3}He, and make measurements on a range of targets for an intermediate Q^2 value. These data will allow us to unambiguously observe 3N-SRC dominance, with scaling measurements at multiple Q^2 values for A/^{3}He ratios, data on a handful of nuclei to map out the A dependence of 3N-SRCs and to test the prediction that $a_3(A) \propto a_2(A)^2$, in addition to probing the momentum-isospin structure of the 3N-SRCs with the ^{3}H/^{3}He measurement.

6 Experimental details and run time estimates

The optimal kinematics for the measurements will depend somewhat on the results from the upcoming E12-06-105 [20] experiment. However, because the higher $Q^2 \approx 3$ GeV^2 running will focus on ^{12}C and ^{4}He, this LOI proposes data taking on additional targets in the scaling region and more carefully mapping out the onset of scaling. With 2-4 weeks of beamtime, we can improve significantly on E12-06-105 with the use of longer ^{3}He and ^{4}He targets, and longer run times compared to the ~1-2 hours per target at $Q^2 \approx 2.1$ GeV^2 and ~1 day per target at $Q^2 \approx$3 GeV^2.

For the tritium comparison, the increased beam energy compared to the 4.4 GeV used in E12-11-112 [13] and 2-3 weeks of running will allow for a significant increase in the Q^2 coverage compared to the $Q^2 = 1.4$. E12-11-112 also took some data at $Q^2 = 1.9$ GeV^2, but this was limited by statistics to $x < 2$.

Details of our runtime estimates for the A/^{3}He and ^{3}H/^{3}He portions are presented in the sections below.

6.1 A/He ratios

Because the 3N-SRC search was a small part of the E12-06-105 proposal, very little is devoted to these kinematics. A combination of increased run time, longer cryogenic targets, and running at the full 11 GeV beam energy will allow for a significant set of new measurements on a reasonable time scale.

We will require long (20 cm) high-density helium targets for this measurements, in order to achieve the needed luminosity. Assuming a 60 uA current, and aiming to obtain 10% statistical uncertainties on the target ratios at x=2.7, 10 days of running with an 11 GeV beam will be needed for ^{3}He. Comparable or higher-precision data for ^{4}He, ^{9}Be, ^{12}C, ^{40}Ca, and Au targets can be obtained in another 10 days of running at 60 uA.

6.2 Tritium Measurement

For the comparisons of ^{3}H to ^{3}He, we propose to use a low-density gas target system based on the successful design from the tritium project in Hall A. The target ladder will include four identical 25 cm-long aluminum cells, based on the Hall A tritium target system, each cell to hold about 10 atmospheres (20 for helium) of ^{1}H, ^{2}H, ^{3}H, or ^{3}He gas. For our projections, we assume luminosities identical to what was achieved in the Hall A measurements with a maximum beam current of 22.5 μA for tritium safety. The Hall C single-arm Monte-Carlo simulation package are used to check acceptance. Rates are estimated with our inclusive cross section model which was tuned to reproduce the E12-11-112 ^{3}H and ^{3}He data at $x > 2$ with $Q^2 \approx 1.5$ GeV^2.

E12-11-112 was limited to $Q^2 \approx 1.5$ GeV^2 because of the lower (4.4 GeV) beam energy, and so was well below the expected threshold for 3N-SRC dominance of $\alpha_{3N} = 1.6$-1.8. In this proposed measurement, we make our estimates for 8.5 degree scattering angle, yielding $Q^2 = 2.5$. We expect to get ~1000 ^{3}H events per day at $\alpha_{3N} = 1.6$ (after acceptance cuts) with the SHMS at 8.5 degrees. The projected ^{3}H/^{3}He ratio with 24 days of beam (12 days on each target) is shown in figure 8. A final choice of kinematics will be based on the cross section measurements in the somewhat larger Q^2 values that will be taken as part of E12-06-105.

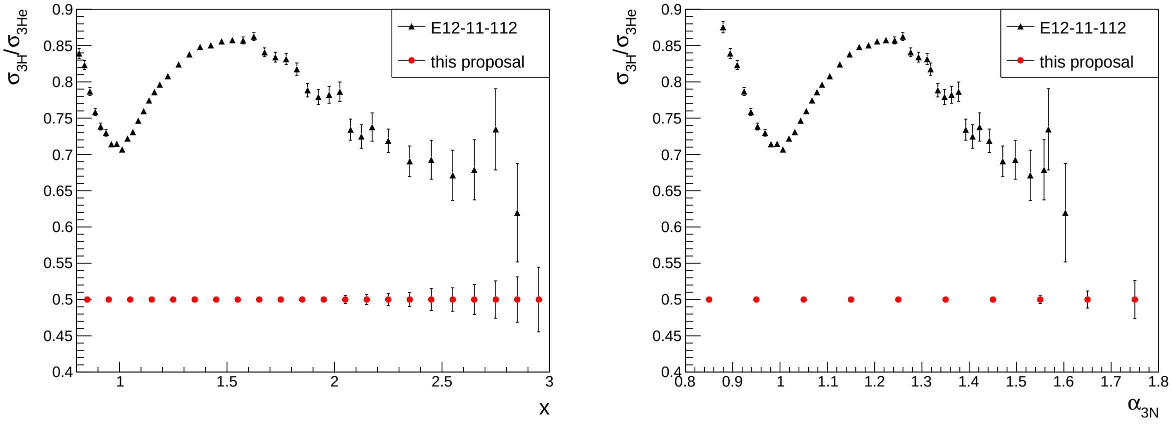

Figure 8: $\sigma_{^3H}/\sigma_{^3He}$ from E12-11-112 as a function of x (left) and α (right), along with the projected statistical uncertainties from the proposed measurement.

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