$A = 3 (e, e') \, x_B \geqslant 1$ cross-section ratios and the isospin structure of short-range correlations

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We study the relation between measured high-x_B, high-Q^2, helium-3 to tritium, (e, e') inclusive-scattering cross-section ratios and the relative abundance of high-momentum neutron-proton (np) and proton-proton (pp) short-range correlated nucleon pairs in three-body ($A = 3$) nuclei. Analysis of these data using a simple pair-counting cross-section model suggested a much smaller np/pp ratio than previously measured in heavier nuclei, questioning our understanding of $A = 3$ nuclei and, by extension, all other nuclei. Here, we examine this finding using spectral-function-based cross-section calculations, with both an *ab initio* $A = 3$ spectral function and effective generalized contact formalism spectral functions using different nucleon-nucleon interaction models. The *ab initio* calculation agrees with the data, showing good understanding of the structure of $A = 3$ nuclei. An 8% uncertainty on the simple pair-counting model, as implied by the difference between it and the *ab initio* calculation, gives a factor of 5 uncertainty in the extracted np/pp ratio. Thus we see no evidence for the claimed "unexpected structure in the high-momentum wave function for hydrogen-3 and helium-3."

Physics advances fastest by comparing high-precision experiments with detailed calculations. Hard scattering reactions on few-body nuclear systems are accessible to both precision measurements and precision calculations, allowing us to advance our knowledge of nuclear structure and dynamics.

Recently helium-3 and tritium inclusive (e, e') [1] and semi-inclusive $(e, e'p)$ [2] scattering measurements were performed to provide new insight into the properties of high-momentum short-range correlated (SRC) nucleon pairs in $A = 3$ nuclei. SRC pairs are fluctuations of strongly interacting nucleon pairs in nuclei. Their measurable properties, such as isospin structure (i.e., neutron-proton to proton-proton pair ratio, np/pp), provide unique insight into the nature of the short-distance nuclear interaction and the behavior of nucleons at very high momenta [3,4].

The measured $(e, e'p)$ cross sections were compared to modern calculations using *ab initio* spectral functions (i.e., spectral functions calculated precisely using a specific *NN* potential) [5] for $A = 3$, agreeing well up to 450 MeV/c initial nucleon momentum. This is a remarkable success of modern nuclear theory in extreme conditions of SRC pair formation [2]. However, the measured (e, e') ^{3}H / ^{3}He cross-section ratios have so far only been analyzed using a simple SRC pair-counting model [1]. This analysis reported a dramatically smaller np/pp SRC ratio than previous $4 \leqslant A \leqslant 208$

measurements [6–10], and $3 \leqslant A \leqslant 40$ calculations [11]. This decrease was attributed to an "unexpected structure in the high-momentum wave-function for hydrogen-3 and helium-3" [1]. As the $A = 3$ few-body system has been thoroughly studied both experimentally and theoretically, such a new structure would be most surprising and could dramatically impact our understanding of all nuclei.

This necessitates a study of the consistency of the measured (e, e') data with modern *ab initio* nuclear structures and reaction theory to determine the accuracy with which it can constrain the SRC isospin structure in $A = 3$ nuclei.

Here, we compare the measured (e, e') cross-section ratios to different theoretical models with different levels of approximations. These include calculations using an *ab initio* spectral function [12] calculated with the Argonne v18 (AV18) interaction [13] and calculations using effective SRC-pair spectral functions obtained using the generalized contact formalism (GCF) [11,14–16] with different nucleon-nucleon (*NN*) interaction models [13,17–23].

We find that the full spectral-function calculation describes the measured (e, e') ^{3}H / ^{3}He cross-section ratios well. This implies that there is no new structure in the $A = 3$ momentum distribution. This calculation disagrees with the simple pair-counting model by 8%. We attribute this difference primarily to non-SRC-pair contributions to the measured cross- section.

An 8% uncertainty in the simple pair-counting model causes a factor of 5 uncertainty in the extracted *np* to *pp* SRC pair ratio, eliminating the discrepancy with previous results.

In inclusive electron scattering, an electron with energy E_e scatters off a target, deflecting by an angle $\theta_{e'}$ and emerging with energy $E_{e'}$. The kinematics is described in terms of the momentum transfer squared $Q^2 = 4E_e E_{e'} \sin^2(\theta_{e'}/2)$ and the Bjorken scaling variable $x_B = Q^2/(2m_N\omega)$, where $\omega = E_e - E_{e'}$ is the energy transfer and m_N is the nucleon mass.

At $Q^2 \geqslant 1.5$ GeV/c^2, measured inclusive (e, e') cross-section ratios of nuclei relative to deuterium "scale" for $1.5 \leqslant x_B \leqslant 1.8$ (i.e., the ratio is independent of x_B) [24–26]. At this high x_B, the electrons interact predominantly with high-momentum nucleons [25]. Thus the observed scaling is interpreted as suggesting that inclusive scattering proceeds predominantly via the hard breakup of SRC pairs.

Using this simple reaction picture, early works introduced the SRC cross-section approximation [27],

$$\sigma_{eA}(x_B, Q^2) = a_2(A)\frac{A}{2}\sigma_{ed}(x_B, Q^2), \quad (1)$$

where $a_2(A)$ is the ratio of the prevalence of SRC pairs in nucleus A relative to the high-momentum fraction of the deuteron momentum distribution, and σ_{ed} is the electron-deuteron scattering cross section. In a high-resolution reaction picture, the latter includes interactions with either the proton or the neutron in the deuteron, i.e., $\sigma_{ed} \approx \sigma_{ep} + \sigma_{en}$, where σ_{ep} and σ_{en} are the off-shell electron-nucleon cross sections [28]. In this approximation, $a_2(A) = \sigma_{eA}/\sigma_{ed}$ provides information on SRC pairing probabilities in nuclei.

As SRC pairs include not only deuteronlike proton-neutron pairs, but also proton-proton and neutron-neutron pairs, the SRC approximation was extended to include all pair types, in what we call the simple pair-counting model [1,29],

$$\sigma_{eA}(x_B, Q^2) = K\left[N_{np}^A(\sigma_{ep} + \sigma_{en}) + N_{pp}^A 2\sigma_{ep} + N_{nn}^A 2\sigma_{en}\right], \quad (2)$$

where K is a kinematic factor and N_{NN}^A is the number of NN-SRC pairs (where NN refers to np, pp, or nn) in a nucleus with mass number A.

For the tritium to helium-3 cross-section ratio, the simple pair-counting approximation gives

$$\frac{\sigma_{\mathrm{T}}}{\sigma_{\mathrm{He}}} = \frac{N_{np}^{\mathrm{T}}(\sigma_{ep} + \sigma_{en}) + N_{nn}^{\mathrm{T}} 2\sigma_{en}}{N_{np}^{\mathrm{He}}(\sigma_{ep} + \sigma_{en}) + N_{pp}^{\mathrm{He}} 2\sigma_{ep}}. \quad (3)$$

Using isospin symmetry (i.e., assuming $N_{nn}^{\mathrm{T}} \approx N_{pp}^{\mathrm{He}}$ and $N_{np}^{\mathrm{T}} \approx N_{np}^{\mathrm{He}}$) this simplifies to

$$\frac{\sigma_{\mathrm{T}}}{\sigma_{\mathrm{He}}} = \frac{1 + \frac{\sigma_{ep}}{\sigma_{en}} + 2\frac{N_{pp}}{N_{np}}}{1 + \frac{\sigma_{ep}}{\sigma_{en}}\left(1 + 2\frac{N_{pp}}{N_{np}}\right)}, \quad (4)$$

where we omit the nucleus notation from the number of SRC pairs and always refer to helium-3.

While simplistic, this model relates the SRC-pair isospin structure $\frac{N_{np}}{N_{pp}}$ to the measured cross-section ratio using known electron-nucleon cross sections (see the solid red line in Fig. 1). However, the cross-section ratio is not very sensitive to the np/pp SRC-pair ratio. A factor of 5 np/pp-ratio variation
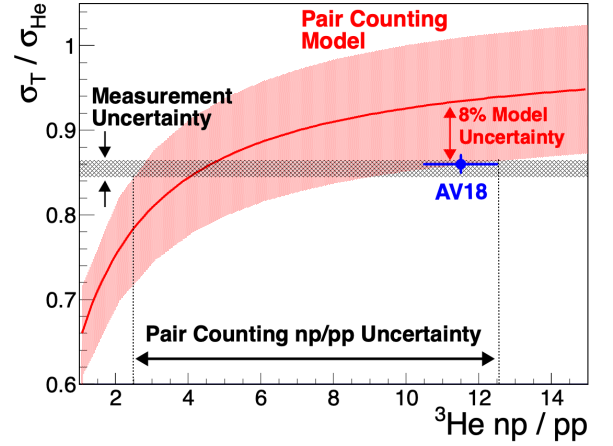

FIG. 1. The relation between the average ${}^3\mathrm{H}/{}^3\mathrm{He}$ cross-section ratio for $1.4 \leqslant x_B \leqslant 1.7$ and the relative number of np and pp SRC pairs in helium-3. The experimental results of Ref. [1] are shown by the black band, whose width equals the data uncertainty. The AV18 prediction is shown by the blue data data point using the np/pp SRC-pair ratio from Ref. [11]. The simple pair-counting model is shown by the red line and its uncertainty is shown by the red band. The uncertainty of $\pm 8\%$ is determined by the difference between the model and the AV18 calculation for the same np/pp ratio. The resulting np/pp SRC-pair ratio uncertainty is shown by the vertical lines.

(from 2 to 10) corresponds to only about 20% change in the cross-section ratio (from 0.75 to 0.95). Thus, to extract the np/pp SRC-pair ratio from inclusive data, one needs both a small data uncertainty and an equally small model uncertainty.

Inelastic scattering (pion production) and rescattering of the outgoing nucleon (final state interactions or FSI) can also impact the cross section and hence the $\frac{N_{np}}{N_{pp}}$ extraction. Inelastic scattering at $x \geqslant 1.3$ is negligible [30–32]. FSI can change the cross section by up to a factor of ~ 2 at high x_B [32,33]. However, at high x_B FSI primarily consists of one nucleon from the SRC pair scattering off the other nucleon in the pair. Therefore, if the reaction is dominated by interactions with np-SRC pairs, then the effects of the FSI effect will be the same and will largely cancel in the cross-section ratio for different nuclei. This cancellation should be even stronger for the cross-section ratio of similar nuclei, e.g., ${}^3\mathrm{He}$ to ${}^3\mathrm{H}$. However, differences in the np and pp (or nn) scattering cross section could lead to different FSI for interactions with np- and pp-SRC pairs, changing their relative contribution to the measured cross section and altering the extracted $\frac{N_{np}}{N_{pp}}$ ratio. This would increase the uncertainty and decrease our confidence in the results of the simple pair-counting model of Ref. [1].

Previous work used Eq. (4) to extract an np/pp SRC pair ratio of $4.34^{+0.49}_{-0.40}$, quoting a 0.4% model uncertainty attributed to possible isospin symmetry breaking and SRC center-of-mass (c.m.) momentum effects [1]. However, additional model uncertainties can come from the difference between the pp and np pair relative wave functions (due to the tensor-force contribution to the $T = 0$, $S = 1$ np state [34]),
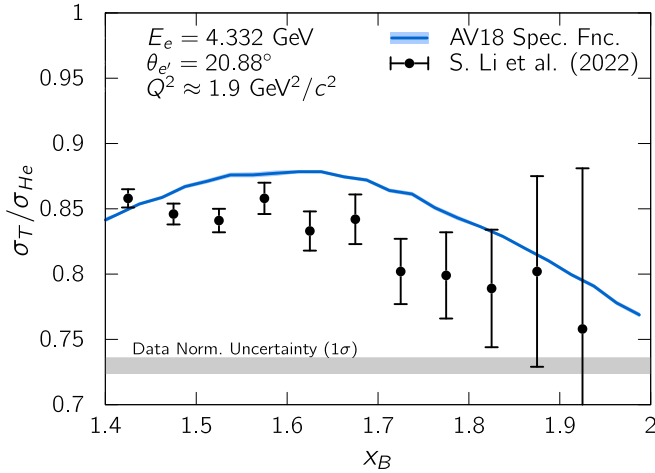
FIG. 2. Tritium to helium-3 (e, e') cross-section ratio, $\sigma_{\mathrm{T}}/\sigma_{\mathrm{He}}$, at $Q^2 \approx 1.9$ GeV^2 as a function of x_B for data [1] (black points) and calculation (blue line). The factorized cross-section calculation [Eq. (5)] uses an exact *ab initio* spectral function calculated using the AV18 interaction [12]. The gray band shows the 1.18% data normalization uncertainty (1σ).
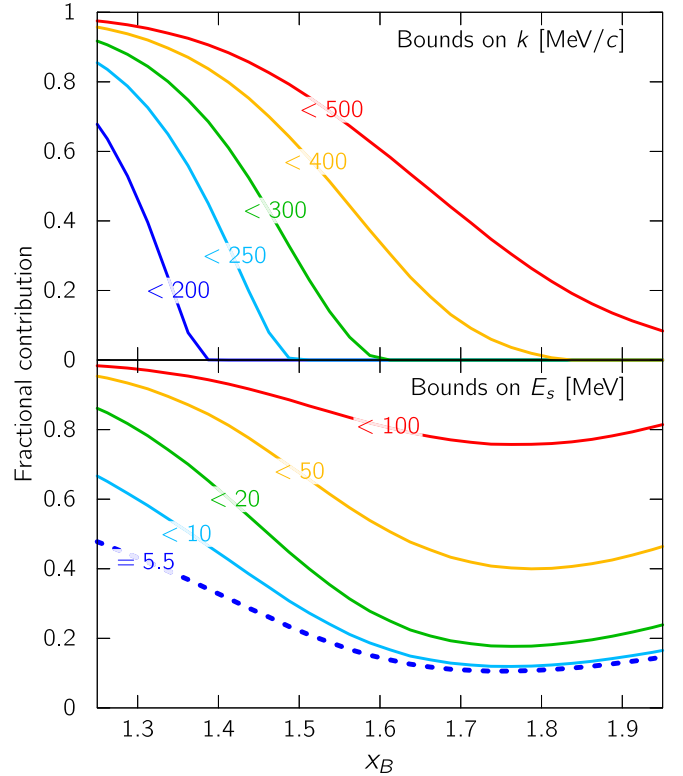

FIG. 3. Calculated contributions to the ^{3}He(e, e') cross section from different initial nucleon states characterized by their initial momentum k (top) and separation energy E_s (bottom) [12]. The dashed blue line in the bottom panel, labeled "$= 5.5$," represents the two-body pd breakup contribution. Calculations are performed using Eq. (5) for the $Q^2 \approx 1.9$ GeV^2 kinematics of Ref. [1], using an *ab initio* AV18 spectral function [12].

their different FSI contributions, and contributions to the cross section from interactions with non-SRC states.

To assess these effects we perform a cross-section ratio calculation using input from *ab initio* nuclear structure calculations.

At high Q^2 the electron scattering cross section can be approximately factorized as [35]

$$\sigma_{eA} = K' \sigma_{eN} S_N(k, E_s), \tag{5}$$

where K' is a kinematic factor, σ_{eN} is the one-body electron-nucleon off-shell cross section [28], and $S_N(k, E_s)$ is the spectral function, defined as the probability for finding a nucleon $(N = p, n)$ in the nucleus with momentum k and separation energy E_s. E_s is defined by $E_s \equiv -m_A + m_N + m_{A-1}^*$, where m_A is the mass of the target nucleus and m_{A-1}^* is the invariant mass of the entire $(A - 1)$ system, which may or may not remain intact.

In the absence of inelastic scattering and final state interactions, the inclusive cross section equals this cross section integrated over all spectral function states (k and E_s) within the experimental acceptance and summed over proton and neutron knockout.

This factorized cross-section approximation encapsulates all of the many-body nuclear structure information in the spectral function. Here, we use a spectral function extracted from exact calculations of the three-body ground state [12] using the AV18 interaction [13] and without irreducible three-body forces. The spectral function accounts for FSI between the two spectator nucleons but not with the leading nucleon.

Figure 2 shows the results for the $Q^2 = 1.9$ GeV^2 kinematics of Ref. [1]. The calculation is in good agreement with the data, showcasing a remarkable success for *ab initio* nuclear structure theory, even at very high x_B.

Figure 1 shows the calculated cross-section ratio averaged over $1.4 \leqslant x_B \leqslant 1.7$ plotted at the corresponding np/pp SRC

ratio of 11.5, which was taken from the AV18-based quantum Monte Carlo (QMC) calculations of Ref. [11] (which also included $3N$ forces). For the same np/pp SRC ratio, this calculation differs from the simple pair-counting approximation by 8%.

This difference provides a measure of the theoretical uncertainty of the pair-counting approximation. The impact of this 8% uncertainty is shown in Fig. 1 by the red band surrounding the pair-counting calculation. Despite the precision of the measured cross-section ratio, this 8% theoretical interpretation uncertainty leads to a large uncertainty in the extracted np/pp SRC ratio, spanning a factor of 5 from 2.5 to 12.

We further used the AV18 spectral-function-based cross-section calculation to quantitatively test the claimed SRC dominance of the measurements in the plateau region ($1.4 \leqslant x_B \leqslant 1.7$) by examining the contributions of low-momentum and low-energy states to the (e, e') cross section.

Figure 3 shows the fractional contribution to the helium-3 cross section as a function of x_B from states with different momentum and energy cutoffs. While low-momentum contributions are suppressed at high x_B, there is still significant strength from $k \leqslant 250$ MeV/c up to $x_B = 1.5$, i.e., the first two data points in the SRC-scaling region of Ref. [1]. More importantly, even at $1.4 \leqslant x_B \leqslant 1.7$ there are still

significant ($\geqslant 20\%$) contributions to the cross section from high-momentum low-energy nuclear states. These states differ from those typically measured in nucleon-knockout SRC studies, where much higher energies are probed and a clear momentum-energy correlation is observed [36]. Even at the highest x_B, the ^{3}He cross section includes a $\sim 10\%$ contribution from two-body breakup [e.g., $(e, e')pd$] that is clearly not associated with SRC-pair breakup. These non-SRC-pair states are one source of the discrepancy between the simple pair-counting model and the *ab initio* spectral-function-based calculation.

While the measured inclusive cross-section ratio has some sensitivity to the SRC isospin structure, the simple pair-counting model ignores the complexities of nuclear structure and therefore has far greater uncertainties than the high-precision data. Thus, we do not see conclusive evidence for the claimed reduction in the neutron-proton pair dominance in the $A = 3$ system.

This conclusion does not preclude a different np/pp SRC-pair ratio in $A = 3$ nuclei, resulting from unique constraints in the $A = 3$ system. The SRC-pair and third-nucleon spins must sum to the total nuclear spin of $1/2$. Similarly, the third nucleon momentum must be equal and opposite to the SRC pair c.m. momentum, potentially limiting the pair formation phase space and mixing three-nucleon correlation effects [37]. These and other effects could change the np/pp SRC ratio in light nuclei without requiring a change to our current understanding of high-momentum short-distance interactions.

Last, we examine the sensitivity of the cross-section ratio to the short-distance NN interaction. Since exact three-body spectral functions using different NN interaction models are not yet available, we turn to the generalized contact formalism (GCF) [11,14–16].

The GCF provides a SRC-pair-based spectral function model that was shown to well reproduce both *ab initio* calculated one- and two-nucleon densities [11,15], as well as exclusive SRC pair breakup measurements [10,16,36,38–40]. The GCF approximates the high-momentum high-energy part of the nuclear spectral function as a sum over SRC-pair spectral functions [16,39]:

$$S_p(k, E_s) = C_{pn}^1 S_{pn}^1(k, E_s) + C_{pn}^0 S_{pn}^0(k, E_s)$$
$$\qquad + 2C_{pp}^0 S_{pp}^0(k, E_s),$$
$$S_n(k, E_s) = C_{pn}^1 S_{pn}^1(k, E_s) + C_{pn}^0 S_{pn}^0(k, E_s)$$
$$\qquad + 2C_{nn}^0 S_{nn}^0(k, E_s), \qquad (6)$$

where S_p and S_n are the proton and neutron spectral functions. C_{NN}^α are the nuclear "contact terms" that specify the number of NN SRC pairs with spin α ($= 0, 1$) in nucleus A, and $S_{NN}^\alpha(k, E_s)$ are pair spectral functions given by

$$S_{NN}^\alpha(k_1, E_s) = \frac{1}{4\pi} \int \frac{d^3 \mathbf{k}_2}{(2\pi)^3} \left| \phi_{NN}^\alpha(\mathbf{k}_{\mathrm{rel}}) \right|^2$$
$$\qquad \times n_{NN}^{A\alpha}(\mathbf{k}_{\mathrm{cm}}) \delta(f(\mathbf{k}_2)). \qquad (7)$$

$\mathbf{k}_{\mathrm{rel}}$ and $\mathbf{k}_{\mathrm{cm}}$ are the pair relative and center-of-mass (c.m.) momenta and $\mathbf{k}_1$ and $\mathbf{k}_2$ are the momenta of nucleons im
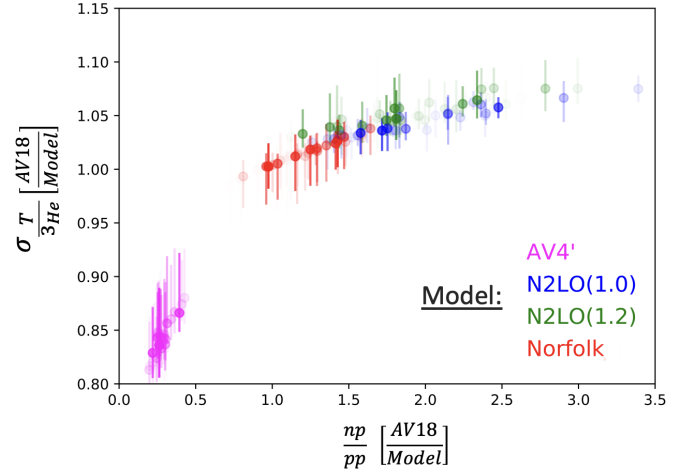

FIG. 4. Tritium to ^{3}He GCF cross-section ratios for different NN interactions [AV4′: magenta; Norfolk: red; N2LO(1.0 fm): blue; N2LO(1.2 fm): green] relative to AV18, plotted vs the corresponding np/pp contact ratio relative to the AV18 ratio. The different points represent different input parameters and intensity of the points is proportional to the probability of the input parameters.

the SRC pair. $\phi_{NN}^\alpha(\mathbf{k}_{\mathrm{rel}})$ are the universal SRC-pair relative wave functions, obtained from the zero-energy solution of the Schrödinger equation for a given NN interaction model and $n_{NN}^{A\alpha}(\mathbf{k}_{\mathrm{cm}})$ is the SRC-pair c.m. momentum distribution for nucleus A, given by a three-dimensional Gaussian [41] (the same for all NN interactions). The delta function $\delta(f(\mathbf{k}_2))$ ensures 4-momentum conservation. See Ref. [16] for details.

While the GCF and the simple pair-counting model both only account for interactions with SRC pairs, the GCF is more realistic by directly accounting for c.m. motion effects and allowing for different pn and pp relative wave functions ϕ_{NN}^α that are calculated using a specific NN interaction. The corresponding SRC contact terms are extracted from *ab initio* nuclear structure calculations using the same NN interaction model (typically also including $3N$ forces).

Figure 4 shows the calculated GCF cross-section ratio for a variety of potentials relative to the AV18 calculation. The calculated cross-section ratios are plotted versus the corresponding np/pp contacts ratio, extracted for the different interactions relative to the AV18 extraction. The calculation follows Ref. [34] using the contact extractions of Ref. [11], where different points represent different samples of the pair c.m. momenta and contact ratios. The intensity of the points is proportional to the probability of the input parameters. The chiral effective field theory (EFT) potentials [18–23] cross-section ratios agree with the AV18 result to about 5%. At the same time their corresponding np/pp ratios vary by a factor of 2.5. The tensorless AV4′ potential [17] gives a cross-section ratio that is only 10%–15% smaller than AV18, but an np/pp ratio that is four times smaller. This is another indication that the $A = 3$ inclusive cross-section ratio has little sensitivity to the SRC-pair isospin structure.

Our previous $A = 3$ GCF cross-section ratio calculation using the AV18 interaction (Fig. S1 of Ref. [34]) is about 15%

larger than the exact AV18 spectral-function calculation of Fig. 2. This difference is likely due to non-SRC-pair contributions to the spectral function (see Fig. 3). Such contributions are not included in SRC-based approximations, such as the GCF or the simple pair-counting model, limiting their applicability for the analysis of inclusive cross sections.

To conclude, Ref. [1] measured the ^{3}He $/ ^3$H inclusive (e, e') cross-section ratio, compared it to a simple pair-counting model, and interpreted the difference as evidence for "unexpected structure in the high-momentum wave function for hydrogen-3 and helium-3."

In contrast, we showed that these ratios agree with a theoretical calculation using a full *ab initio* AV18-interaction-based three-body spectral function (Fig. 2). This suggests that the data are consistent with current nuclear theory and contradicts the claim of Ref. [1].

The *ab initio* calculation differs from the simple pair-counting model by 8% (Fig. 1) and from the less-simple GCF pair-counting model for the same NN interaction by 15%. These differences appear to stem from one- and three-nucleon contributions to the claimed SRC-pair scaling region (Fig. 3). This difference is amplified by the small sensitivity of the measured inclusive cross-section ratio to the underlying SRC pair isospin structure, leading to a factor of 5 uncertainty in the np/pp ratio.

Using the GCF we found that the cross-section ratio is not sensitive to the NN-interaction model (see Fig. 4) and hence not sensitive to the np/pp SRC-pair ratio. This is in contrast with one- and two-nucleon knockout cross-section ratios that are very sensitive to the NN-interaction model.

Therefore, current inclusive cross-section ratios are consistent with our knowledge of the nuclear structure of the $A = 3$ system and cannot be used to precisely quantify the np/pp SRC-pair ratio. The overarching quest to fully understand the short-distance structure of the $A = 3$ system requires additional work through varied experimental measurements and state-of-the-art theoretical calculations with quantified uncertainties.

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