Study of inclusive electron scattering scaling using the generalized contact formalism

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The relative abundances of short-range correlated (SRC) nucleon pairs in atomic nuclei are typically extracted from measurements of the per-nucleon inclusive electron scattering cross-section ratio of nucleus A to the deuteron, \(a_2 = (\sigma_A/A)/(\sigma_d/2)\), at high-\(x_B\) and large-\(Q^2\). Despite extensive measurements, theoretical calculations of \(a_2\) are sparse. Here we study the sensitivity of \(a_2\) to the abundance of SRC nucleon pairs using the generalized contact formalism (GCF), which successfully describes nucleon knockout from SRC pairs up to 1000 MeV/c of initial momentum. The GCF reproduces the measured plateau in the cross-section ratio and the values of \(a_2\). However, using a non-relativistic instant-form formulation, the data are only reproduced using model parameters that are inconsistent with ab-initio many body calculations. The calculations also show large sensitivity to the model parameters. Using a light-cone GCF formulation significantly decreases this sensitivity and improves the agreement with ab-initio calculations. We conclude that empirical SRC pair abundances extracted directly from \(a_2\) measurements cannot be regarded as having accuracy that is better than \(\sim 20\%\) and that precision studies of the nuclear mass and asymmetry dependence of SRC pair abundances must rely on cross-section calculations that properly account for relativistic effects.

Short-range correlations (SRCs) are pairs of strongly-interacting nucleons at short-distance [1, 2]. As SRC pairs cannot be described by traditional independent-particle (i.e., mean-field) nuclear models, modeling their abundances is a formidable task that is primarily undertaken by ab-initio many-body calculations [3–10]. Measurements of SRC abundances and characteristics can provide insight to two-particle correlations in nuclear systems and be used to test ab-initio nuclear calculations.

Most recent experimental data on SRCs comes from measurements of high momentum transfer electron-scattering reactions. These include measurements of inclusive (\(e, e'\)) cross sections, used to extract the abundances of SRC pairs [11–16], and semi-inclusive (\(e, e'N\)) and exclusive (\(e, e'NN\)) reactions that are used to quantify the detailed properties of SRC pairs such as their isospin structure and the underlying short-ranged nucleon-nucleon (\(NN\)) interactions [17–25].

Here we study the extraction of SRC pair abundances from inclusive (\(e, e'\)) measurements. The extraction of SRC abundances from experimental data has far reaching implications, due to their use in modeling the impact of SRCs on the nuclear symmetry energy and neutron-star properties [26–28] and in studies of the modification of quark distributions in nuclei [1, 14, 29–33] and its implications for studies of QCD symmetry breaking mechanisms [34, 35].

We used the generalized contact formalism (GCF) to calculate high-\(x_B\) high-\(Q^2\) inclusive scattering cross-sections (where \(x_B = Q^2/2m\omega\), \(Q^2 = q^2 - \omega^2\), \(q\) and \(\omega\) are the three-momentum and energy transfer respectively, and \(m\) is the nucleon mass). By comparing measured and GCF-calculated cross-sections using different parameters we provide a new, quantitative understanding of the model dependency of SRC pair abundance extraction and the interpretation of inclusive scattering cross-sections.

The GCF is an effective model of SRCs, used to connect experimental data and ab-initio nuclear structure calculations [10, 36, 37]. Due to their strong interaction and small separation, nucleons in SRC pairs can be modeled as being scale-separated from the surrounding nuclear environment, which gives rise to a universal behavior for nucleons in SRC pairs. Therefore, the distributions of nucleons in SRC pairs are modeled using universal two-particle functions and system- and state-dependent contact terms that describe the abundance of SRC pairs. The parameters of the GCF were previously determined from ab-initio calculations or from data [38, 39].

The GCF was shown to successfully reproduce ab-initio calculated nucleon distributions at short-distance and high-momentum, enabling a meaningful extraction of contact terms [10, 36, 37]. More recently, it was extended to model nuclear spectral and correlation functions [40, 41] enabling a successful reproduction of a wide range of (\(e, e'N\)) and (\(e, e'NN\)) measurements [23, 37–39, 41, 42]. It thus provides an established and robust formalism to describe experimental data using effective parameters obtained from many-body calculations.

Our calculations are done within the one-photon exchange approximation, where the electron emits a virtual photon of momentum \(\vec{q}\) and energy \(\omega\) that is absorbed by a single nucleon in the target nucleus A. In inclusive scattering only the electron is measured, and the cross section is denoted by \(\sigma_A(x_B, Q^2)\).
The experimental extraction of SRC abundances relies on the observation that at $Q^2 \gtrsim 1.4 \text{ GeV}^2$ and $1.5 \leq x_B \leq 1.9$, the per-nucleon cross-section ratio for nucleus $A$ relative to deuterium $(\sigma_A(x_B,Q^2)/A)/(\sigma_d(x_B,Q^2)/2)$ appears to “scale,” i.e., is independent of $x_B$ [11–16]. According to common interpretation [1, 11–16], this scaling plateau measures the relative number of neutron-proton $(np)$ deuteron-like SRC pairs in $A$ relative to deuterium. The average value of $(\sigma_A(x_B,Q^2)/A)/(\sigma_d(x_B,Q^2)/2)$ for $1.5 \leq x_B \leq 1.9$ is defined as $a_2(A/d)$ or simply $a_2$. This scaling naturally arises in a simplistic SRC picture where the struck nucleon belongs to a stationary deuteron-like pair. In this picture the nuclear recoil momentum is primarily carried by a single nucleon in both deuterium and heavier nuclei, and the $A – 2$ residual nucleus does not recoil. Therefore, the minimum allowed initial momenta $k_{min}$ of the struck nucleon, and its ground-state momentum distribution, are similar in deuterium and heavier nuclei, resulting in cross-section ratio scaling.

The measured cross-section ratios scale starting at $x_B \approx 1.5$ for $Q^2 \gtrsim 1.4 \text{ GeV}^2$. This corresponds, for the deuteron, to $k_{min} \sim k_F$ (see Fig. 1). Here $k_F \approx 250 \text{ MeV}/c$ is the typical nuclear Fermi momentum. Nucleons with these momenta are predominantly part of deuteron-like SRC pairs [18, 19], and therefore the cross-section for this reaction should be proportional to the number of such pairs.

It is important to note that final-state interaction (FSI) can contribute to the measured $(e,e')$ cross-sections and disrupt this simplistic interpretation of $a_2$. While such contributions grow with $x_B$ and can reach up to 50%, it was argued by several calculations [11, 43–48] (but not all [47]) that they are confined to within SRC pairs and cancel to a first approximation in the $A/d$ ratio.

Even when neglecting FSIs, this intuitive interpretation of $a_2$ in terms of SRC abundances neglects important differences between the deuteron and SRCs in heavier nuclei, including: (1) the presence of non-deuteron-like SRCs (proton-proton $(pp)$, neutron-neutron $(nn)$, and $pn$ pairs with $s \neq 1$), (2) pair center-of-mass (CM) motion [21], and (3) possible excitation of the residual $A – 2$ system. CM motion and $A – 2$ excitation alone can dramatically affect $k_{min}$, see Fig. 1. These $k_{min}$ differences can significantly affect the simplistic interpretation of $a_2$.

To quantify the impact of these effects we perform GCF calculations of inclusive cross-section ratios using various parameters and compare them to each other and to experimental data. Due to the high initial momentum of the nucleons involved, relativistic effects might be significant. Therefore, we examine both non-relativistic instant-form (IF) and light-cone (LC) GCF formulations.

We previously derived the GCF cross-section expressions for $(e,e'N)$ and $(e,e'NN)$ SRC measurements in IF and LC formulations. Both showed excellent agreement with data [38, 39]. By integrating these cross-sections over the knocked-out nucleons, we obtain the inclusive $(e,e')$ cross-section.

Within the plane-wave impulse approximation (PWIA), the IF GCF $(e,e'N)$ cross-section for the breakup of an SRC pair is given by [39]

$$d^3\sigma_A \overline{dE_\odot d\Omega_\odot d\overline{p}_{CM} d\overline{p}_{rel}} = \kappa_{IF} \sum_{N_1,N_2,\beta} s_\sigma C_{N_1,N_2}^{A,\beta} \mid f_{F,N_1,N_2}(\overline{p}_{rel}) \mid^2 n_{N_1,N_2}^{A,\beta} \langle \overline{p}_{CM} \rangle$$

$$\equiv \sum_{N_1,N_2,\beta} C_{N_1,N_2}^{A,\beta} \times s_\sigma \langle \overline{p}_{CM} \rangle$$

(1)

where $E_\odot$ and $\Omega_\odot$ are the energy and solid angle of the scattered electron, and $\overline{p}_{CM}$ and $\overline{p}_{rel}$ are the CM and relative momenta of the initial-state SRC pair, respectively. $\sigma_{N_1}$ is the off-shell electron-nucleon cross section, $s$ is a symmetry factor ($s = 1$ for $np$ and $pm$ and $s = 2$ for $nn$ and $pp$), and $\kappa_{IF} \equiv \sum_{N_1,N_2,\beta} \langle \overline{p}_{rel}^\beta E_1^\beta E_2^\beta \rangle_{IF}$ is a kinematic factor, where $(\overline{p}_1^\beta, E_1^\beta)$ and $(\overline{p}_2^\beta, E_2^\beta)$ are the knocked-out and spectator nucleon four-momenta, respectively. $|\overline{p}_{rel}|$ is fixed by energy-momentum conservation.

$C_{N_1,N_2}^{A,\beta}$ are nucleus-dependent nuclear contacts, measuring the probability to find an $N_1 N_2$ SRC pair $(pp, nn, np$ or $pn)$ in nucleus $A$ with quantum numbers $\beta$. $\beta = 1$ denotes spin-one deuteron-like pairs, and $\beta = 0$ is for the spin-zero $s$-wave pairs. $n_{N_1,N_2}^{A,\beta} \langle \overline{p}_{CM} \rangle$ is the SRC pairs CM momentum distribution, approximated by a three-dimensional Gaussian with an $A$-dependent width.
$\sigma_{CM}$ [21, 46, 49]. $\varphi_{NN}^o$ are the universal two-body functions of the relative momentum distribution of nucleons in SRC pairs, obtained by solving the zero-energy two-body Schrödinger equation with a given $NN$ interaction model (e.g., AV18, N2LO etc.).

There are no free parameters in this model. The contacts are fixed by comparison with ab-initio calculations [10] and $\sigma_{CM}$ was measured in Ref. [21]. The excitation energy of the residual system $E_{A-2}^*$ was not measured but is bound by the typical excitation energy of the system.

Light-cone four-momentum vectors are expressed in terms of longitudinal (along the $q$ direction) plus- and minus-momentum $p^\pm \equiv p^0 \pm p^3$ and transverse momentum $p^\perp \equiv (p^1, p^2)$. The light-cone momentum fraction is $\alpha \equiv p^-/\tilde{m}$, where $\tilde{m} = m_A/A$. The advantages of studying inclusive reactions using LC are discussed in [11].

The PWIA LC GCF ($e, e'NN$) cross section is given by [39]

$$\frac{d^3\sigma_A}{dE_{\nu}d\Omega_{\nu}d^3p_{CM}d\Omega_{rel}} = \kappa_{LC} \sum_{N_1,2} s\sigma_{eN_1} C_{N_1,N_2}^{A,\beta}(\Omega_{rel}, \vec{p}_{rel}) \rho_{N_1,N_2}(\alpha_{CM}, \vec{p}_{CM}) \equiv \sum_{\beta} C_{N_1N_2}^{A,\beta} \times \sigma_{N_1N_2,LC},$$

where $\alpha_{CM}$, $\vec{p}_{CM}$; $\alpha_{rel}$, and $\vec{p}_{rel}$ are the LC longitudinal, LC transverse, CM, and relative momenta of the SRC pair, respectively. $\kappa_{LC} = \kappa_{IF} \frac{8\pi^3 \alpha_{A-2}}{\alpha_{CM} E_{A-2}}$ is a phase-space factor. $\rho_{N_1N_2}(\alpha_{CM}, \vec{p}_{CM})$ is a three-dimensional gaussian of width $\sigma_{CM}$ and $\psi_{N_1N_2}^{\beta}(\alpha_{rel}, \vec{p}_{rel}) = \frac{\sqrt{m_A^2 + k^2}}{2\alpha_{rel} N_1N_2} (\vec{p}_{rel}^0 N_1 + k)^2$ is the LC equivalent of the IF universal function [50] where $k = \frac{m_A^2 + k^2}{\alpha_{rel} (2\sigma_{rel})} - m^2$.

We can then integrate Eqs. (1) or (2) to get the IF or LC GCF inclusive cross section for kinematics sensitive to two-nucleon densities at short distance for nucleus $A$ and the deuteron [9, 32]. This approach reproduces $\alpha_2$ values, but cannot model the $x_B$ or $Q^2$ dependences of the ratio or provide insight into specific pair characteristics.

Fig. 2 (top panels) shows the measured GCF-calculated ($\sigma_A/A$)/($\sigma_d/d$) cross-section ratio for $^4$He [15] and $^{12}$C [14] using nuclear contacts and c.m. motion width from refs. [10, 19, 21], $E_{A-2}^* = 0 - 30$ MeV, and universal functions calculated with the AV18 $NN$ interaction [51]. The calculation is shown as a 68% confidence band, due to the uncertainty in these input parameters. Both IF and LC ratios show scaling plateaus (i.e. are constant for $1.4 < x_B < 1.9$), but the IF ratio is about a factor of $1.5 - 2$ too low. The larger c.m. motion of pairs in $^{12}$C makes the calculation less flat and in better, but not good, agreement with the data. Calculations of additional nuclei, and using different $NN$ interactions, are shown in the online supplementary materials and show a similar disagreement with experimental data.

This is very surprising, as the IF calculation reproduces ($e, e'N$) and ($e, e'NN$) data at similar kinematics remarkably well [39]. The LC ratios are better, but are
still ≈ 25% for $^4$He and ≈ 10% for $^{12}$C below the data. Possible reasons for this disagreement include the effects of $A$-dependent FSIs [47]. From the theoretical side, one should note that the $(e, e')N$ and $(e, e'N)N$ data are sensitive to contact ratios for a given nucleus and not for nuclei relative to deuterium. Furthermore, we cannot rule out the possibility that the observed disagreement with $a_2$ data points to an issue with the contact extraction of from ab-initio calculations. In the LC case it could also be that this extraction requires corrections for relativistic effects that are missing in these calculations.

To better understand this discrepancy we go back to Fig. 1 and Eq. 3 which show that the cross-section ratio $a_2$ will only equal the relative abundance of SRC pairs, $C_{np}^{A,s=1}/C_{np}^{d,s=1}$, if (1) the SRC CM motion in nucleus $A$ is zero ($\sigma_{CM} = 0$), (2) no extra energy is needed to knockout the $pn$ SRC pair (i.e., there is no binding energy or residual nuclear excitation energy), and (3) Non deuteron-like SRCs contributions are negligible. Violations of these approximations change the traditional interpretation of $a_2(A/d)$ in terms of SRC abundances.

While the calculation shown in Fig. 2 (top panels) accounts for these effects, it is instructive to examine their individual impacts. To this end we calculated the ratio of the $^{4}$He cross-section for $\sigma_{CM} = 50, 100$ and $150$ MeV/c and $E_{A-2} = 0$ and $15$ MeV, divided by the same cross-section at $\sigma_{CM} = 100$ MeV/c and $E_{A-2} = 15$ MeV. This is shown in Fig. 2 (bottom panels) for both IF and LC GCF formulations.

The IF calculation is very sensitive to the values of $\sigma_{CM}$ and $E_{A-2}^*$. A $15$ MeV change in $E_{A-2}^*$ changes the cross-section by $\sim 20\%$. A $50$ MeV/c change in $\sigma_{CM}$ changes the cross section dramatically starting at $x_B = 1.7$. Ref. [53] also predicted large effects (up to $70\%$) due to pair CM motion, which is very different than the $19 \pm 6\%$ $x_B$-independent correction used by Ref. [15], motivated by a simplistic one-dimensional gaussian smearing of the deuteron momentum distribution [54].

This sensitivity raises concerns about the ability to empirically study the nuclear mass and asymmetry dependence of SRC pairs abundances using $(e, e')$ measurements of light nuclei where $\sigma_{CM}$ and $E_{A-2}^*$ vary significantly.

Lastly we studied what values of GCF parameters would be necessary to describe the data and if these values were physically reasonable. We varied the GCF parameters, $\sigma_{CM}$, $E_{A-2}^*$ and the spin-1 contact ratio $C_{np}^{A,s=1}/C_{np}^{d,s=1}$, to fit the $^{4}$He [15] and $^{12}$C data [14]. We used both the AV18 [51] and N2LO [55] interactions with both IF and LC GCF formulations. We kept the $C_{np}^{d,s=1}/C_{NN}^{d,s=1}$ ratio fixed at the values determined in Ref. [10]. We also choose to exclude the highest $x_B$ data point from the fit as its very close to the kinematical limit of deuterium. The IF and LC results both described the data well. See online supplementary materials for details.

Table I compares the fitted model parameters to previous extractions. The confidence intervals of the model

![Graph](image)

### Table I: GCF model parameters obtained by fitting Eq. 1 - 3 to $^4$He [15] and $^{12}$C [14] data. Contact values extracted from ab-initio VMC calculations [10], pairs c.m. motion widths extracted from $A(e,e'pN)$ data [19, 21], and measured $a_2$ values [14, 15], are also listed for reference. Uncertainties are shown at the $68\%$ or $1\sigma$ level. See text for details.

| $^4$He Exp. | $^12$C Exp. | $a_2(A/d)$ | $C_{np}^{A,s=1}(A/d)$ | $\sigma_{CM}$ (MeV/c) | $E_{A-2}^*$ (MeV) |
|-------------|-------------|-------------|-----------------------|----------------------|------------------|
| $^{4}$He Exp. | $^4$He Exp. | $3.66 \pm 0.07$ | $-1.36 \pm 0.07$ | $100 \pm 20$ | $-100$ |
| AV18        | N2LO       | $2.57 \pm 0.25$ | $1.11 \pm 0.15$ | $77^{+4}_{-2}$ | $<16$         |
| IF Fit      | Fit-IF     | $1.44 \pm 0.10$ | $112^{+3}_{-16}$ | N/A      |
| LC Fit      | Fit-LC     | $2.64 \pm 0.29$ | $52^{+5}_{-3.5}$ | $<4$      |
| Ab-Initio   | Ab-Initio  | $3.26 \pm 0.21$ | $95^{+3}_{-15}$  | N/A      |
| $^{12}$C Exp. | $^{12}$C Exp. | $4.49 \pm 0.17$ | $-143 \pm 5$ | $-100$ |
| AV18        | N2LO       | $3.32 \pm 0.37$ | $88^{+5}_{-2}$ | N/A      |
| IF Fit      | IF Fit     | $5.06^{+0.33}_{-0.17}$ | $88^{+5}_{-2}$ | N/A      |
| LC Fit      | IF Fit     | $4.39^{+0.33}_{-0.25}$ | $110^{+3}_{-3.5}$ | N/A      |
| Ab-Initio   | Ab-Initio  | $2.27 \pm 0.23$ | $65^{+5}_{-2}$  | $<10$     |
| $^{12}$C Exp. | $^{12}$C Exp. | $3.88^{+0.27}_{-0.10}$ | $88^{+5}_{-2}$ | N/A      |
| AV18        | N2LO       | $4.03^{+0.33}_{-0.09}$ | $87^{+5}_{-2}$  | N/A      |
parameters and their correlations are shown in Fig. 3. Results for using N2LO and for $^3\text{He}$ are shown in the on-line supplementary materials. The fitted contacts have overall large uncertainties reaching 30% for IF and just under 10% for LC. This is significantly higher than the typical 2% experimental uncertainties in $a_2$ measurements. For the LC case this comes primarily from the freedom in determining $\sigma_{CM}$ in the fit (IF is also sensitive to $E^\ast$). While we fixed the ratio of spin-0 to spin-1 contacts to the VMC value, treating it as a free fit parameter would increase the contacts’ uncertainties even more.

Thus, future $a_2$ measurements might be very precise, but the uncertainty in the extracted SRC abundances (i.e. contact ratio) will be of the order of 10-20%. This will not allow a precise $A$-dependence study. These can be improved by supplementing $a_2$ measurements with $\sigma_{CM}$ and $pp/pm$ measurements to allow accurate experimental extraction of deuteron-like SRC abundances.

Comparing with VMC calculations, the IF fitted contact ratios for deuteron-like $np$ pairs are higher by $50-150\%$ for both $NN$ interactions and both nuclei, as expected from the results of Fig. 2. The LC fitted contacts are $20-30\%$ higher than the $^4\text{He}$ VMC calculations for both $NN$ interactions, which is not much more than the $\sim 10\%$ uncertainties on both the calculated and fitted contacts. For $^{12}\text{C}$ the same holds true for AV18 but a larger 80% disagreement is observed for N2LO.

Comparing with $a_2$, that are traditionally interpreted as a measure of deuteron-like $np$ pairs, the fitted values are within $10-15\%$ of the data for both $^4\text{He}$ and $^{12}\text{C}$, except for IF N2LO where its $\sim 30\%$. However, this is an accidental result of the cancellation between the effects of $\sigma_{CM}$ and the contribution of non-deuteron-like pairs, which increase the ratio, and the effect of $E_{A-2}^\ast$ (especially for IF) which decreases the ratio. This cancellation should be quite different in light and asymmetric nuclei where $\sigma_{CM}$ and $E_{A-2}^\ast$ and the $np/pp$-pair ratio can change rapidly with $A$.

The results obtained using AV18 and N2LO are very similar. As they have very different short-distance $NN$ interaction, our observations support the previous claims that $a_2$ measurements have minimal sensitivity to the underlying nature of the short-distance high-momentum $NN$ interaction [10].

Therefore, our calculations suggest that the traditional interpretation of $a_2(A/d)$ as an empirical measure of the abundance of deuteron-like $np$-SRC pairs in nucleus $A$ relative to the deuteron is accurate to about 20%. This has significant implications for planned precision measurements [56] of the nuclear mass and asymmetry dependence of $a_2$, especially for light nuclei. While the cross section ratio $a_2$ can be measured precisely, supplemental ($e, e'N$) and ($e, e'NN$) measurements and detailed cross section calculations are needed for its accurate interpretation.

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