2018

Center of Mass Motion of Short-Range Correlated Nucleon Pairs Studied Via the A(e, e'pp) Reaction

CLAS Collaboration

L. B. Weinstein
Old Dominion University

M. J. Amaryan
Old Dominion University, mamaryan@odu.edu

F. Hauenstein
Old Dominion University

A. Klein
Old Dominion University

See next page for additional authors

Follow this and additional works at: https://digitalcommons.odu.edu/physics_fac_pubs

Part of the Nuclear Commons

Repository Citation
CLAS Collaboration; Weinstein, L. B.; Amaryan, M. J.; Hauenstein, F.; Klein, A.; and Kuhn, S. E., "Center of Mass Motion of Short-Range Correlated Nucleon Pairs Studied Via the A(e, e'pp) Reaction" (2018). Physics Faculty Publications. 227.
https://digitalcommons.odu.edu/physics_fac_pubs/227

Original Publication Citation

This Article is brought to you for free and open access by the Physics at ODU Digital Commons. It has been accepted for inclusion in Physics Faculty Publications by an authorized administrator of ODU Digital Commons. For more information, please contact digitalcommons@odu.edu.
Center of Mass Motion of Short-Range Correlated Nucleon Pairs studied via the $A(e,e'pp)$ Reaction


1School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
2Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
3Old Dominion University, Norfolk, Virginia 23529, USA
4Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile
5Argonne National Laboratory, Argonne, Illinois 60439, USA
6Arizona State University, Tempe, Arizona 85287-1504, USA
7California State University, Dominguez Hills, Carson, California 90747- USA
8Canisius College, Buffalo, New York 14208, USA
9Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
10Catholic University of America, Washington, DC 20064, USA
11IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
12Christopher Newport University, Newport News, Virginia 23606, USA
13University of Connecticut, Storrs, Connecticut 06269, USA
14Duke University, Durham, North Carolina 27708-0305, USA
15Fairfield University, Fairfield Connecticut 06824, USA
16Università di Ferrara, 44121 Ferrara, Italy
17Florida International University, Miami, Florida 33199, USA
18Florida State University, Tallahassee, Florida 32306, USA
19INFN, Sezione di Ferrara, 44121 Ferrara, Italy
20INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy
21INFN, Sezione di Genova, 16146 Genova, Italy
22INFN, Sezione di Roma Tor Vergata, 00133 Rome, Italy
23INFN, Sezione di Torino, 10125 Torino, Italy
24Institut de Physique Nucléaire, CNRS/IN2P3 and Université Paris-Sud, Orsay, France
25Institute of Theoretical and Experimental Physics, Moscow, 117259, Russia
26James Madison University, Harrisonburg, Virginia 22807, USA
27Kyoungpook National University, Daegu 41566, Republic of Korea
28Mississippi State University, Mississippi State, Mississippi 37962-5167, USA
29University of New Hampshire, Durham, New Hampshire 03824-3568, USA
30Nuclear Research Centre Negev, Beer-Sheva, Israel
31Norfolk State University, Norfolk, Virginia 23504, USA
32Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019, USA
33University of Perugia, I-06123 Perugia, Italy
34University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
35University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
36University of São Paulo, São Paulo, Brazil
37University of Texas at Dallas, Richardson, Texas 75080, USA
38University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
39Virginia Commonwealth University, Richmond, Virginia 23284, USA
40Weizmann Institute of Science, Rehovot, Israel
41Washington State University, Pullman, Washington 99163, USA
42Western Carolina University, Cullowhee, North Carolina 28723, USA
43Western University, London, Ontario N6A 5B7, Canada
44Mississippi State University, Mississippi State, Mississippi 37962-5167, USA
45University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
46University of York, Heslington, York YO10 5DD, United Kingdom
0031-9007/18/121(9)/092501(7) © 2018 American Physical Society

PHYSICAL REVIEW LETTERS 121, 092501 (2018)
Short-range correlated (SRC) nucleon pairs are a vital part of the nucleus, accounting for almost all nucleons with momentum greater than the Fermi momentum ($k_F$). A fundamental characteristic of SRC pairs is having large relative momenta as compared to $k_F$, and smaller center of mass (c.m.) which indicates a small separation distance between the nucleons in the pair. Determining the c.m. momentum distribution of SRC pairs is essential for understanding their formation process. We report here on the extraction of the c.m. motion of proton-proton ($pp$) SRC pairs in carbon and, for the first time in heavier and asymmetric nuclei: aluminum, iron, and lead, from measurements of the $A(e,e'pp)$ reaction. We find that the pair c.m. motion for these nuclei can be described by a three-dimensional Gaussian with a narrow width ranging from 140 to 170 MeV$/c$, approximately consistent with the sum of two mean-field nucleon momenta. Comparison with calculations appears to show that the SRC pairs are formed from mean-field nucleons in specific quantum states.

The atomic nucleus is a complex, strongly interacting, many-body system. Effective theories can successfully describe the long-range part of the nuclear many-body wave function. However, the exact description of its short-range part is challenging. This difficulty is due to the complexity of the nucleon-nucleon ($NN$) interaction and the large nuclear density, which make it difficult to simplify the problem using scale-separated approaches when describing the short-range part of the nuclear wave function.

Recent experimental studies have shown that approximately 20% of the nucleons in the nucleus belong to strongly interacting, momentary, short-range correlated (SRC) nucleon pairs [1–4]. These pairs are predominantly proton-neutron pairs with a center-of-mass (c.m.) momentum $p_{c.m.}$ that is comparable to any two nucleons in the nuclear ground state and a much higher relative momentum $p_{rel}$ between the nucleons in the pair ($>k_F$, the nuclear Fermi momentum) [5–10]. They account for almost all of the nucleons in the nucleus with momentum greater than $k_F$ and for 50% to 60% of the kinetic energy carried by nucleons in the nucleus [10–14]. See Refs. [15–17] for recent reviews. SRC pairs are thus a vital part of nuclei with implications for many important topics including the possible modification of bound nucleon structure and the extraction of the free neutron structure function [15,18–22], neutrino-nucleus interactions and neutrino oscillation experiments [23–28], neutrino-less double beta decay searches [29,30], as well as neutron star structure and the nuclear symmetry energy [31–33].

The smaller c.m. momentum as compared to the large relative momentum of SRC pairs is a fundamental characteristic of such pairs, and is an essential indications that the nucleons in the pair are in close proximity with limited interaction with the surrounding nuclear environment [34]. Modern calculations [35] indicate that SRC pairs are temporary fluctuations due to the short-range part of the $NN$ interaction acting on two nucleons occupying shell-model (“mean-field”) states. The exact parenting and formation process of SRC pairs is not well understood. While state-of-the-art many-body calculations of one- and two-body momentum densities in nuclei [12,36,37] seem to produce SRC features that are generally consistent with measurements, they do not offer direct insight into the effective mechanisms of SRC pair formation.

Effective calculations using scale-separated approaches agree with many-body calculations [11,34,38,39], suggesting that, at high-momenta, the momentum distribution of SRC pairs can be factorized into the c.m. and relative momentum distributions,

$$n_{\text{SRC}}(\vec{p}_1, \vec{p}_2) \approx n^A_{\text{c.m.}}(\vec{p}_{\text{c.m.}}) n^{NN}_{\text{rel}}(\vec{p}_{\text{rel}}),$$

(1)

The atomic nucleus is a complex, strongly interacting, many body system. Effective theories can successfully describe the long-range part of the nuclear many-body wave function. However, the exact description of its short-range part is challenging. This difficulty is due to the complexity of the nucleon-nucleon ($NN$) interaction and the large nuclear density, which make it difficult to simplify the problem using scale-separated approaches when describing the short-range part of the nuclear wave function.

Recent experimental studies have shown that approximately 20% of the nucleons in the nucleus belong to strongly interacting, momentary, short-range correlated (SRC) nucleon pairs [1–4]. These pairs are predominantly proton-neutron pairs with a center-of-mass (c.m.) momentum $p_{c.m.}$ that is comparable to any two nucleons in the nuclear ground state and a much higher relative momentum $p_{rel}$ between the nucleons in the pair ($>k_F$, the nuclear Fermi momentum) [5–10]. They account for almost all of the nucleons in the nucleus with momentum greater than $k_F$ and for 50% to 60% of the kinetic energy carried by nucleons in the nucleus [10–14]. See Refs. [15–17] for recent reviews. SRC pairs are thus a vital part of nuclei with implications for many important topics including the possible modification of bound nucleon structure and the extraction of the free neutron structure function [15,18–22], neutrino-nucleus interactions and neutrino oscillation experiments [23–28], neutrino-less double beta decay searches [29,30], as well as neutron star structure and the nuclear symmetry energy [31–33].

The smaller c.m. momentum as compared to the large relative momentum of SRC pairs is a fundamental characteristic of such pairs, and is an essential indications that the nucleons in the pair are in close proximity with limited interaction with the surrounding nuclear environment [34]. Modern calculations [35] indicate that SRC pairs are temporary fluctuations due to the short-range part of the $NN$ interaction acting on two nucleons occupying shell-model (“mean-field”) states. The exact parenting and formation process of SRC pairs is not well understood. While state-of-the-art many-body calculations of one- and two-body momentum densities in nuclei [12,36,37] seem to produce SRC features that are generally consistent with measurements, they do not offer direct insight into the effective mechanisms of SRC pair formation.

Effective calculations using scale-separated approaches agree with many-body calculations [11,34,38,39], suggesting that, at high-momenta, the momentum distribution of SRC pairs can be factorized into the c.m. and relative momentum distributions,

$$n_{\text{SRC}}(\vec{p}_1, \vec{p}_2) \approx n^A_{\text{c.m.}}(\vec{p}_{\text{c.m.}}) n^{NN}_{\text{rel}}(\vec{p}_{\text{rel}}),$$

(1)
where $|\vec{p}_{\text{rel}}|$ is greater than $k_F$ and $|\vec{p}_{\text{c.m.}}| < |\vec{p}_{\text{rel}}|$ [34,39,40]. This implies that the relative momentum distribution of SRC pairs, $n_{\text{rel}}^\pm(\vec{p}_{\text{rel}})$, is a universal function of the short-range part of the $(N/N)$ interaction, such that the many-body nuclear dynamics affect only the c.m. momentum distribution, $n_{\text{c.m.}}^\pm(\vec{p}_{\text{c.m.}})$. Therefore, extracting the c.m. momentum distribution of SRC pairs can provide valuable insight into their formation process.

The c.m. momentum distributions of SRC pairs in $^4\text{He}$ and C have been extracted previously from $A(e,e'pN)$ and $A(p,2pn)$ measurements [5,7,9]. Here we present the first study of the c.m. momentum distribution of $pp$ SRC pairs in nuclei heavier than C using the $A(e,e'pp)$ reaction. The cross section for this $(e,e'pp)$ two-nucleon knockout reaction in some kinematics approximately factorizes as a kinematic term times the elementary electron-proton cross section times the nuclear decay function, which defines the combined probability of finding the knocked-out nucleon pair with given energies and momenta [6,35,41–43]. The decay function also factorizes into relative and c.m. parts, just like Eq. (1) [6]. Therefore, the $A(e,e'pp)$ cross section is approximately proportional to the c.m. momentum distributions of SRC pairs [6,35,43–45]:

$$\sigma(e,e'pp) \propto n_{\text{c.m.}}^\pm(\vec{p}_{\text{c.m.}}).$$  (2)

To increase sensitivity to the initial state properties of $pp$-SRC pairs, the measurement was done using high energy electrons scattering at large momentum transfer (hard scattering), in kinematics dominated by the hard breakup of SRC pairs, as discussed in detail in Ref. [15]. In this kinematics, Eq. (2) is a good approximation since rescattering of the two outgoing nucleons does not distort the width of the momentum distribution (see discussion below).

The data presented here were collected as part of the EG2 run period that took place in 2004 in Hall B of the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The experiment used a 5.01 GeV electron beam, impinging on $^3\text{H}$ and natural C, Al, Fe, and Pb targets at the CEBAF Large Acceptance Spectrometer (CLAS) [46]. The analysis was carried out as part of the Jefferson Lab Hall B data-mining project.

CLAS used a toroidal magnetic field and six independent sets of drift chambers for charged particle tracking, time-of-flight scintillation counters for hadron identification, and Čerenkov counters and electromagnetic calorimeters for electron-pion separation. The polar angular acceptance was $8^\circ \leq \theta \leq 140^\circ$ and the azimuthal angular acceptance ranged from 50% at small polar angles to 80% at larger polar angles. See Refs. [10,47] for details on the electron and proton identification and momentum reconstruction procedures.

The EG2 run period used a specially designed target setup, consisting of an approximately 2-cm LD$_2$ cryotarget followed by one of six independently insertable solid targets (thin Al, thick Al, Sn, C, Fe, and Pb, all with natural isotopic abundance, ranging between 0.16 and 0.38 g/cm$^2$), see Ref. [48] for details. The LD$_2$ target cell and the inserted solid target were separated by about 4 cm. The few-mm vertex reconstruction resolution of CLAS for both electrons and protons was sufficient to unambiguously separate particles originating in the cryotarget and the solid target.

The kinematics of the $A(e,e'pp)$ reaction is shown schematically in Fig. 1. Identification of exclusive $A(e,e'pp)$ events, dominated by scattering off 2N-SRC pairs, was done in two stages: (i) selection of $A(e,e'p)$ events in which the electron predominantly interacts with a single proton belonging to an SRC pair in the nucleus [8,10,47], and (ii) selection of $A(e,e'pp)$ events by requiring the detection of a second, recoil, proton in coincidence with the $A(e,e')$ reaction.

We selected $A(e,e'p)$ events in which the knocked-out proton predominantly belonged to an SRC pair by requiring a large Bjorken scaling parameter $x_B = Q^2/(2m_p\omega) \geq 1.2$ (where $Q^2 = \vec{q}^2 - \omega^2$, $\vec{q}$ and $\omega$ are the three-momentum and energy, respectively, transferred to the nucleus, and $m_p$ is the proton mass). This requirement also suppressed the effect of inelastic reaction mechanisms (e.g., pion and resonance production) and resulted in $Q^2 \geq 1.4$ GeV$^2$ [7,49]. We also required large missing momentum $300 \lesssim |\vec{p}_{\text{miss}}| \lesssim 600$ MeV/c, where $|\vec{p}_{\text{miss}}| = |\vec{p}_p - \vec{q}|$ with $\vec{p}_p$ the measured proton momentum. We further suppressed contributions from inelastic excitations of the struck nucleon by limiting the reconstructed missing mass of the two-nucleon system $m_{\text{miss}} = [(\omega + 2m - E_p)^2 - \vec{p}_{\text{miss}}^2]^{1/2} \leq 1.1$ GeV/c$^2$ (where $E_p$ is the total energy of the leading proton). We identified events where the leading proton absorbed the transferred momentum by requiring that its momentum $\vec{p}_p$ was within $25^\circ$ of $\vec{q}$ and that $0.60 \leq |\vec{p}_p/|\vec{q}|| \leq 0.96$ [10,47]. As shown by previous experimental and theoretical studies, these conditions enhance the contribution of scattering off nucleons in SRC pairs and suppress contribution from competing effects [49–56].

![Figure 1. Kinematics of the hard breakup of a $pp$-SRC pair in a hard two-nucleons knockout $A(e,e'pp)$ reaction. See text for details.](image)
A( e, e′ p p) events were selected by requiring that the A( e, e′ p) event had a second, recoil proton with momentum |p_{rec} | ≥ 350 MeV/c. There were no events in which the recoil proton passed the leading proton selection cuts described above. The recoil proton was emitted opposite to p_{miss} [10], consistent with the measured pairs having large relative momentum and smaller c.m. momentum.

In the Plane Wave Impulse Approximation (PWIA), where the nucleons do not rescatter as they leave the target, the data shown are not corrected for the CLAS acceptance and resolution effects. As the data shown are not corrected for the CLAS acceptance and resolution effects. We next explain how each effect is accounted for in the data analysis.

(i) Kinematical offsets in the c.m. momentum direction: Since the relative momentum distribution of pairs falls rapidly for increasing |p_{rel}|, it is more likely for an event with a large nucleon momentum (p_{miss}) to be the result of a pair with smaller p_{rel} and a p_{c.m.} oriented in the direction of the nucleon momentum. This kinematical effect will manifest as a shift in the mean of the c.m. momentum distribution in the p_{miss} (nucleon initial momentum) direction. To isolate this effect, we worked in a reference frame in which z∥p_{miss} and x and y are perpendicular to p_{miss}. The extracted c.m. momentum distributions in the x and y directions were observed to be independent of p_{miss} as expected.

(ii) Reaction mechanism effects: These include mainly contributions from meson-exchange currents (MECs), isobar configurations (ICs), and rescattering of the outgoing nucleons (final-state interactions or FSIs) that can mimic the signature of SRC pair breakup and/or distort the measured distributions [50–52].

This measurement was performed at an average Q^2 of about 2.1 GeV^2 and x_g ≥ 1.2 to minimize the contribution of MEC and IC relative to SRC breakup [49,53–55]. Nucleons leaving the nucleus can be effectively “absorbed,” where they scatter inelastically or out of the phase space of accepted events. The probability of absorption ranges from about 0.5 for C to 0.8 for Pb [47,57–60]. Nucleons that scatter by smaller amounts (i.e., do not scatter out of the phase space of accepted events) are still detected, but have their momenta changed. This rescattering includes both rescattering of the struck nucleon from its correlated partner and from the other A − 2 nucleons. Elastic rescattering of the struck nucleon from its correlated partner will change each of their momenta by equal and opposite amounts, but will not change p_{c.m.} [see Eq. (3)] [49,55]. To minimize the effects of rescattering from the other A − 2 nucleons, not leading to absorption, we selected largely antiparallel kinematics, where p_{miss} has
a large component antiparallel to $\vec{q}$ [49]. Relativistic Glauber calculations show that, under these conditions, FSI are largely confined to within the nucleons of the pair [17,49,55,56,61].

The probability of the struck nucleon rescattering from the $A-2$ nucleons is expected to increase with $A$. Such rescattering, when not leading to reduction of the measured flux (i.e., absorption), should broaden the extracted c.m. momentum distribution. The measured widths do not increase strongly with $A$. This provides evidence that, in the kinematics of this measurement, FSI with the other $A-2$ nucleons do not distort the shape of the measured c.m. momentum distribution, in agreement with theoretical calculations [49,55,56].

In addition, single charge exchange $(n,p)$ processes can lead to the detection of an $A(e,e'pp)$ event that originate from the hard breakup of an np-SRC pair. While such SCX processes have relatively low cross sections, the predominance of SRC pairs by $np$ pairs enhances its impact in measurements of the $A(e,e'pp)$ reaction. Using the formalism of Ref. [55], assuming the abundance of np-SRC pairs is 20 times higher than that of $pp$-SRC pairs, we estimate that such SCX processes account for approximately 40% of the measured $A(e,e'pp)$ events. This is a large fraction that could impact the interpretation of the data. However, as $pp$- and $np$-SRC pairs are expected to have very similar c.m. momentum densities [35,55], this effect should not have a significant impact on the width of the c.m. momentum density.

(iii) Detector acceptance and resolution effects: While CLAS has a large acceptance, it is not complete, and the measured c.m. momentum distributions need to be corrected for any detector related distortions. Following previous analyses [7–9], we corrected for the CLAS acceptance in a 6-stage process. (i) We modeled the c.m. momentum distribution as a three-dimensional Gaussian, parametrized by a width and a mean in each direction. In the directions transverse to $\hat{p}_{\text{miss}}$, the widths were assumed to be constant and equal to each other ($\sigma_x = \sigma_y = \sigma_z$) and the means were fixed at zero. In the direction parallel to $\hat{p}_{\text{miss}}$, both the mean and the width were varied over a wide range. (ii) For a given set of parameters characterizing the c.m. momentum distribution in step (i), we generated a synthetic sample of $A(e,e'pp)$ events by performing multiple selections of a random event from the measured $A(e,e'p)$ events and a random $\hat{p}_{c.m.}$ from the 3D Gaussian. The combination of the two produced a sample of recoil protons with momentum ($\hat{p}_{\text{recoi}} = \hat{p}_{c.m.} - \hat{p}_{\text{miss}}$). (iii) We determined the probability of detecting each recoil proton using GSIM, the GEANT3-based CLAS simulation [62]. (iv) We analyzed the Monte Carlo events in the same way as the data to extract the c.m. momentum distributions and fit those distributions in the directions transverse to $\hat{p}_{\text{miss}}$ with a Gaussian to determine their reconstructed width. (v) We repeated steps (i) to (iv) using different input parameters for the 3D Gaussian model used in step (i) and obtained a “reconstructed” $\sigma_i$ for each set of input parameters. $\sigma_i$ was varied between 0 and 300 MeV/c. The mean and width in the $\hat{p}_{\text{miss}}$ direction were sampled for each nucleus from a Gaussian distribution centered around the experimentally measured values with a nucleus dependent width ($1\sigma$) ranging from 45 to 125 MeV/c for the mean and 30 to 90 MeV/c for the width. The exact value of the width of the distribution is a function of the measurement uncertainty for each nucleus. It extends far beyond the expected effect of the CLAS acceptance. (vi) We examined the distribution of the generated vs reconstructed widths in the directions transverse to $\hat{p}_{\text{miss}}$ to determine the impact of the CLAS acceptance on the measured values.

The net effect of the acceptance corrections was to reduce the widths of the c.m. momentum distributions by 15–20 MeV/c for each nucleus and to increase the uncertainties.

As a sensitivity study for the acceptance correction procedure, we examined two additional variations to the event generator in the $\hat{p}_{\text{miss}}$ direction: (A) a constant width of 70 MeV/c and (B) a width and mean that varied as a linear function of $|p_{\text{miss}}|$. The variation among the results obtained using each method was significantly smaller than the measurement uncertainties and gives a systematic uncertainty of 7%. We also performed a “closure” test where we input pseudodata with known width and statistics that matched the measurements, passed it through the CLAS acceptance to see the variation in the “measured” width and then applied the acceptance correction to successfully retrieve the generated value.

The CLAS reconstruction resolution, $\sigma_{\text{res}}$, for the c.m. momentum of $pp$ pairs was measured using the exclusive $d(e,e'pnp)$ reaction and was found to equal 20 MeV/c. We subtracted this in quadrature from the measured c.m. width: $\sigma^2_{\text{corrected}} = \sigma^2_{\text{measured}} - \sigma^2_{\text{res}}$, which amounts to a small, 2–3 MeV/c, correction.

Figure 3 shows the extracted $\sigma_{c.m.} = \sigma_j$, in the directions transverse to $\hat{p}_{\text{miss}}$, including acceptance corrections and subtraction of the CLAS resolution. The uncertainty includes both statistical uncertainties as well as systematical uncertainties due to the acceptance correction procedure.

The extracted value of $\sigma_{c.m.}$ for C is consistent with previous $C(e,e'pp)$ measurements of $\sigma_{c.m.}^{pp}$ [7] and $C(p,ppn)$ measurements of $\sigma_{c.m.}^{pn}$ [5], with significantly reduced uncertainty. The extracted width grows very little from C to Pb, and is consistent with a constant value within uncertainties (i.e., it saturates). The saturation of $\sigma_{c.m.}$ with $A$ supports the claim that, in the chosen kinematics, FSI with the $A-2$ nucleons primarily reduces the measured flux, while not significantly distorting the shape of the extracted c.m. momentum distribution.

Figure 3 also compares the data to several theoretical predictions for the c.m. momentum of the nucleons which couple to create the SRC pairs. Reference [14] considers all
possible NN pairs from shell-model orbits, while Ref. [35] considers both all pairs, and nucleons in a relative \( ^1S_0 \) state (i.e., nodeless s-wave with spin 0) \([64,65]\). The simplistic Fermi-gas prediction samples two random nucleons from a Fermi sea with \( k_F \) from \([63]\).

The agreement of the data with calculations supports the theoretical picture of SRC pair formation from temporal fluctuations of mean-field nucleons \([15]\). The experimentally extracted widths are consistent with the Fermi-Gas prediction and are higher than the full mean-field calculations that consider formation from all possible pairs. The data are lower than the \( ^1S_0 \) calculation that assumes restrictive conditions on the mean-field nucleons that form SRC pairs \([35]\).

We note that the SRC-pair c.m. momentum distributions extracted from experiment differ from those extracted directly from \textit{ab initio} calculations of the two-nucleon momentum distribution. The latter are formed by summing over all two-nucleon combinations in the nucleus and therefore include contributions from non-SRC pairs. See discussion in Ref. [34].

In conclusion, we report the extraction of the width of the c.m. momentum distribution, \( \sigma_{c.m.} \), for \( pp \)-SRC pairs from \( A(e, e'pp) \) measurements in C, Al, Fe, and Pb. The new data are consistent with previous measurements of the width of the c.m. momentum distribution for both \( pp \) and \( pn \) pairs in C. \( \sigma_{c.m.} \) increases very slowly and might even saturate from C to Pb, supporting the claim that final state interactions are negligible between the two outgoing nucleons and the residual \( A = 2 \) nucleus. The comparison with theoretical models supports the claim that SRC pairs are formed from mean-field pairs in specific quantum states. However, improved measurements and calculations are required to determine the exact states.