The isospin and the neutron-to-proton excess dependence of short-range correlations

Jan Ryckebusch and Wim Cosyn

Department of Physics and Astronomy, Ghent University

INPC 2019, Glasgow

- Is there a comprehensive picture of nuclear SRC? (quest to learn about stylized facts of nuclear SRC)
- How to forge links between nuclear-structure theory and $A(e, e'pX)$ observables sensitive to nuclear SRC? (forging bridges between theories of “nuclear structure” and of “nuclear reactions”)

(Ghent University)  N to Z dependence of SRC  INPC 2019, Glasgow
1. Low-order correlation operator approximation (LCA) to compute effect of SRC (nuclear structure & nuclear reactions)

2. Apply LCA to the computation of nuclear momentum distributions (NMDs) for 15 nuclei $A(N, Z): 4 \leq A \leq 208$ and $1 \leq \frac{N}{Z} \leq 1.54$

   CHECK: Compare LCA results to ab-initio ones

3. Aggregated effect of SRC and its evolution with $A$ and $N/Z$

   CHECK: $a_2$ data from $A(e, e')$

4. Isospin composition ($pp$&$nn$&$pn$) of SRC

   CHECK: $A(e, e'pp), A(e, e'pn), A(e, e'p)$ data for $^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb$ in “SRC” kinematics

5. $N/Z$ asymmetry dependence of SRC

   CHECK: $A(e, e'pp), A(e, e'pn), A(e, e'p), A(e, e'n)$ data for $^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb$ in “SRC” kinematics
Single-nucleon momentum distributions in LCA

- Single-nucleon momentum distribution $n^{[1]}(p)$
  \[
  n^{[1]}(p) = \frac{A}{(2\pi)^3} \int d^2\Omega_p \int d^3r_1 d^3r_1' d^3(A^{-1}) \{\vec{r}_{2-A}\} \\
  \times e^{-i\vec{p} \cdot (\vec{r}_1' - \vec{r}_1)} \psi^*(\vec{r}_1, \vec{r}_{2-A}) \psi(\vec{r}_1', \vec{r}_{2-A})
  \]

- Universal correlation operators
  \[
  |\Psi\rangle = \hat{G} |\Phi\rangle / \sqrt{\langle\Phi| \hat{G}^\dagger \hat{G} |\Phi\rangle},
  \]

- $\hat{G}$: Central $g_c(r)$, spin-isospin $f_{\sigma\tau}(r)$, tensor $f_{t\tau}(r)$ correlations

- Truncation at $O(G^2)$: SRC part of $n^{[1]}(p) = 2$-body contributions

- Quantify the $pp$, $nn$, $pn$ and $np$ contribution to $n^{[1]}(p)$
Two distinct momentum regimes ("IPM" and "SRC")

Momentum dependence of fat tail of $n^{[1]}$ is "universal"
Probability distribution $P(p) \sim p^{2n[1]}(p)$

Nucleon Momentum $p$ [fm$^{-1}$]

- $^4$He
- $^{16}$O
- $^{40}$Ca
- $^{208}$Pb

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Probability distribution $P(p) \sim p^2 n^{[1]}(p)$
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![Graph of probability distribution $P^A(p)$ for $^{208}$Pb with nucleon momentum $p [\text{fm}^{-1}]$.

- $P_{pp}$
- $P_{nn}$
- $P_{pn+np}$
- $P_{\text{total}}$]
Ratios of probability distributions: $P^A(p)/P^d(p)$

\[
P^A(p) = P^A_{pp}(p) + P^A_{pn}(p) + P^A_{nn}(p) + P^A_{np}(p).
\]

- $P^A_{pp}(p)$ (proton part)
- $P^A_{pp}(p)$ (neutron part)

\[\begin{align*}
N=Z: & \, ^4\text{He}, \, ^{12}\text{C}, \, ^{16}\text{O}, \, ^{40}\text{Ca} \\
N\neq Z: & \, ^9\text{Be}, ^{27}\text{Al}, ^{40}\text{Ar}, ^{48}\text{Ca}, ^{56}\text{Fe}, ^{63}\text{Cu}, ^{84}\text{Kr}, ^{108}\text{Ag}, ^{124}\text{Xe}, ^{197}\text{Au}, ^{208}\text{Pb}
\end{align*}\]
Ratios of probability distributions: \( P^A(p) / P^d(p) \)

\[
P^A(p) = P^A_{pp}(p) + P^A_{pn}(p) + P^A_{nn}(p) + P^A_{np}(p).
\]

\( P^A_{pp}(p) \) (proton part)  
\( P^A_{pn}(p) \)  
\( P^A_{nn}(p) \) (neutron part)  
\( P^A_{np}(p) \)

Nucleon Momentum \( p \) [fm\(^{-1}\)]

\[ \begin{align*}
N=Z: & & 4^\text{He}, & 12^\text{C}, & 16^\text{O}, & 40^\text{Ca} \\
N\neq Z: & & 9^\text{Be}, & 27^\text{Al}, & 40^\text{Ar}, & 48^\text{Ca}, & 56^\text{Fe}, & 63^\text{Cu}, & 84^\text{Kr}, & 108^\text{Ag}, & 124^\text{Xe}, & 197^\text{Au}, & 208^\text{Pb}
\end{align*} \]

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N to Z dependence of SRC  
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$a_2(A/^2H)$ from $A(e,e')$ at $x_B \gtrsim 1.5$ and LCA

Aggregated quantitative effect of SRC in A relative to d

$$a_2(A) = \frac{\int_{p > 2 \text{ fm}^{-1}} dp P_A(p)}{\int_{p > 2 \text{ fm}^{-1}} dp P_d(p)}; \quad a_2^{\text{exp}}(A) = \frac{2}{A} \frac{\sigma^A(e,e')}{\sigma^d(e,e')} \quad (1.5 \lesssim x \lesssim 1.9; \ Q^2 \approx 2 \text{ GeV}^2)$$

1. $A \lesssim 27$: soft A dependence
2. $A \gtrsim 27$: SATURATION
3. Ca isotopes: $a_2(^{40}\text{Ca}) \approx a_2(^{48}\text{Ca})$

DATA: N. Fomin et al., PRL108(2012); B. Schmookler et al., Nature566(2019)
\( a_2(A/\sqrt{2}H) \) from \( A(e, e') \) at \( x_B \gtrsim 1.5 \) and LCA

Aggregated quantitative effect of SRC in \( A \) relative to \( d \)

\[
a_2(A) = \frac{\int_{p>2 \text{ fm}^{-1}} dp P_A(p)}{\int_{p>2 \text{ fm}^{-1}} dp P_d(p)}; \quad a_2^{\text{exp}}(A) = \frac{2 \sigma^A(e,e')}{A \sigma^d(e,e')} \quad (1.5 \lesssim x \lesssim 1.9; \quad Q^2 \approx 2 \text{ GeV}^2)
\]

DATA: N. Fomin et al., PRL108(2012); B. Schmookler et al., Nature566(2019)
Nuclear momentum distribution: pair composition

Pair composition: \( n^{[1]}(p) \equiv n^{[1]}_{pp}(p) + n^{[1]}_{pn}(p) + n^{[1]}_{nn}(p) + n^{[1]}_{np}(p) \)

- SRC pair fractions

\[ r_{pp}(p) = \frac{n^{[1]}_{pp}(p)}{n^{[1]}(p)} \]

- \( r_{nn} \) are momentum dependent

- DATA: O. Hen et al., Science 346 (2014)
Pair composition of SRC: LCA versus experiment

LCA: Ratios from computed $n^{[1]}(p)$ for 15 nuclei

\[
\frac{\int_{p_l}^{p_h} dp \ p^2 \ n^{[1]}_p(p)}{\int_{p_l}^{p_h} dp \ p^2 \ \left[ n^{[1]}_{pn}(p) + n^{[1]}_{np}(p) \right]}
\]

M. Duer et al., PRL122(2019): Ratios from measured

\[
\frac{\sigma_{en} \ \frac{A(e, e'pp)}{A(e, e'np)}}{2\sigma_{ep} \ \frac{A(e, e'pn)}{A(e, e'np)}} \bigg|_{p_l \leq p_m \leq p_h}
\]

for $A=^{12}\text{C},^{27}\text{Al},^{56}\text{Fe},^{208}\text{Pb}$

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N to Z dependence of SRC  
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Fourth moment of $n^{[1]}(p)$ from LCA

Fourth moment of $n^{[1]}(p)$: $\langle T_p \rangle = \frac{1}{2M_p} \int_0^\Lambda dp \, p^4 \left[ \frac{n^{[1]}_{pp}(p) + n^{[1]}_{pn}(p)}{n^{[1]}_{pp}(p) + n^{[1]}_{pn}(p)} \right]$

![Graph showing N to Z dependence of SRC](image)
SRC induce inversion of kinetic energy sharing in neutron-rich nuclei

Ratio \( \langle T_n = \frac{p_n^2}{2M_n} \rangle / \langle T_p = \frac{p_p^2}{2M_p} \rangle \) from computed \( n^\uparrow(p) \)

After correcting for SRC in LCA, minority component has largest kinetic energy (strongly depends on \( N/Z \))
SRC induce inversion of kinetic energy sharing in neutron-rich nuclei

\[
\frac{\langle T_n = \frac{p_n^2}{2M_n} \rangle}{\langle T_p = \frac{p_p^2}{2M_p} \rangle} \text{ from computed } n[p] \]

After correcting for SRC in LCA, minority component has largest kinetic energy (strongly depends on N/Z)

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**Weight of neutrons relative to protons in** $n^{[1]}(p)$

$$\text{IPM: } \frac{\int_0^{p_F} dpp^2 n^{[1]}_n(p)}{\int_0^{p_F} dpp^2 n^{[1]}_p(p)}.$$ 

**Neutron Excess N/Z**

|   | 12C | 27Al | 56Fe | 208Pb |
|---|-----|------|------|-------|
| 0.8 |     |      |      |       |
| 1.0 |     |      |      |       |
| 1.1 |     |      |      |       |
| 1.2 |     |      |      |       |
| 1.3 |     |      |      |       |
| 1.4 |     |      |      |       |
| 1.5 |     |      |      |       |
| 1.6 |     |      |      |       |

**DATA:** M. Duer et al., Nature 560 (2018) 617
Weight of neutrons relative to protons in \( n^{[1]}(p) \)

**IPM:**
\[
\frac{\int_{0}^{p_F} dp p^2 n_n^{[1]}(p)}{\int_{0}^{p_F} dp p^2 n_p^{[1]}(p)}.
\]

**SRC:**
\[
\frac{\int_{0.4 \text{ GeV}}^{1 \text{ GeV}} dp p^2 n_n^{[1]}(p)}{\int_{0.4 \text{ GeV}}^{1 \text{ GeV}} dp p^2 n_p^{[1]}(p)}.
\]

**DATA:** M. Duer *et al.*, Nature *560* (2018) 617

Relative weight of the protons and neutrons is very different in “IPM” and “SRC” regions!

1. IPM: \( 0.93 \frac{N}{Z} + 0.07 \)
2. SRC: \( 0.29 \frac{N}{Z} + 0.71 \)
Superratio of $A(e, e'N)$ for $A=\text{Al, Fe, Pb}$ relative to $C(e, e'N)$

$$
R_{N}^{\text{SRC/IPM}}(A) \equiv \frac{\int_{0.4 \text{ GeV}}^{1.0 \text{ GeV}} dpp^2 n_N^{[1]}(p)}{\int_{0}^{p_F} dpp^2 n_N^{[1]}(p)} (N \equiv p,n)
$$

![Graph showing neutron excess N/Z and SRC fraction relative to 12C for Al, Fe, and Pb.]

**DATA:** M. Duer et al., Nature **560** (2018) 617
Superratio of $A(e, e'N)$ for $A=$Al, Fe, Pb relative to $C(e, e'N)$

\[
\mathcal{R}^\text{SRC/IPM}_N(A) \equiv \frac{\int_{0.4 \text{ GeV}}^{1.0 \text{ GeV}} dpp^2 n_1^N(p)}{\int_0^{p_F} dpp^2 n_1^N(p)} (N \equiv p,n)
\]

- **Data:** M. Duer et al., *Nature* **560** (2018) 617
- **Weight of the minority component in the tail (SRC) part of $n_1^N(p)$ increases with the asymmetry $N/Z$**
SUMMARY

- **LCA**: suited for systematic studies of SRC contributions to $n[1](p)$ and SRC-sensitive reactions
  
  1. Reasonable predictions for $\alpha_2$ factors
  2. $A \leq 40$: LCA predictions for fat tails in line with QMC ones
  3. Natural explanation for the “universal” behavior of the fat tails of NMD

- Distinct isospin and $N/Z$ SRC effects: in line with $A(e, e'pN)$ findings

- Neutron rich nuclei in SRC regime: protons are punching above their weight ($\approx 35\%$ in Pb)

- SRC induced spatio-temporal fluctuations in nuclei are measurable, are significant and are quantifiable
Thank you for your attention! Any questions?
Selected publications

- JR, W. Cosyn, T. Vieijra, C. Casert “Isospin composition of the high-momentum fluctuations in nuclei from asymptotic momentum distributions” arXiv:1907.07259.

- JR, W. Cosyn, S. Stevens, C. Casert, J. Nys “The isospin and neutron-to-proton excess dependence of short-range correlations” arXiv:1808.09859 and PLB B792 (2019), 21.

- S. Stevens, JR, W. Cosyn, A. Waets “Probing short-range correlations in asymmetric nuclei with quasi-free pair knockout reactions” arXiv:1707.05542 and PLB B777 (2018), 374.

- C. Colle, W. Cosyn, JR “Final-state interactions in two-nucleon knockout reactions” arXiv:1512.07841 and PRC 93 (2016) 034608.

- JR, M. Vanhalst, W. Cosyn “Stylized features of single-nucleon momentum distributions” arXiv:1405.3814 and JPG 42 (2015) 055104.

- C. Colle, O. Hen, W. Cosyn, I. Korover, E. Piasetzky, JR, L.B. Weinstein “Extracting the Mass Dependence and Quantum Numbers of Short-Range Correlated Pairs from A(e, e'p) and A(e, e'pp) Scattering” arXiv:1503.06050 and PRC 92 (2015), 024604.