Short-Range Correlated nucleon pairs in nuclei

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Busan, Republic of Korea
Nucleon-nucleon interaction

- Dominated by the **scalar interaction**
- Scalar $\rightarrow 0$: strong **tensor attraction**
  
  spin/isospin dependent
Nucleon-nucleon interaction

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  spin/isospin dependent

- **NN models:**
  - contain experimentally determined parameters
  - large model dependence at short-distance / high-momentum

![Graph showing V(r) vs r [fm] with labels for attractive and repulsive regions.](image-url)
Short-Range Correlations (SRC)

- Nucleon pairs in close proximity

\[ \rho \sim (2-5)\rho_0 \]

\[ 2N\text{-SRC} \]

\[ \rho_0 = 0.16 \text{ fm}^{-3} \]

\[ \rho \sim 1 \text{ fm} \]

\[ 1.7 \text{ fm} \]
Short-Range Correlations (SRC)

- Nucleon pairs in close proximity
- Large *relative* \(k_{\text{rel}} > k_F\) momentum and small *center-of-mass* \(k_{\text{c.m.}} < k_F\) motion (relative to the Fermi momentum \(k_F \approx 250\) MeV/c)

\[
k_{\text{rel}} = (k_1 - k_2)/2 \quad \quad k_{\text{c.m.}} = k_1 + k_2
\]
SRC picture of nuclei

Nuclear Shell Model

Wigner, Mayer and Jensen
1963 Nobel Prize

1st successful description

- ground-state energies
- excitation spectra
- ...

Mean-Field

\( \sim k_F \)
SRC picture of nuclei

Mean-Field

$\sim k_F$

High-momentum tail

A-1

A-2
Correlations and High Momentum

Universal!

\[ P(p) = p^2 n(p)/A \]
SRC picture of nuclei

- Mean-Field
- High-momentum tail
- High-momenta $\Rightarrow$ probing Pairs
Why do we care?

nucleon-nucleon interaction

Mean-Field Theory

Short distance structure of nuclei

asymmetric nuclear matter

quark-gluon structure of bound nucleons (EMC effect)
Why do we care?

nucleon-nucleon interaction

Mean-Field Theory

100%

60-70%

Lapikas, NPA 553 (1993)

short distance structure of nuclei

Deuteron

n(k)

k [GeV/c]

0.1 0.3 0.5 0.7 0.9

asymmetric nuclear matter

quark-gluon structure of bound nucleons (EMC effect)
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Deuteron

asymmetric nuclear matter

Lapikas, NP 553 (1993)
How do we study SRC?

- **Hard knockout reaction**
  - high-energy (several GeV)
  - large momentum-transfer
- Breakup the SRC pair
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How do we study SRC?

- **Hard knockout reaction**
  - high-energy (several GeV)
  - large momentum-transfer
- Breakup the SRC pair
- Triple coincidence measurement $A(e,e'NN) N=p/n$
- Reconstruct the initial state
SRC @ Jefferson Lab

- Located in Virginia, USA
- Electron beam (12 GeV)
- 4 experimental halls
CEBAF Large Acceptance Spectrometer

- Drift chambers
- Scintillators
- Cherenkov
- Target
- Calorimeters
- Electron beam
- Large-acceptance
- Open \((e,e')\) trigger
- Low luminosity
Do high-momentum nucleons come in pairs?

Yes!

I. Korover et al., PLB (2021)
Do high-momentum nucleons come in pairs? Yes!

Incident electron

Scattered electron

Knocked-out proton

Correlated partner

Back-to-back = SRC pairs

O. Hen et al., Science (2014)
Do high-momentum nucleons come in pairs? Yes!

"large relative and small center-of-mass motion"

E. Cohen et al., PRL (2018)
Do high-momentum nucleons come in pairs? Yes!

Consistent with Mean-Field calculations

E. Cohen et al., PRL (2018)
What kind? Predominantly neutron-proton pairs

No A dependence -> Universal!

MD, PRL (2019); MD, Nature (2018); Hen, Science (2014); Korover, PRL (2014); Subedi, Science (2008); Shneor, PRL (2007); Piasetzky, PRL (2006); Tang, PRL (2003);
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MD, PRL (2019); MD, Nature (2018); Hen, Science (2014); Korover, PRL (2014); Subedi, Science (2008); Shneor, PRL (2007); Piasetzky, PRL (2006); Tang, PRL (2003);

Schiavilla et al., PRL 98 (2007)

Sargsian et al., PRC 71 (2005); Ciofi and Alvioli, PRL 100 (2008)
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Schiavilla et al., PRL 98 (2007)
Sargsian et al., PRC 71 (2005); Ciofi and Alvioli, PRL 100 (2008)
What do excess neutrons do?

- don’t correlate?
- correlate with core protons?
- correlate with each other?
Comparing proton & neutron dynamics

Protons grow  Neutrons saturate

Correlation probability

Protons ‘Speed-Up’ in neutron-rich nuclei

MD et al., Nature 560 (2018)
Comparing proton & neutron dynamics

Protons grow  Neutrons saturate

Correlation probability

Protons may have an outsize influence on the properties of neutron stars and other neutron-rich objects.

Protons strongly influence the behaviour of neutron stars.

Surprising Accelerator Finding Could Change the Way We Think About Neutron Stars.
Nuclear symmetry energy

Phenomenological models
60 examples

Microscopic & ab initio theories
11 examples

N.-B. Zhang & B.-A. Li, APJ 902 (2020)
SRC effects on nuclear symmetry energy

Phenomenological nucleon momentum distribution $n^J_k (J=\rho/n)$
guided by microscopic theories & experimental findings

$\Delta_J + \beta_J \left( \frac{|k|}{k_F'} \right)^4 , \quad 0 < |k| < k_F'$,

$n^J_k (\rho, \delta) \equiv n^J_\rho (|k|, \delta) = \begin{cases} \Delta_J + \beta_J \left( \frac{|k|}{k_F'} \right)^4 , & 0 < |k| < k_F' , \\ C_J \left( \frac{k_F'}{|k|} \right)^4 , & k_F' < |k| < \phi_J k_F'. \end{cases}$

* parameters assumed to have linear isospin-asymmetry dependence
based on predictions from self-consistent Green’s function (SCGF)

FFG = free Fermi gas

SRC effects on nuclear symmetry energy

Consequence: symmetry energy gets softened


FFG = free Fermi gas
HMT = high-momentum tail
SCGF = self-consistent Green's function
SNM = symmetric nuclear matter
PNM = pure neutron matter
Going more neutron-rich

- Limited to stable nuclei $N/Z \leq 1.5$

- Radioactive-ion beams
  - larger $N/Z$ asymmetry
  - systematics of isospin-asymmetry

- Kinematically complete measurement $A(p,2pN)A-2$
1\textsuperscript{st} measurement in inverse kinematics

- BM@N setup, JINR (2018)
- Well known system: $^{12}\text{C}$
- High-energy: 3 GeV/nucleon

→ Identify SRC signal in inverse kinematics
**1st measurement in inverse kinematics**

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- Well known system: $^{12}\text{C}$
- High-energy: 3 GeV/nucleon

→ **Identify SRC signal in inverse kinematics**

**np-pairs:** $^{12}\text{C}(p,2p)^{10}\text{B}$ – 23 events

**pp-pairs:** $^{12}\text{C}(p,2p)^{10}\text{Be}$ – 2 events

→ np-dominance

* correlated partner not measured

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Patsyuk, Kahlbow et al., Nature Physics 17 (2021)
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→ Identify SRC signal in inverse kinematics

**Identifying the Signal**

\[ ^{12}\text{C}_{(p,2p)}^{10}\text{B} \]

- Cohen et al., PRL 121 (2018)
- Patsyuk, Kahlbow et al., Nature Physics 17 (2021)

**Experimental Setup**

- BM@N setup, JINR (2018)
- Well known system: $^{12}\text{C}$
- High-energy: 3 GeV/nucleon

**Fragment Momentum to c.m. Motion**

- Identify SRC signal in inverse kinematics

**Graphical Representation**

- Recoil fragment momentum \( p_{10B,y} \) vs. c.m. motion

- Cohen et al., PRL 121 (2018)

**Experimental Data**

- JINR $^{12}\text{C}_{(p,2p)}^{10}\text{B}$
- JLab $(e,e'n)$
- Colle et al. ${^1\text{S}_0}$ pairs
- Fermi-Gas (All Pairs)

Patsyuk, Kahlbow et al., Nature Physics 17 (2021)
SRC @ R³B/GSI

- Pioneering experiment with radioactive-ion beam
  **May 2022** (A. Corsi et al.)

- R³B setup at GSI

- \(^{16}\text{C}\) \((^{12}\text{C} \text{ as ref.})\) at 1.25 GeV/nucleon

- First **fully exclusive** measurement \(A(p,2pN)A-2\)

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**Diagram:**

- \(^{16}\text{C}\) beam
- \((p,2p)\) reaction
- CALIFA (LH target + Si tracker inside)
- GLAD magnet
- NeULAND
- TOFD
- Recoil proton
- Recoil neutron
- Residual fragment
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**Online spectrum**
 SRC @ R³B/GSI

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- Main reactions of interest:
  $^{16}\text{C}(p,2pn)^{14}\text{B}$ (np-pairs)
  $^{16}\text{C}(p,2pp)^{14}\text{Be}$ (pp-pairs)
- Correlation probability
Thank you!