Mass dependence of short-range correlations in nuclei

Camille Colle, W. Cosyn , S. Stevens, J. Ryckebusch

Department of Physics and Astronomy, Ghent University, Belgium

European Nuclear Physics Conference 2015

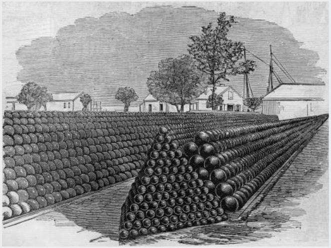
Overview

- Correlations in nuclei
  - **Short-Range Correlations (SRC)**
- Probing SRC in scattering reactions
  - Exclusive two nucleon knockout reactions
  - Final-state interactions
  - Mass dependence of SRC
- Conclusion

Nuclear packing fraction (NPF)

Fraction of the nuclear volume that is occupied by nucleons

- Rough estimate: nuclei and nucleons are uniform spheres with radii r_A and r_N
- Nuclear radius $\approx 1.2A^{\frac{1}{3}}$ fm
- Nucleon is a diffuse system
  - Hard core (repulsion) ≈ 0.5 fm
  - RMS charge radius from (e,e') $= 0.897(18)$ fm
- $0.07 \lesssim \text{NPF} \lesssim 0.42$
  - closest packing fraction of spheres ≈ 0.74
  - packing fraction of Argon liquid ≈ 0.032
  - packing fraction of Argon gas $\approx 3.75 \cdot 10^{-5}$
- The nuclear medium is a rather **dense quantum liquid**



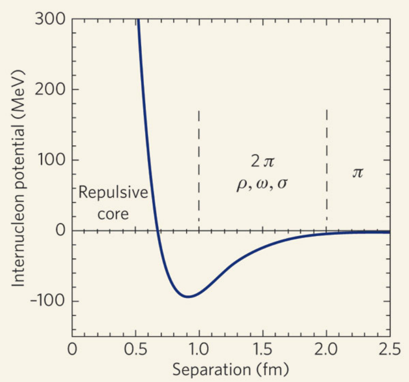
Correlations

Mean field models often give a remarkably good description of the nuclear structure.

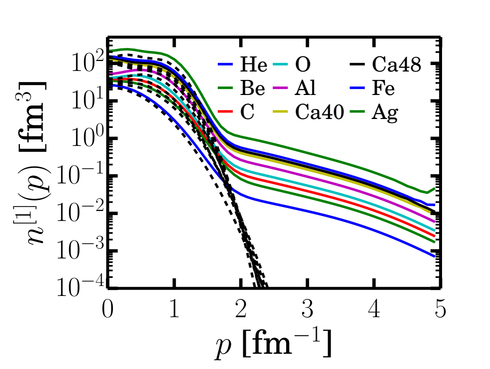
- Mean field → **no** correlations
  - Spectroscopic factor smaller than 1 → indications of correlations
- Nucleon-nucleon force introduces **short** and long-range correlations

The nucleon-nucleon potential has a **strong repulsive core** and a **tensor component**.
Gives rise to **correlated pairs** with

- high relative momentum ($> k_F$)
  - **Fat tail** in one-body momentum distributions
- low center-of-mass momentum ($< k_F$)



One body momentum distributions



$n^{[1]}(p)$: probability to find a nucleon with momentum p in the nucleus.

`Journal of Physics G 42 055104, M. Vanhalst et al.`

- Shape of high-momentum tail is **universal**
- Short-Range Correlations (**SRC**) = fast nucleons

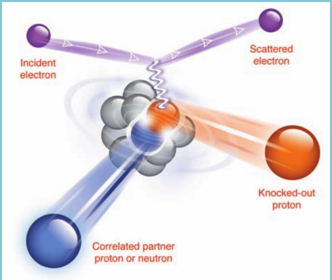
Probing SRC with electron scattering

Momentum distributions cannot be measured directly. Have to be probed in **scattering** experiments.

- Exclusive $A(e, e'N)$
- **Exclusive** $A(e, e'NN)$
- Inclusive $A(e, e')$
- Correlation with magnitude of the EMC effect (DIS)
  - **EPJ 66 02022, M. Vanhalst et al.**
- ...

Probing SRC with electron scattering

Probing short-range correlations with electron scattering



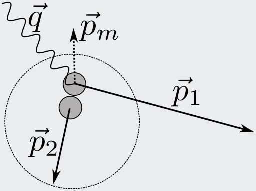
Science 320 1476, R Subedi et al.

- Energy transfer :
  $\omega = E_e - E_{e'}$
- Momentum transfer :
  $\vec{q} = \vec{k}_e - \vec{k}_{e'}$
- Four momentum transfer :
  $Q^2 = \vec{q} \cdot \vec{q} - \omega^2$
  The higher Q^2 the smaller the distance scale probed!
- Bjorken scaling variable : $x_B = \frac{Q^2}{2m\omega}$
  - $1 < x_B \leq 2$: single nucleon contribution $k < k_F$ dies off, sensitive to high momenta associated with $2N$ configurations

Exclusive $A(e, e'NN)$. Hallmark of SRC.

Exclusive measurements allow us to access more detailed information compared to inclusive scattering. Kinematics have to be carefully tuned to select knockout of correlated pairs.

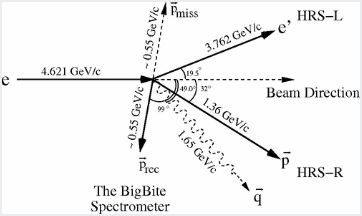
- High momentum probe, proton knock out, leaving the rest of the system unaffected
- Knockout from correlated pair: missing momentum $\vec{p}_m$ predominantly balanced by single recoiling nucleon



Exclusive $A(e, e'NN)$. Hallmark of SRC.

Exclusive measurements allow us to access more detailed information compared to inclusive scattering. Kinematics have to be carefully tuned to select knockout of correlated pairs.

- High momentum probe, proton knock out, leaving the rest of the system unaffected
- Knockout from correlated pair: missing momentum $\vec{p}_m$ predominantly balanced by single recoiling nucleon



A vector diagram of the layout of the ^{12}C(e,e′pp) experiment.

PRL99 072501, JLab Hall A Collaboration

Exclusive $A(e, e'NN)$. Hallmark of SRC.

For close-proximity pairs $\vec{r}_{12} \approx 0$ (Zero-Range Approximation, **ZRA**) the $A(e, e'NN)$ cross section factorizes as,

$$\frac{\mathrm{d}^8\sigma(e, e'NN)}{\mathrm{d}^2\Omega_{k_{e'}}\mathrm{d}^3\vec{P}_{12}\mathrm{d}^3\vec{k}_{12}} = K_{eNN}\sigma_{e2N}(\vec{k}_{12})F^D(\vec{P}_{12})$$

- $\sigma_{e2N}(\vec{k}_{12})$ encodes the coupling to a correlated nucleon pair.
- $F^D(\vec{P}_{12})$ is the two body center of mass momentum distribution of the SRC pair (= probability to find correlated pair with c.m. momentum $\vec{P}_{12}$)

Exclusive $A(e, e'NN)$. Hallmark of SRC.

For close-proximity pairs $\vec{r}_{12} \approx 0$ (Zero-Range Approximation, **ZRA**) the $A(e, e'NN)$ cross section factorizes as,

$$\frac{\mathrm{d}^8\sigma(e, e'NN)}{\mathrm{d}^2\Omega_{k_{e'}}\mathrm{d}^3\vec{P}_{12}\mathrm{d}^3\vec{k}_{12}} = K_{eNN}\sigma_{e2N}(\vec{k}_{12})F^D(\vec{P}_{12})$$

- $\sigma_{e2N}(\vec{k}_{12})$ encodes the coupling to a correlated nucleon pair.
- $F^D(\vec{P}_{12})$ is the two body center of mass momentum distribution of the SRC pair (= probability to find correlated pair with c.m. momentum $\vec{P}_{12}$)

Exclusive $A(e, e'NN)$. Hallmark of SRC.

For close-proximity pairs $\vec{r}_{12} \approx 0$ (Zero-Range Approximation, **ZRA**) the $A(e, e'NN)$ cross section factorizes as,

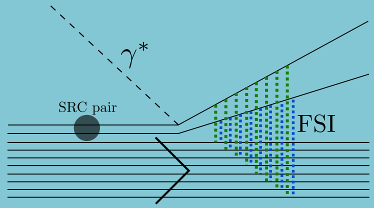
$$\frac{d^8\sigma(e, e'NN)}{d^2\Omega_{k_{e'}} d^3\vec{P}_{12} d^3\vec{k}_{12}} = K_{eNN}\sigma_{e2N}(\vec{k}_{12})F^D(\vec{P}_{12})$$

- $\sigma_{e2N}(\vec{k}_{12})$ encodes the coupling to a correlated nucleon pair.
- $F^D(\vec{P}_{12})$ is the two body center of mass momentum distribution of the SRC pair (= probability to find correlated pair with c.m. momentum $\vec{P}_{12}$)

- PLB 383 1, J. Ryckebusch
- PRC 89 024603, C. Colle et al.
- PRC 92 024604, C. Colle et al.

Final-state interactions

In nuclear knockout reactions, **final-state interactions** play an important role. A major effect is the attenuation of the cross section.

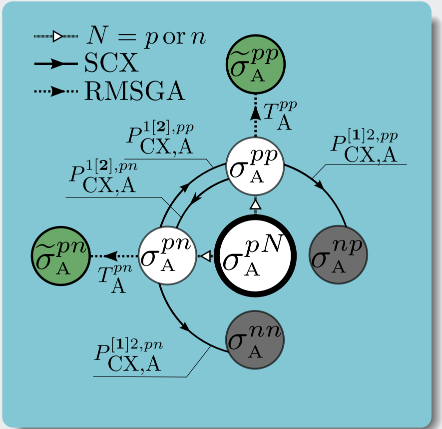


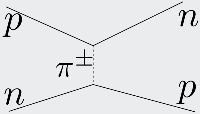
Relativistic Multiple Scattering Glauber Approximation. (RMSGA)

- "Soft" final-state interactions
  - elastic or mildly inelastic re-scattering
- Explicit nucleon-nucleon scattering
  - only a few parameters from nucleon-nucleon scattering data
  - broad applicability over whole nuclear mass range

Final-state interactions II

Escaping nucleons can change isospin through Charge Exchange (CX) reactions. Will mix channels!





Charge exchange probabilities calculated in a semiclassical high energy approximation.

- Parameters extracted from elastic proton-neutron CX scattering.

Mass dependence of pN SRC

- Absolute cross sections are difficult
- Mass dependence of SRC-pairs investigated in exclusive $(e, e'pN)$ reactions can be investigated through cross section ratios

$$\frac{\sigma[A(e,e'pN)]}{\sigma[^{12}C(e,e'pN)]} \approx \frac{\int \mathrm{d}^2\Omega_{k_{e'}} \mathrm{d}^3\vec{k}_{12} K_{\mathrm{epN}} \sigma_{\mathrm{epN}}(\vec{k}_{12}) \int \mathrm{d}^3\vec{P}_{12} F_{\mathrm{A}}^{D}(\vec{P}_{12})}{\int \mathrm{d}^2\Omega_{k_{e'}} \mathrm{d}^3\vec{k}_{12} K_{\mathrm{epN}} \sigma_{\mathrm{epN}}(\vec{k}_{12}) \int \mathrm{d}^3\vec{P}_{12} F_{^{12}\mathrm{C}}^{D}(\vec{P}_{12})}$$

$$\approx \frac{\int \mathrm{d}^3\vec{P}_{12} F_{\mathrm{A}}^{D}(\vec{P}_{12})}{\int \mathrm{d}^3\vec{P}_{12} F_{^{12}\mathrm{C}}^{D}(\vec{P}_{12})}$$

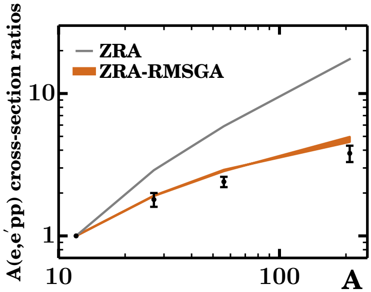
- Only sensitive to 2 body center of mass momentum distribution $F_{\mathrm{A}}^{D}(\vec{P}_{12})$
- Independent of photon-nucleon coupling → **robust** results

Mass dependence of pp cross section ratio

Calculations performed for ^{12}C, ^{27}Al, ^{56}Fe and ^{208}Pb.

Mass dependence **much softer** than naive $Z(Z-1)$ counting

- **Number of correlated pairs** scale softer than $Z(Z-1)$
- **Final-state interactions** soften the mass dependence significantly



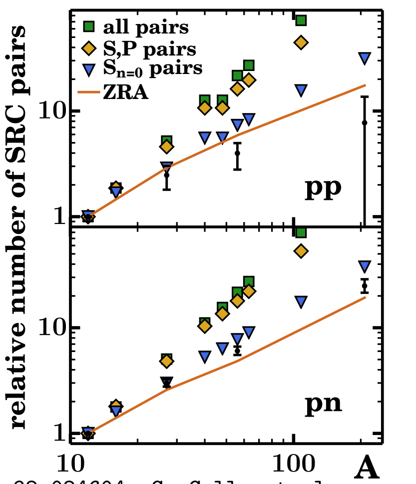
PRC 92 024604, C. Colle et al.

Science 320 1476, R Subedi et al.

Ratio $\frac{^{208}Pb}{^{12}C}$

- $\propto Z(Z-1) = 221$
- measured 3.8 ± 5
- calculated ≈ 4.7

Mass dependence of SRC pairs



PRC 92 024604, C. Colle et al.

PRC 84 031302, M. Vanhalst et al.

Methodology allows us to extract relative number of SRC pairs.

- ZRA : full calculations

SRC pairs have highly selective quantum numbers.
$\propto$ **relative $S_{n=0}$ pairs**

- SRC = **local** effect

Conclusion

- The number of SRC pairs can be estimated by counting the close-proximity pairs in a nucleus (relative distance ≈ 0).For close-proximity pairs the $A(e, e'pN)$ cross section factorizes into
  - relative momentum containing the photon-2 nucleon coupling
  - c.m. momentum containing the probability distribution of the SRC nucleon pairs.
- The mass dependence of the number of SRC prone pairs is much softer than a naive combinatorial prediction ($Z(Z-1)$ for pp and NZ for pn). Inclusions of final-state interactions have a large effect on the mass dependence and soften it substantially.
- Calculations are in agreement with CLAS data.

J. Ryckebusch, Phys. Lett. **B383**, 1 (1996), nucl-th/9605043.

C. Colle, W. Cosyn, J. Ryckebusch, and M. Vanhalst, Phys. Rev. C **89**, 024603 (2014), URL http://link.aps.org/doi/10.1103/PhysRevC.89.024603.

C. Colle, O. Hen, W. Cosyn, I. Korover, E. Piasetzky, J. Ryckebusch, and L. B. Weinstein, Phys. Rev. C **92**, 024604 (2015), URL http://link.aps.org/doi/10.1103/PhysRevC.92.024604.

J. Ryckebusch, M. Vanhalst, and W. Cosyn, Journal of Physics G: Nuclear and Particle Physics **42**, 055104 (2015), URL http://stacks.iop.org/0954-3899/42/i=5/a=055104.

R. Subedi, R. Shneor, P. Monaghan, B. Anderson, K. Aniol, J. Annand, J. Arrington, H. Benaoum, F. Benmokhtar, W. Boeglin, et al., Science **320**, 1476 (2008).

M. Vanhalst, W. Cosyn, and J. Ryckebusch, Phys. Rev. **C84**, 031302 (2011), 1105.1038.