Mass dependence of short-range correlations in nuclei

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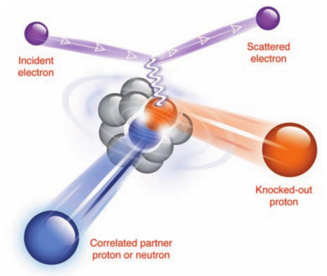
ESNT workshop neutrino-nucleus scattering

Overview

Short-range correlations (SRC) in nuclei

- Probing SRC in scattering reactions
  - Exclusive two nucleon knockout reactions
  - **Final-state interactions**
  - Mass dependence of SRC
- Conclusion



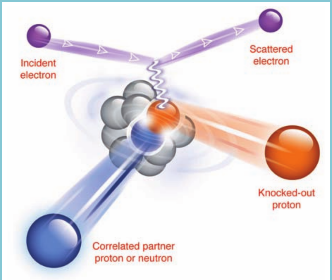
Probing SRC with electron scattering

We are interested in the momentum distributions **but** they 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



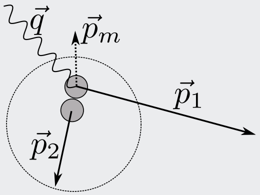
Science 320 1476, R Subedi et al.

- 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



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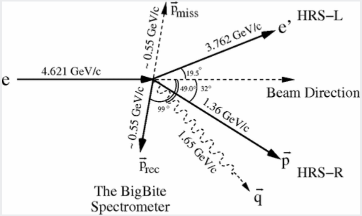

A vector diagram of the layout of the ^{12}C(e,e′pp) experiment.
PRL99 072501, JLab Hall A Collaboration

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

Close-proximity pairs $\vec{r}_{12} \approx 0$ (Zero-Range Approximation, **ZRA**)

- $\propto$ pairs in relative S-wave ($\ell = 0$)

In the 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 $\vec{P}_{12}$)

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- `PLB 383 1, J. Ryckebusch`
- `PRC 89 024603, C. Colle et al.`
- `PRC 92 024604, C. Colle et al.`
- `PRC 93 034608, C. Colle et al.`

Center of mass momentum distribution

$$F^D(\vec{P}_{12}) = \sum_{\substack{s_1,s_2,m_1,m_2 \\ n_1,\kappa_1,n_2,\kappa_2}} \left| \int d\vec{R}_{12}\, e^{i\vec{P}_{12}\cdot\vec{R}_{12}}\, \bar{u}(\vec{p}_1, s_1)\psi_{n_1\kappa_1 m_1}(\vec{R}_{12}) \right.$$

$$\left. \bar{u}(\vec{p}_2, s_2)\psi_{n_2\kappa_2 m_2}(\vec{R}_{12})\mathcal{F}_{\mathrm{FSI}}(\vec{R}_{12}, \vec{R}_{12}) \right|^2 .$$

- $\psi_{n\kappa m}$ calculated in a Hartree approximation of the relativistic Walecka σ–ω model.
- $\mathcal{F}_{\mathrm{FSI}}(\vec{R}_{12}, \vec{R}_{12})$ encodes the interactions between the ejected nucleons and the residual nucleons left in the $A-2$ system in the Relativistic Multiple Scattering Glauber Approximation (RMSGA).

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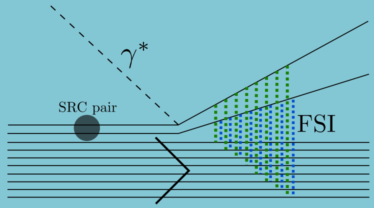
Final-state interactions

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

Glauber approximation

- Glauber theory has origins in optics
- High-energy diffractive scattering: **small angles**
- Applicable when wavelength of scattering particle is significantly smaller than interaction range $\longrightarrow$ momenta of a few 100 MeV
- Eikonal method: outgoing wave gets complex phase $\phi_{\text{scat}}(r) = e^{i\chi(r)}\phi_{\text{in}}(r)$

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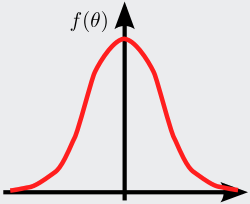
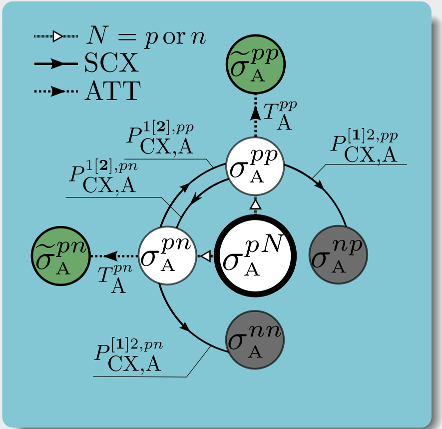
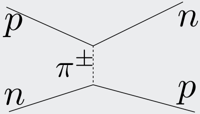


Scattering amplitude parameterized as

$$f(\theta) \approx \frac{k\sigma_{NN'}^{\text{tot}}}{4\pi}(\varepsilon_{NN'} + i)\exp\left(-\frac{\vec{b}^2}{2\beta_{NN'}{}^2}\right)$$

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



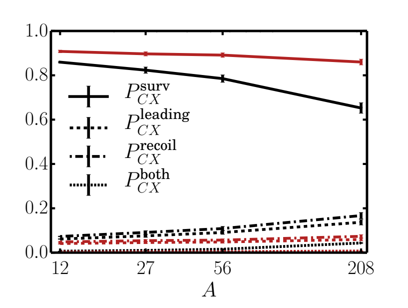


Charge exchange probabilities calculated in a semiclassical high energy approximation.

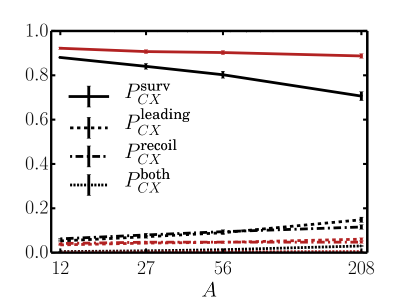
- Parameters extracted from elastic proton-neutron CX scattering.

Charge Exchange probabilities

CX probabilities **with** and without RMSGA FSI.



CX probabilities for pp knock out.



CX probabilities for pn knock out.

RMSGA suppresses knock out from high density regions. The regions will be most affected by CX reactions → inclusion of RMSGA lowers the CX probabilities.

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

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

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

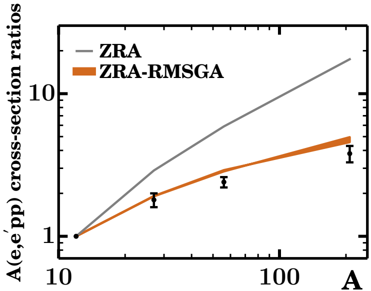
- Only sensitive to 2 body center of mass momentum distribution $F^D_{\mathrm{A}}(\vec{P}_{12})$
- Independent of photon-nucleon coupling $\rightarrow$ **robust** results

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 ± 0.5
- calculated ≈ 4.7

Nuclear Transparency

The **attenuation** (calculated in the RMSGA) can be used to extract the **nuclear transparency** T_A^{pN}

- Defined as the ratio of the $A(e, e'pN)$ cross-section ratio with and without the RMSGA attenuations
- It is a measure for attenuation caused by the nuclear medium
- In the ZRA we have

$$T_A^{pN} \approx \frac{\int \mathrm{d}^3 \vec{P}_{12} \, F_A^{pN,D}(\vec{P}_{12})}{\int \mathrm{d}^3 \vec{P}_{12} \, F_A^{pN}(\vec{P}_{12})} .$$

  - Only sensitive to 2 body center of mass momentum distribution $F_{\mathrm{A}}^{D}(\vec{P}_{12})$
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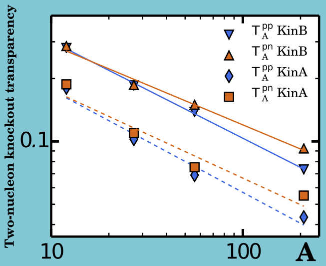
Nuclear Transparency II



- KinB:
  $T_A^{pp} \propto A^{-\mathbf{0.46 \pm 0.02}}$, $T_A^{pn} \propto A^{-\mathbf{0.38 \pm 0.03}}$
- KinA:
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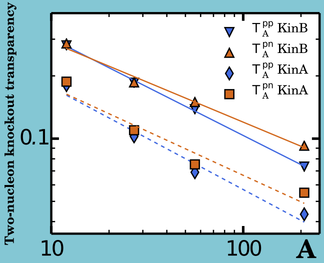

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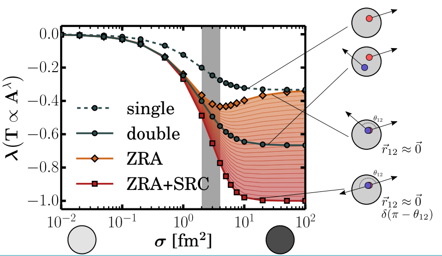
Toy model

- Nucleus is a homogeneous sphere with radius $R = 1.20 A^{\frac{1}{3}}$
- Attenuation calculated using classical survival probability

$$P(\vec{r}) = \exp\left[-\sigma \int_z^{+\infty} dz' \rho(\vec{r}')\right]$$



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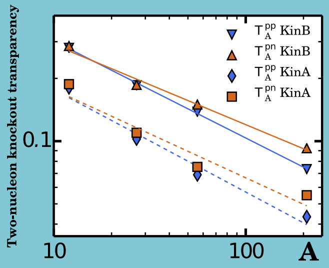

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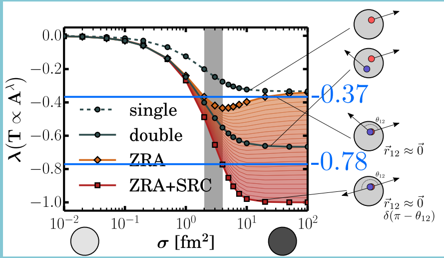
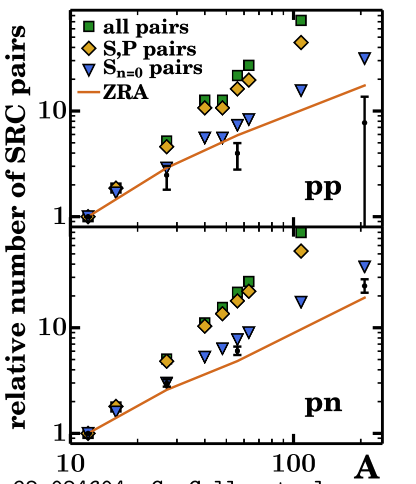


Mass dependence of SRC pairs



PRC 92 024604, C. Colle et al.

PRC 84 031302, M. Vanhalst et al.

Methodology allows us to extract relative number of SRC pairs from cross-section ratios.

- 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.
- The calculated nuclear transparency mass dependence agrees with the bounds set by a geometrical toy model
- Calculations are in agreement with CLAS data.

- C. Colle, W. Cosyn, and J. Ryckebusch, Phys. Rev. C **93**, 034608 (2016), URL `http://link.aps.org/doi/10.1103/PhysRevC.93.034608`.
- 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).

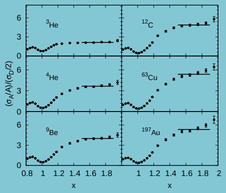
M. Vanhalst, W. Cosyn, and J. Ryckebusch, Phys. Rev. **C84**, 031302 (2011), `1105.1038`.

back up

Inclusive $A(e, e')$

Inclusive $A(e, e')$ scattering at $1.5 \lesssim x_B$

Scaling of $A(e, e')$ response to ^2D



N.Fomin et al.
PRL108 092502 (2012)

- Quantify scaling behaviour:

$$a_2(A/D) \equiv \frac{2}{A} \frac{\sigma^A\left(x_B, Q^2\right)}{\sigma^D\left(x_B, Q^2\right)}$$

- Assume that signal is dominated by the proton–neutron correlations due to dominant tensor force.
- Assume that $\sigma_{epN}(Q^2, x_B) \approx \sigma_{eD}(Q^2, x_B)$
- Naive counting (all pn pairs contribute): $a_2 \propto A$
- Our suggestion : $a_2(A/D) \propto \frac{2}{A} N_{pn(L=0,S=1)}(A, Z)$ (number of close-proximity deuteron-like pn pairs → local effect)

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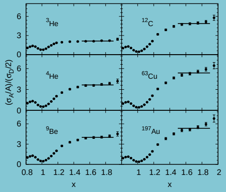

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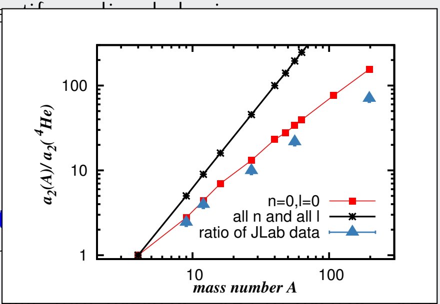
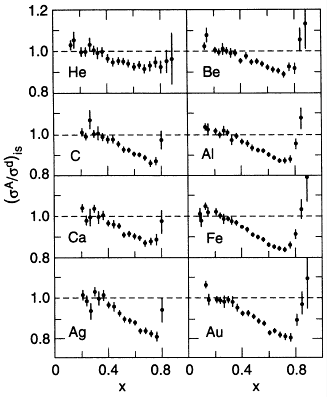


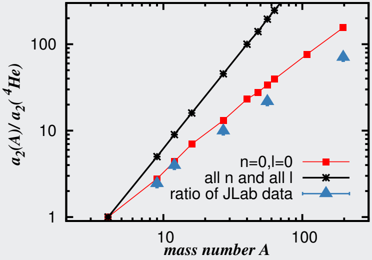
M. Vanhalst et al, PRC86 044619 (2

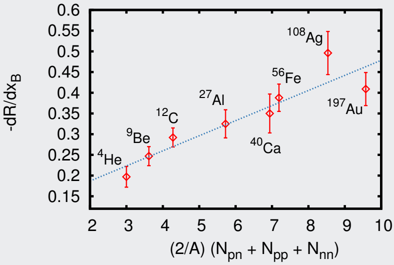
EMC effect



J.Gomez et al. PRD49 4348 (1994)

- The structure of nucleon in a nucleus is modified
- (Valence) quark distribution is changed
- Size of the effect is mass dependent
  - local density dependence
- The EMC effect was a surprise (1983)
- A plethora of models: Everyone's Model is Cool





M. Vanhalst et al, PRC86 044619 (2012)

Magnitude of EMC effect as well as the a_2 mass dependence can be connected to the number of SRC pairs in a nucleus. SRC are **local** effects in nuclei.

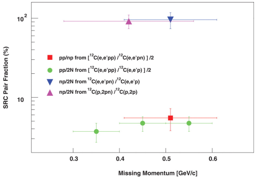
Isospin dependence of SRC

Exclusive scattering $^{12}C(e, e'pN)$ at $Q^2 \approx 2\text{GeV}$ and $x_B \approx 1.2$

`Science 320, 1476 (2008)`

- $\frac{\#pn}{\#pp} = \frac{\#pn}{\#nn} = 18 \pm 5$

Fig. 2. The fractions of correlated pair combinations in carbon as obtained from the (e,e'pp) and (e,e'pn) reactions, as well as from previous (p,2pn) data.



R Subedi et al. Science 2008;320:1476-1478

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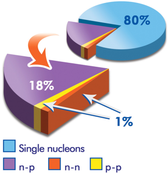
Fig. 3. The average fraction of nucleons in the various initial-state configurations of 12C.



R Subedi et al. Science 2008;320:1476-1478

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