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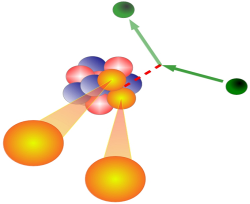
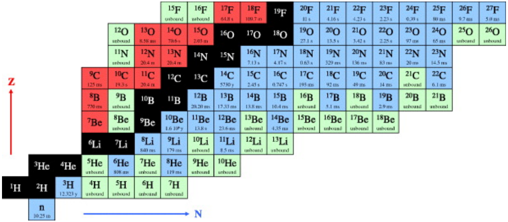
Probing nuclear properties of imbalanced Fermi systems with quasi-free proton knockout reactions

Sam Stevens,
Jan Ryckebusch,
Wim Cosyn,
Andreas Waets



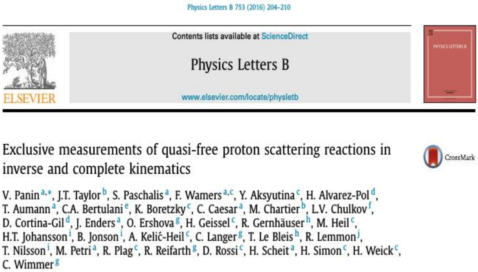
How to Probe Asymmetric Nuclei?



Quasi-free Proton-induced Knockout Reactions in Inverse Kinematics

- highly asymmetric nuclei unstable ⇒ accelerated nuclei
- in inverse kinematics we can also study deeply bound nucleons

Experimentally



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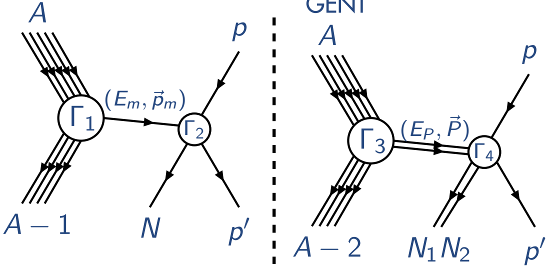
Exclusive measurements of quasi-free proton scattering reactions in inverse and complete kinematics

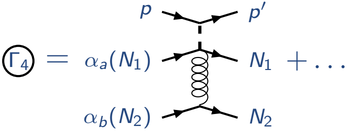
V. Panin[a,*], J.T. Taylor[b], S. Paschalis[a], F. Wamers[a,c], Y. Aksyutina[c], H. Alvarez-Pol[d], T. Aumann[a], C.A. Bertulani[e], K. Boretzky[c], C. Caesar[a], M. Chartier[b], L.V. Chulkov[f], D. Cortina-Gil[d], J. Enders[a], O. Ershova[g], H. Geissel[c], R. Gernhäuser[h], M. Heil[c], H.T. Johansson[i], B. Jonson[i], A. Kelić-Heil[c], C. Langer[g], T. Le Bleis[h], R. Lemmon[j], T. Nilsson[i], M. Petri[a], R. Plag[c], R. Reifarth[g], D. Rossi[c], H. Scheit[a], H. Simon[c], H. Weick[c], C. Wimmer[g]

Sufficiently High Beam Momenta

- reveal SRC effects ⇒ need to probe high momentum tails
- lower contribution of other possible reactions to the cross section
- create conditions to make the eikonal approxiation valid

Theoretically





Distorted Wave Impulse Approximation

- $A-1$ $(A-2)$ degrees are frozen in the interaction Hamiltonian (can be kinematically controlled)
- one “hard” interaction process
- nucleons subject to intranuclear attenuation
  - modeled by using distorted plane waves in eikonal approximation

(T. Aumann, C. A. Bertulani, and J. Ryckebusch, Phys. Rev. C 88, 064610 (2013))

One-nucleon Knockout Reactions

$p(A, p'N)A-1$

Factorized Cross Section in the DWIA

- knockout of a nucleon N with quantum numbers $\alpha(l, j, m)$:

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}\vec{p}_m\,\mathrm{d}\Omega_N} \propto \frac{S(lj)}{j+1}\,\mathcal{K}\left(\frac{\mathrm{d}\sigma^{pN}}{\mathrm{d}\Omega_N}\right)\sum_{\alpha}\rho_{\alpha}^{D}\left(\vec{p}_m\right)$$

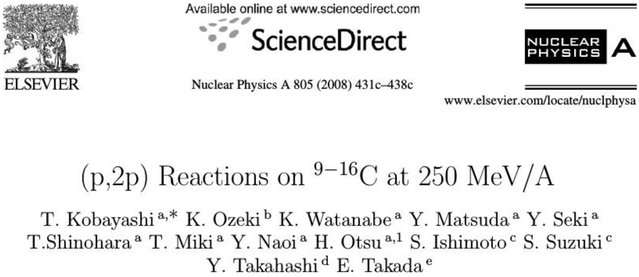
- scaling variable: missing momentum

$$\vec{p}_m = \vec{p}_N - \vec{q}$$

- scaling function: distorted momentum distribution

$$\rho_{\alpha}^{D}\left(\vec{p}_m\right) = \frac{1}{(2\pi)^3}\left|\int d\vec{r}\; e^{-i\vec{p}_m\cdot\vec{r}}\;\widehat{S}_{IFSI}\left(\vec{r}\right)\;\psi_{\alpha}\left(\vec{r}\right)\right|^2$$

Application to Available $(p, 2p)$ Data



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Nuclear Physics A 805 (2008) 431c–438c

NUCLEAR PHYSICS A

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(p,2p) Reactions on $^{9-16}$C at 250 MeV/A

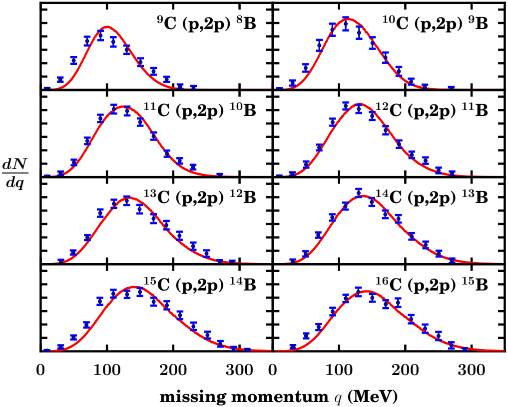
T. Kobayashi [a,*] K. Ozeki [b] K. Watanabe [a] Y. Matsuda [a] Y. Seki [a]
T.Shinohara [a] T. Miki [a] Y. Naoi [a] H. Otsu [a,1] S. Ishimoto [c] S. Suzuki [c]
Y. Takahashi [d] E. Takada [e]

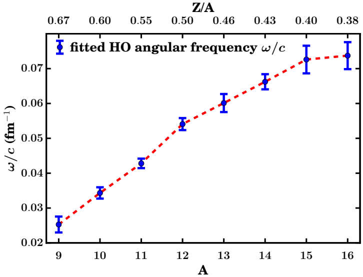
T. Kobayashi et al.: C$(p, 2p)$B reactions on $^{9-16}$C

- experiment conducted at HIMAC accelerator
- beams of different carbon isotopes $^{9-16}$C
- beam kinetic energy of 250 A MeV
- solid-hydrogen target
- knockout of valence *p*-state and deeply bound *s*-state protons
- two final protons detected at angles ±39°
- residual nucleus (fragments) detected using a forward magnetic spectrometer
- selection of the reaction through boron detection and appropriate energy gates

(T. Kobayashi et al., Nucl. Phys. 805, 431c (2008))

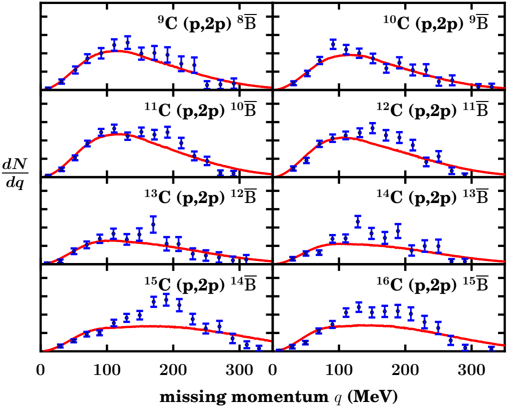
T. Kobayashi: p-shell knockout C(p,2p)B reactions on $^{9-16}$C

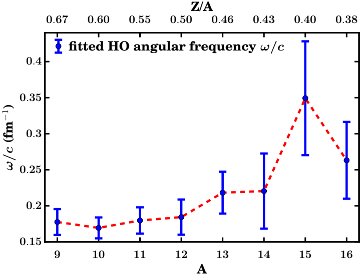




Fit of the theoretical **cross sections** to the experimental **momentum distributions** for the knockout of *p*-**state protons**.

T. Kobayashi: s-shell knockout C(p,2p)$\overline{\mathrm{B}}$ reactions $^{9-16}$C

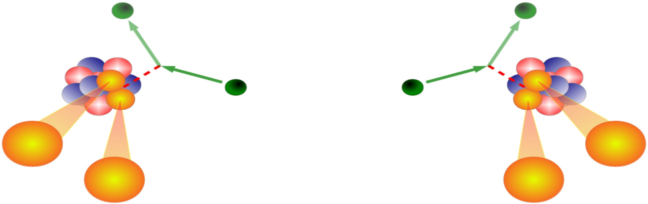




Fit of the theoretical **cross sections** to the experimental **momentum distributions** for the knockout of *s*-**state protons**.

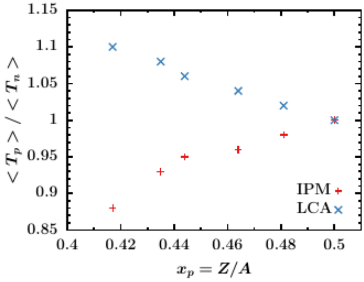
Two-nucleon Knockout Reactions

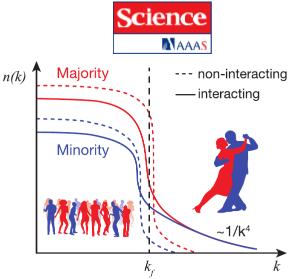
$p(A, p' N_1 N_2)A - 2$



SRC Effects

- **Spectacular SRC effect** on x_p dependence of kinetic energy ⇒ What happens at neutron-star conditions?
- Higher average momentum for the **minority** fermions in asymmetric nuclei ↔ IPM



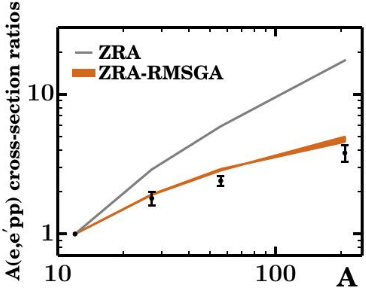


(O. Hen et al., Science 346, 614 (2014))

(J. Ryckebusch, M. Vanhalst, and W. Cosyn, Journal of Physics G: Nuclear and Particle Physics 42, 055104 (2015))

Factorized $p(A, p' N_1 N_2)A - 2$ Cross Section

- Factorized model based on assumptions also applied in $A(e, e' N_1 N_2)A - 2$ reactions
- Assumptions that have shown to provide very good results in comparison with experiment
  - **ZRA** (Zero range approximation)
  - **RMSGA** (Glauber eikonal approach for IFSI)



(C. Colle, O. Hen, W. Cosyn, I. Korover, E. Piasetzky, J. Ryckebusch, L.B. Weinstein, Phys. Rev. C 92, 024604 (2015))

Factorized $p(A, p'N_1N_2)A-2$ Cross Section

- knockout of two nucleons N_1 and N_2 with quantum numbers α and β:
  - kinematical selection of 1 "slow" nucleon N_2
  - zero-range approximation

$$\frac{d^8\sigma}{\mathrm{d}E_f\,\mathrm{d}\Omega_f\,\mathrm{d}E_{N2}\,\mathrm{d}\Omega_{N2}\,\mathrm{d}\Omega_{N1}} \propto \mathcal{K}\left(\frac{\mathrm{d}\sigma^{pN}}{\mathrm{d}\Omega_{N1}}\right) G(\vec{k}_{12}) \sum_{\alpha,\beta} \rho_{\alpha,\beta}(\vec{K}_{12})$$

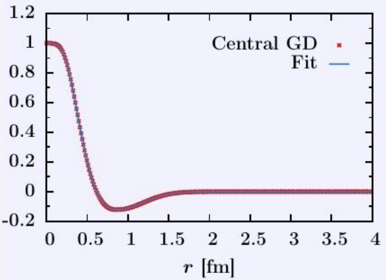
- scaling function: the conditional probability for finding a pair of nucleons with quantum numbers α and β at very small internucleon distances

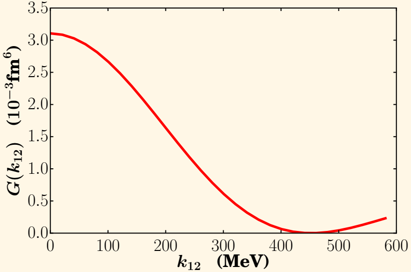
$$\rho_{\alpha,\beta}\left(\vec{K}_{12}\right) = \frac{1}{(2\pi)^3}\left|\int d\vec{R}\; e^{-i\vec{K}_{12}\cdot\vec{R}}\;\psi_\alpha\left(\vec{R}\right)\;\psi_\beta\left(\vec{R}\right)\right|^2$$

with $\vec{K}_{12}$ the initial center of mass momentum of the pair.

Central correlation function

$$G\left(\vec{k}_{12}\right) = \frac{1}{(2\pi)^3} \left| \int d\vec{r}\, e^{-i\vec{k}_{12}\cdot\vec{r}}\, g_c(r) \right|^2$$

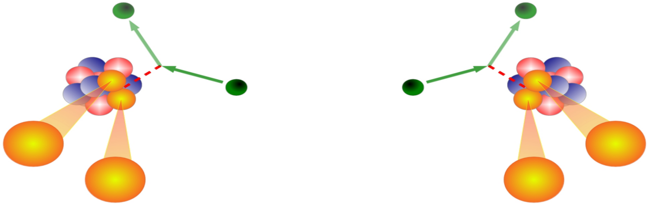




(M Vanhalst, PhD thesis (Ghent University, Ghent, 2014))

(C. Gearheart, PhD thesis (Washington University, St. Louis, 1994))

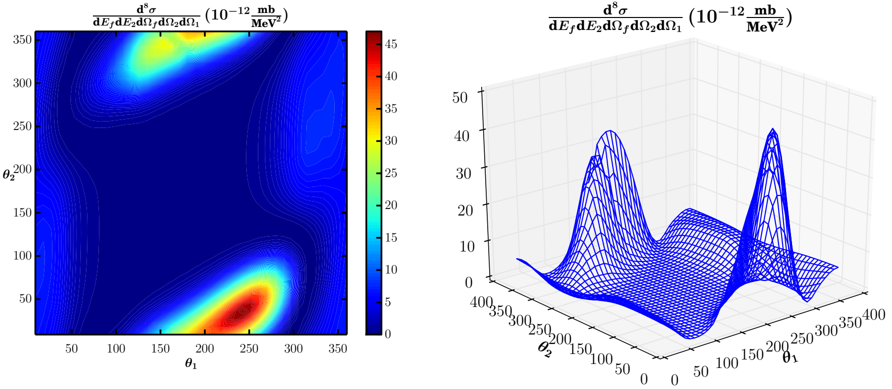
Simulation of $(p, 3p)$ Cross Sections



Simulation parameters

- Quasi-free $^{12}C(p,3p)^{10}Be$ reaction
- Proton beam kinetic energy 830 MeV
- Scattered proton kinetic energy 521 MeV
- Angle between incoming beam and scattered proton 10.30°
- Knocked out proton N_1 kinetic energy 150 MeV
- Vary angles θ_1 and θ_2 between the knocked out protons and the transferred momentum
  $\Rightarrow$ varying kinetic energy of the second knocked out proton N_2
- Calculation of the cross section as a function of these angles

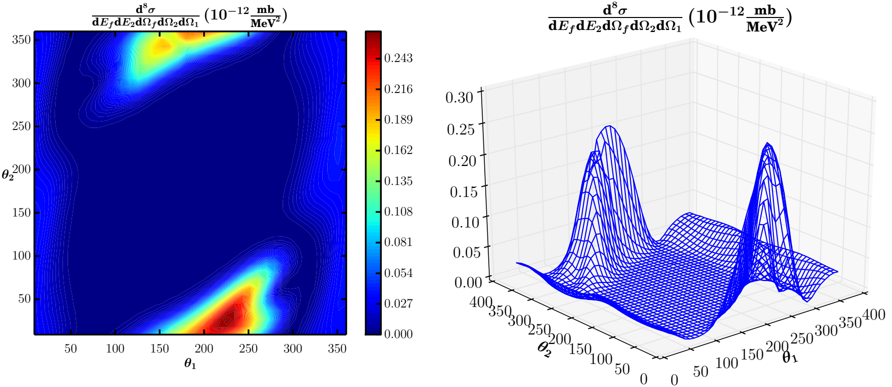
Knockout of two 1s-shell protons



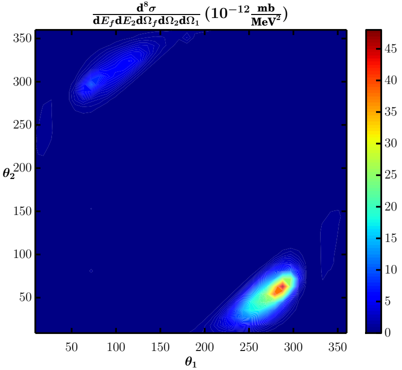
$\frac{\mathbf{d}^8\sigma}{\mathbf{d}E_f\mathbf{d}E_2\mathbf{d}\Omega_f\mathbf{d}\Omega_2\mathbf{d}\Omega_1}\,(10^{-12}\frac{\mathbf{mb}}{\mathbf{MeV}^2})$

$\frac{\mathbf{d}^8\sigma}{\mathbf{d}E_f\mathbf{d}E_2\mathbf{d}\Omega_f\mathbf{d}\Omega_2\mathbf{d}\Omega_1}\,(10^{-12}\frac{\mathbf{mb}}{\mathbf{MeV}^2})$

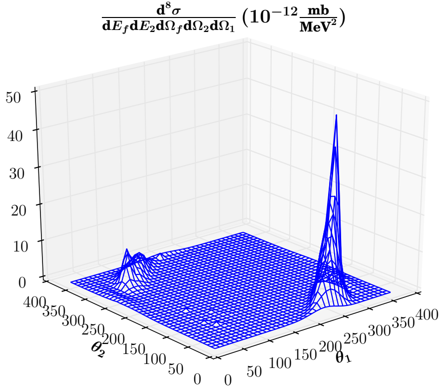
Knockout of a 1s-shell and a 1p-shell proton



Knockout of two 1p-shell protons



$\frac{\mathbf{d}^8\sigma}{\mathbf{d}E_f\mathbf{d}E_2\mathbf{d}\Omega_f\mathbf{d}\Omega_2\mathbf{d}\Omega_1}\,(10^{-12}\frac{\mathbf{mb}}{\mathbf{MeV^2}})$



$\frac{\mathbf{d}^8\sigma}{\mathbf{d}E_f\mathbf{d}E_2\mathbf{d}\Omega_f\mathbf{d}\Omega_2\mathbf{d}\Omega_1}\,(10^{-12}\frac{\mathbf{mb}}{\mathbf{MeV^2}})$

OUTLOOK

- Include **single charge exchange**
- Include **initial and final state interactions** in the model for two-nucleon knockout
  - computationally very challenging: 4 nucleons
- Include **tensor** and **spin-isospin** correlations in the model for two-nucleon knockout

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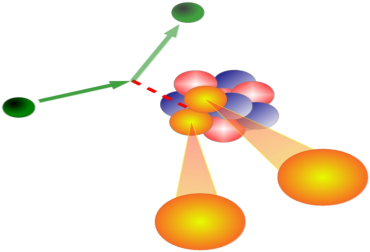
THANK YOU FOR YOUR ATTENTION

BriX



EXTRA SLIDES

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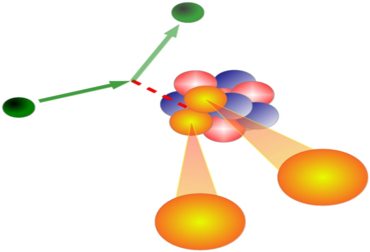


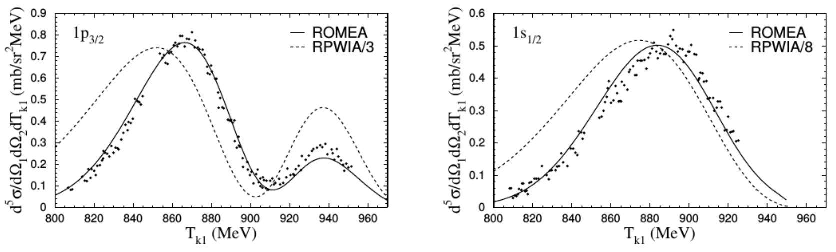
Distorted momentum distribution

$$\rho_{\alpha}^{D}\left(\vec{p}_m\right) = \frac{1}{(2\pi)^3}\left|\int d\vec{r}\; e^{-i\vec{p}_m\cdot\vec{r}}\; \widehat{S}_{IFSI}\left(\vec{r}\right)\; \psi_{\alpha}\left(\vec{r}\right)\right|^2$$

- α: quantum number of bound nucleon
- $\widehat{S}_{IFSI}\left(\vec{r}\right)$ encodes the **attenuation** for the 3 nucleons that are subject to **initial and final state interactions**
- two different **eikonal approaches** to calculate $\widehat{S}_{IFSI}\left(\vec{r}\right)$

(B. Van Overmeire, W. Cosyn, P. Lava, and J. Ryckebusch, Phys. Rev. C 73, 064603 (2006))

Relativistic Optical Model Eikonal Approximation (ROMEA)



Differential cross section for the $^{12}C(p,2p)$ reaction in the kinetic energy range $800MeV < T_1 < 1GeV$.

For most asymmetric nuclei: no optical potential available
⇒ need to use a **Multiple Scattering Glauber model**

Relativistic Multiple Scattering Glauber Approximation (RMSGA)

- eikonal approximation based on **diffractive scattering**
- more natural at **higher energies**
- **multiple scattering** theory with “frozen” nucleons
- based only on individual **nucleon-nucleon scattering**:
  - data readily available from free *pp* and *pn* scattering

$\Longrightarrow$ can be used for the **whole mass range**!

Single Charge Exchange

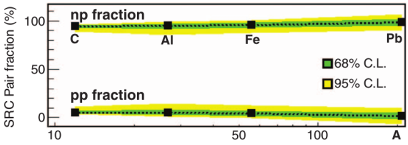
- charge exchange in initial and final state interactions
- only **single charge exchange** is taken into account
- modelled in a **semi-classical** way:

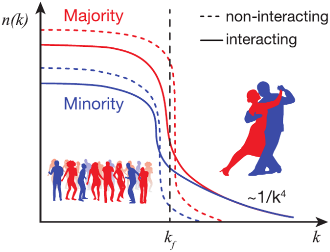
$$P^{\mathrm{CX}}_{N_1 \to N_2}(\vec{r}, T_k) \;=\; 1 - \exp\left[-\sigma_{CX}(T_{N_1}) \int_{z}^{+\infty} \mathrm{d}z' \, \rho_{N_2}(x, y, z')\right]$$

- use average probabilities:

$$\overline{P}^{\mathrm{CX}}_{N_1 \to N_2}(T_k) \;=\; \int \mathrm{d}\vec{r} \, \rho_{N_1}(\vec{r}) \, P^{\mathrm{CX}}_{N_1 \to N_2}(\vec{r}, T_k)$$

SRC Effects on Momentum Distributions



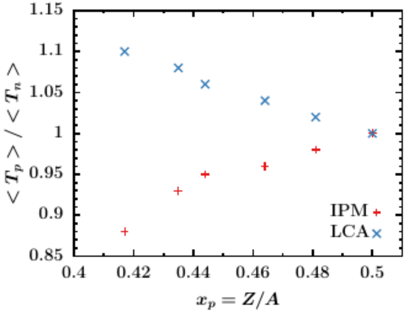


- **SRC are highly dominated by correlated np pairs**
  - Fat **high-momentum** tails in momentum distributions
  - Higher average momentum for the **minority** fermions in imbalanced nuclei ↔ **IPM**

(O. Hen et al., Science 346, 614 (2014))

SRC Effects on Average Kinetic Energies

- Higher average momentum for the **minority** fermions in asymmetric nuclei ↔ IPM

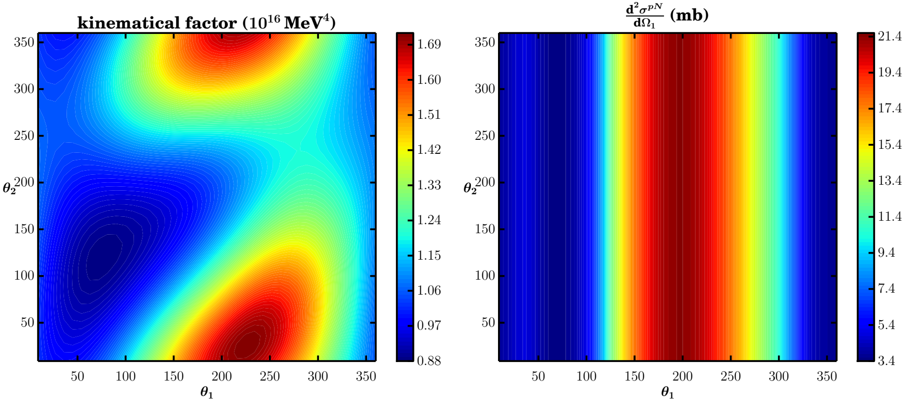


LCA:

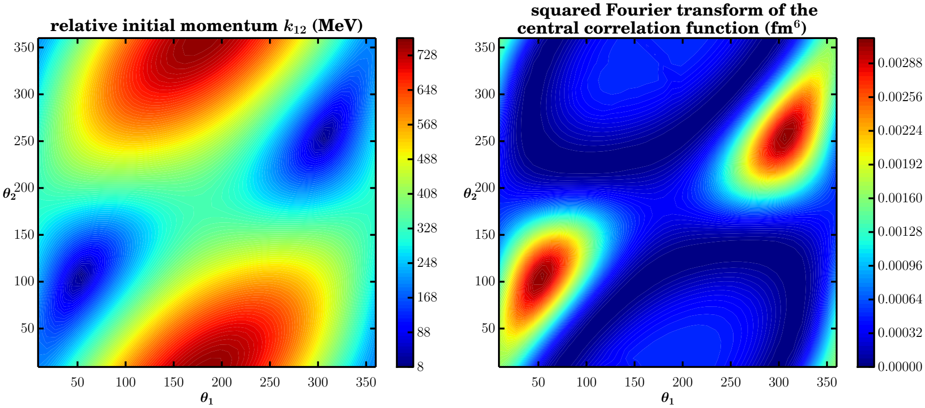
- lowest order correlation-operator approximation
- efficient way of implementing SRC in stable and unstable nuclei

(M. Vanhalst, W. Cosyn, and J. Ryckebusch, Stylized features of single-nucleon momentum distributions (2014), arXiv:1405.3814 [nucl-th])

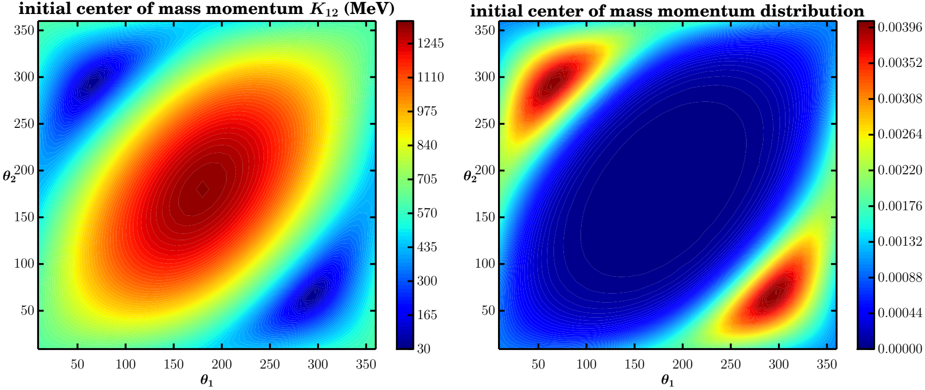
Kinematical Factor and Free Cross Section



Correlation Factor

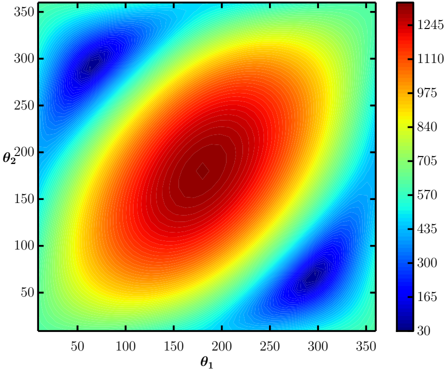


Knockout of two 1s-shell protons: Momentum Distribution

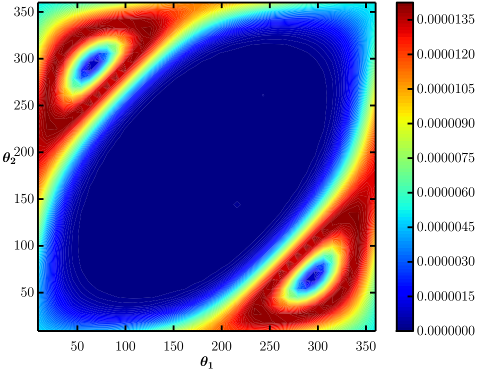


Knockout of a 1s-shell and a 1p-shell proton: Momentum Distribution

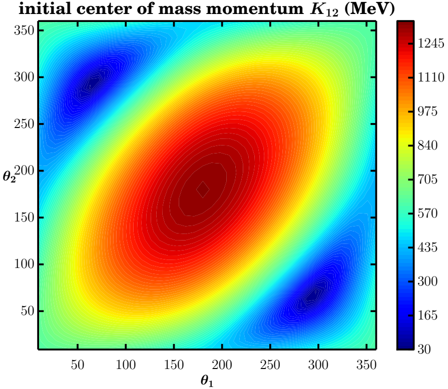
initial center of mass momentum K_{12} (MeV)



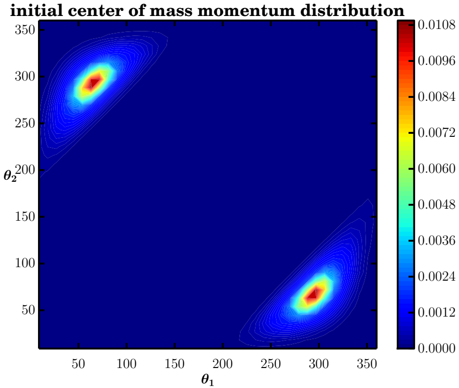
initial center of mass momentum distribution



Knockout of two 1p-shell protons: Momentum Distribution

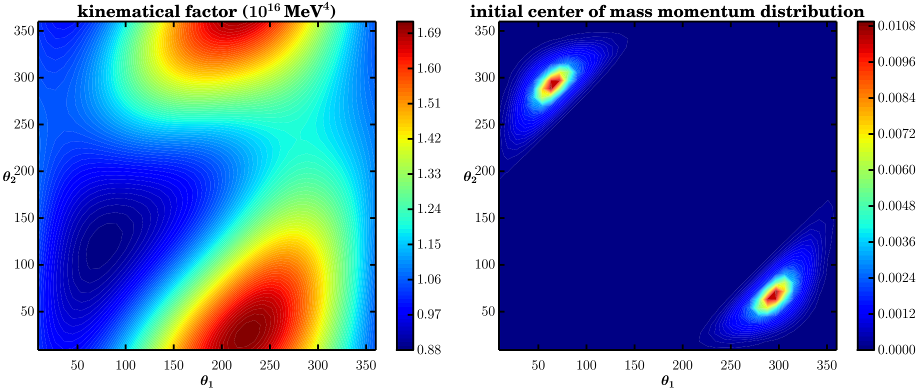


initial center of mass momentum K_{12} (MeV)



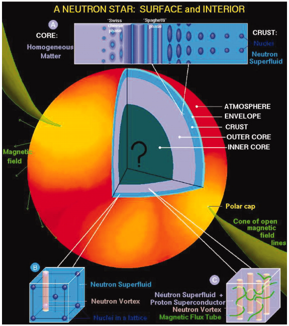
initial center of mass momentum distribution

Knockout of two 1p-shell protons: Kinematical Factor and Momentum Distribution



Asymmetric nuclei have some unusual properties

- halo nuclei
- new magic numbers in neutron-rich nuclei
- special dynamical properties due to short-range correlations (SRC)
- ...



Neutron stars:

- extremely imbalanced Fermi systems ($x_p = Z/A \ll 0.5$)
- look for clues of their properties in the study of neutron-rich nuclei ($\mathbf{x_p < 0.5}$)

Understanding the properties of exotic nuclei is important for nuclear astrophysics