Claudio Ciofi degli Atti

SHORT-RANGE CORRELATIONS IN NUCLEI:
theoretical predictions and experimental evidences

WORKSHOP

on

Nuclear Structure and Dynamics at Short Distances

February 11 - 22, 2013, INT, Seattle, USA

OUTLINE

1. Introduction: why Short Range Correlations?

2. Ab initio solutions of the non relativistic many-body problem and theoretical predictions of SRC.

3. Experimental observations of SRC.

4. Impact of SRC on various fields of physics.

5. Conclusions.

1 *INTRODUCTION: WHY SHORT RANGE CORRELATIONS (SRC)?*

- Many properties of nuclei measured at low Q^2 and generated by the average and collective motions of point-like nucleons can be successfully described in terms of the nuclear Mean Field (Shell Model).
- Nowadays it is possible to investigate nuclei at high Q^2, probing distances of the order of the nucleon radius ($\simeq 1fm$), and the following longstanding questions arise:

1. *Do nucleon and meson d.o.f. play still a role at short distance, or quark and gluon d.o.f. are the relevant ones?*
2. *Is the two-nucleon short-range behavior strongly affected by the surrounding nucleons?*
3. *Does the short-range behavior of nuclei affect cold matter at high densities, e.g. neutron stars?*
4. *Does the short-range structure of nuclei affect high energy scattering, e.g. pA and AA?*

Answering these questions implies the study of Short-Range Correlations (SRC). To this end, one needs dedicated experiments and a well-defined theoretical framework to interpret them.

2 *AB INITIO SOLUTIONS OF THE NUCLEAR MANY-BODY PROBLEM AND THEORETICAL PREDICTIONS OF SRC*

THE STANDARD MODEL OF NUCLEI

QCD $\Longrightarrow$ Nuclei- non perturbative regime $\Longrightarrow$ too difficult
Many-body systems $\Longrightarrow$ single out the leading effective d.o.f.
Effective d.o.f. in Nuclei $\Longrightarrow$ nucleons and gauge bosons.
Reduction of a field theoretical description to an instantaneous potential description (Schroedinger equation) $\Longrightarrow$ two-body, three-body,........,A-body potentials are generated.

Primakoff,Holstein 1944

$$\text{(m-body potential)} \simeq \left(\frac{v_N}{c}\right)^{\text{(m-2)}} \times \text{(two-body potential)}$$

$$\left[-\frac{\hbar^2}{2\,m_N}\sum_i \hat{\nabla}_i^2 + \sum_{i<j}\hat{v}_2(i,j) + \sum_{i<j<k}\hat{v}_3(i,j,k)\right]\Psi_o(1\ldots A) = E_o\,\Psi_0$$

$$\Psi_o \equiv \Psi_o(1\ldots A) \qquad i \equiv \mathbf{x}_i \equiv \{\sigma_i, \tau_i, \mathbf{r}_i\} \qquad \sum_{i=1}^{A}\boldsymbol{r}_i = 0$$

Theoretical framework: Solve *ab initio* the standard model with realistic interactions $\Longrightarrow$ compare with experimental data (energy, form factors, transition matrix elements, etc); if agreement is found $\Longrightarrow$ OK; if not $\Longrightarrow$ look for new d.o.f.

Modern bare two-nucleon interactions ($\simeq$ *2000 phase shifts*)

$$\hat{v}_2(x_i, x_j) = \sum_{n=1}^{18} v^{(n)}(r_{ij})\hat{\mathcal{O}}_{ij}^{(n)} \qquad r_{ij} \equiv |\mathbf{r}_i - \mathbf{r}_j|$$

$$\mathcal{O}_{ij}^{(1)} = 1, \qquad \mathcal{O}_{ij}^{(2)} = \sigma_i \cdot \sigma_j, \quad \mathcal{O}_{ij}^{(3)} = \tau_i \cdot \tau_j$$

$$\mathcal{O}_{ij}^{(4)} = (\sigma_i \cdot \sigma_j)(\tau_i \cdot \tau_j), \quad \mathcal{O}_{ij}^{(5)} = \hat{S}_{ij}, \quad \mathcal{O}_{ij}^{(6)} = \hat{S}_{ij}\tau_i \cdot \tau_j,$$

$$\hat{S}_{ij} = 3(\hat{r}_{ij} \cdot \sigma_i)(\hat{r}_{ij} \cdot \sigma_j) - \sigma_i \cdot \sigma_j$$

- short-range repulsion (common to many systems)
- intermediate- to long-range tensor character (unique to nuclei)

THE MEAN FIELD APPROXIMATION

$$\sum_{i<j} \hat{v}_2(i,j) + \sum_{i<j<k} \hat{v}_3(i,j,k) \Longrightarrow \sum_i V_i(i).$$

$$\Downarrow$$

$$\left[-\frac{\hbar^2}{2\,m_N} \sum_i \hat{\nabla}_i^2 + \sum_i V(r_i)\right] \Phi_o(1,\ldots,A) = \epsilon_o \, \Phi_o(1,\ldots,A)$$

Mean-field (shell model) wave function

$$\Phi_0(1,2,\ldots,A) = \hat{\mathcal{A}} \prod_i^A \phi_{\alpha_i}(x_i) \equiv \Phi_{0p0h} \quad \alpha_i > \alpha_F, \phi_{\alpha_i} = 0$$

Exact correlated wave function

$$\Psi_0(1,2,\ldots,A) = C_{0p0h}\,\phi_{0p0h} + C_{1p1h}\,\Phi_{1p1h} + C_{2p2h}\,\Phi_{2p2h} + \ldots$$

$$SRC \longrightarrow \sum_{n=1}^{\infty} C_{np\,nh} \Phi_{np\,nh}$$

VARIOUS *ab initio* THEORETICAL METHODS

- Direct solution for few-body systems (Faddeev, Fadeev-Yakubowsky): Gloeckle & co.
- Expansion in complete set of basis functions: Suzuki & co.
- No Core Shell Model Vary & Co.
- Introduction of correlations into the mean field wave function by proper correlation operators: Roth, Neff & co.
- SRG: Furnstahal, Schwenk & co,
- Correlated basis functions with Green Function Monte Carlo: Schiavilla, Wiringa & co..
- Correlated basis functions and cluster expansion: Pisa & Perugia Groups

OUR APPROACH

$$\Psi_o = \hat{\mathbf{F}}\,\Phi_o$$

$$\hat{\mathbf{F}} = \hat{\mathcal{S}} \prod_{i<j} \hat{f}_{ij} = \hat{\mathcal{S}} \prod_{i<j} \left[\sum_n f^{(n)}(r_{ij})\, \hat{\mathcal{O}}_{ij}^{(n)} \right]$$

THE RELEVANT QUANTITY: DENSITY MATRICES

Diagonal one-body density matrix (***1BDM***)(***matter distribution***):

$$\rho_{(1)}(\boldsymbol{r}_1) = \int |\Psi_0(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)|^2 \prod_{i=2}^{A} d\boldsymbol{r}_i$$

Non diagonal (***1BDM***) (***One-body density fluctuations***):

$$\rho_{(1)}(\boldsymbol{r}_1, \boldsymbol{r}'_1) = \int \Psi_0^*(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)\, \boldsymbol{r}_i)\Psi_0(\boldsymbol{r}'_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A) \prod_{i=2}^{A} d\boldsymbol{r}_i$$

Non diagonal 2-body density matrix (***2BDM***)(two body density fluctuations):

$$\rho_{(2)}(\boldsymbol{r}_1, \boldsymbol{r}_2; \boldsymbol{r}'_1, \boldsymbol{r}'_2) = \int \Psi_0^*(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)\, \Psi_0(\boldsymbol{r}'_1, \boldsymbol{r}'_2 \ldots, \boldsymbol{r}_A) \prod_{i=3}^{A} d\boldsymbol{r}_i$$

Diagonal 2BDM:

$$\rho_{(2)}(\boldsymbol{r}_1, \boldsymbol{r}_2) = \int |\Psi_0(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)|^2 \prod_{i=3}^{A} d\boldsymbol{r}_i$$

The relative (rel) and center-of-mass (CM) density matrices

$$\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2 \qquad \boldsymbol{R} = (\boldsymbol{r}_1 + \boldsymbol{r}_2)/2$$

$$\rho_{(2)}(\boldsymbol{r}, \boldsymbol{R}) = \int |\Psi_0(\boldsymbol{R} + \frac{\boldsymbol{r}}{2}, \boldsymbol{R} - \frac{\boldsymbol{r}}{2}, \boldsymbol{r}_3 \ldots, \boldsymbol{r}_A)|^2 \prod_{i=3}^{A} d\boldsymbol{r}_i$$

$$\rho_{CM}(\boldsymbol{R}) = \int \rho_{(2)}(\boldsymbol{r}, \boldsymbol{R}) d\boldsymbol{r}$$

$$\rho_{rel}(\boldsymbol{r}) = \int \rho_{(2)}(\boldsymbol{r}, \boldsymbol{R}) d\boldsymbol{R}$$

The relative 2BDM has been calculated by different groups within different many-body approaches and realistic *bare* NN interactions.

The RELATIVE 2BDM and the CORRELATION HOLE in FEW-NUCLEON SYSTEMS

Schiavilla *et al*, Nucl. Phys. A267 (1987) 267

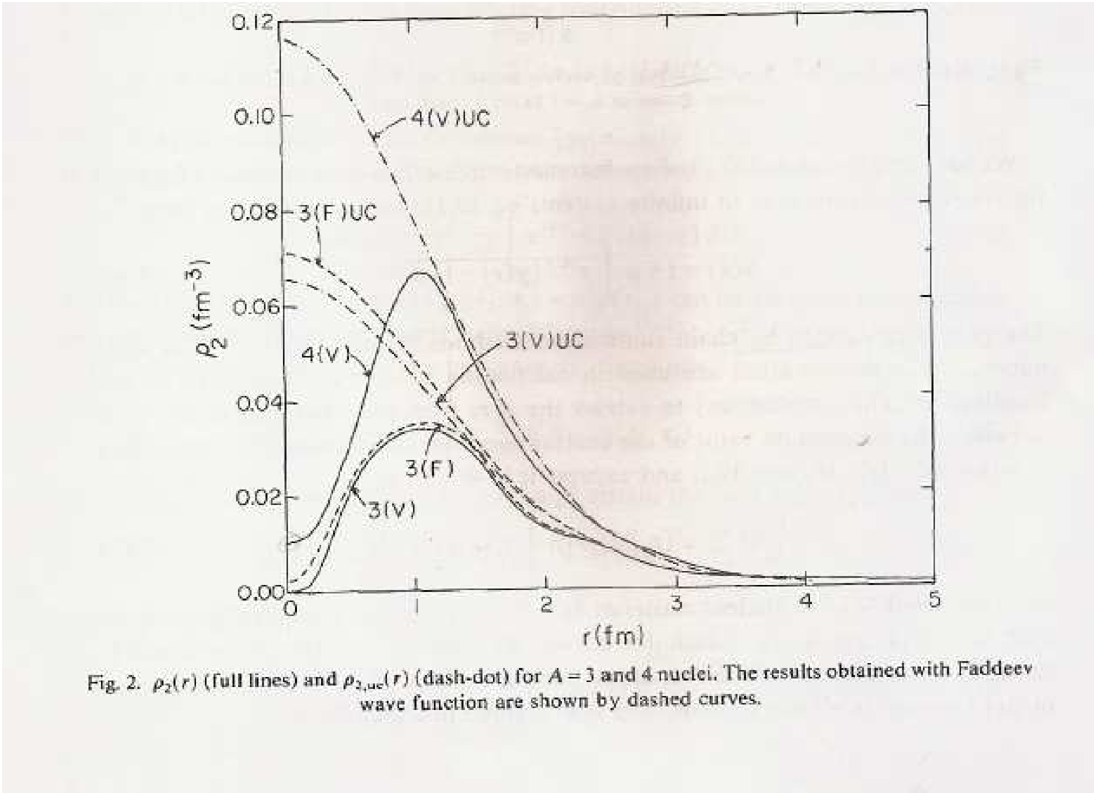


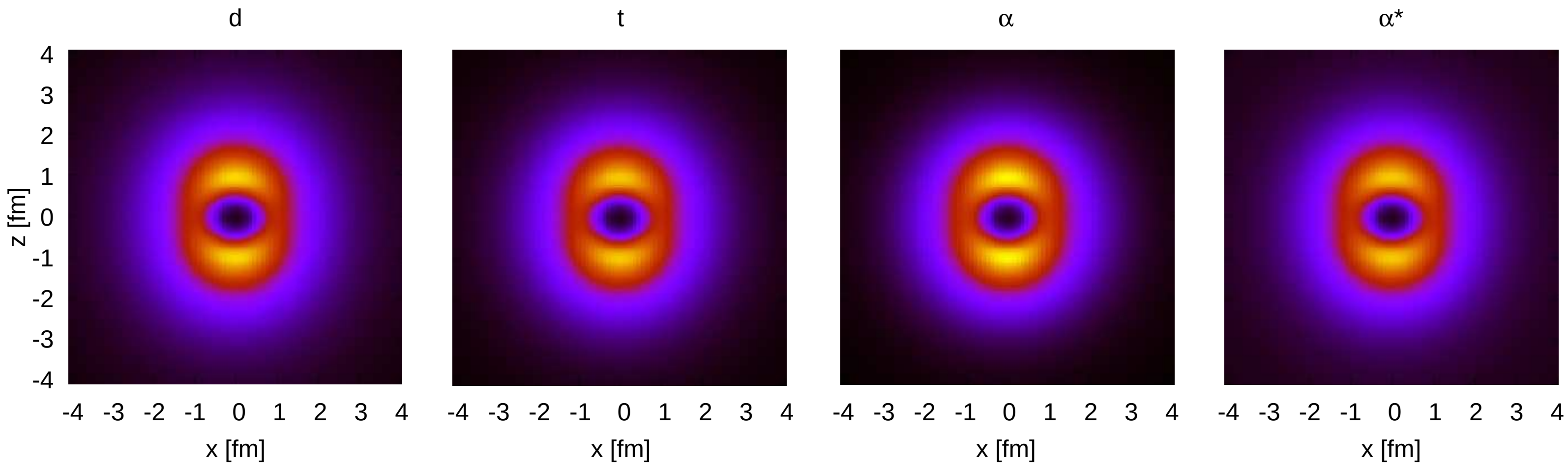
Figure 1: The two-body relative distribution in ^3He and ^4He (After Ref. [?])

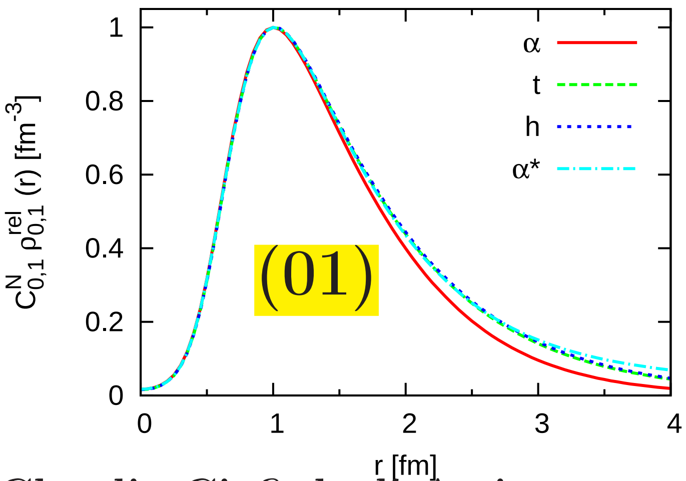
The 2BDM $\rho_{(2)}$ in few-nucleon systems in (ST)=(10) and (01) states

Suzuki, Horiuchi, Nucl. Phys. A818, 188 (2009)

Feldmaier, Horiuchi, Neff, Suzuki, Phys. Rev. C84,054013(2011)

(10)





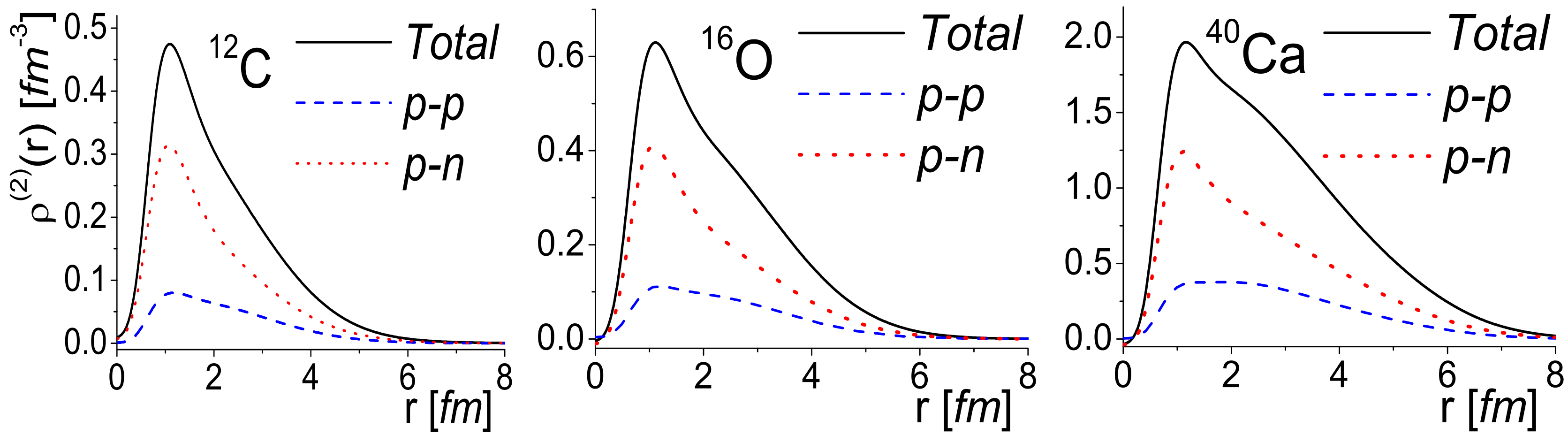
At $r < 1.5 fm$ the 2BDM exhibits A-independence

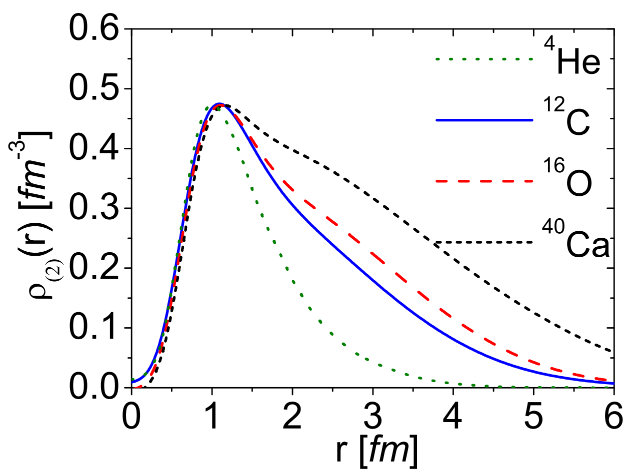
⇓

UNIVERSALITY of SRC

The 2BDM $\rho_{(2)}(r)$ in COMPLEX NUCLEI

Alvioli, CdA, Morita, ArXiv: 0709:3989 (2007) Submitted





At $r < 1.5 fm$ the 2BDM exhibits A-independence in complex nuclei as well

$\Downarrow$

UNIVERSALITY of SRC

The Correlated 2BDM versus the Mean-Field 2BDM

Pieper, Wiringa, Pandharipande, Phys. Rev. C46 1741 (2000)

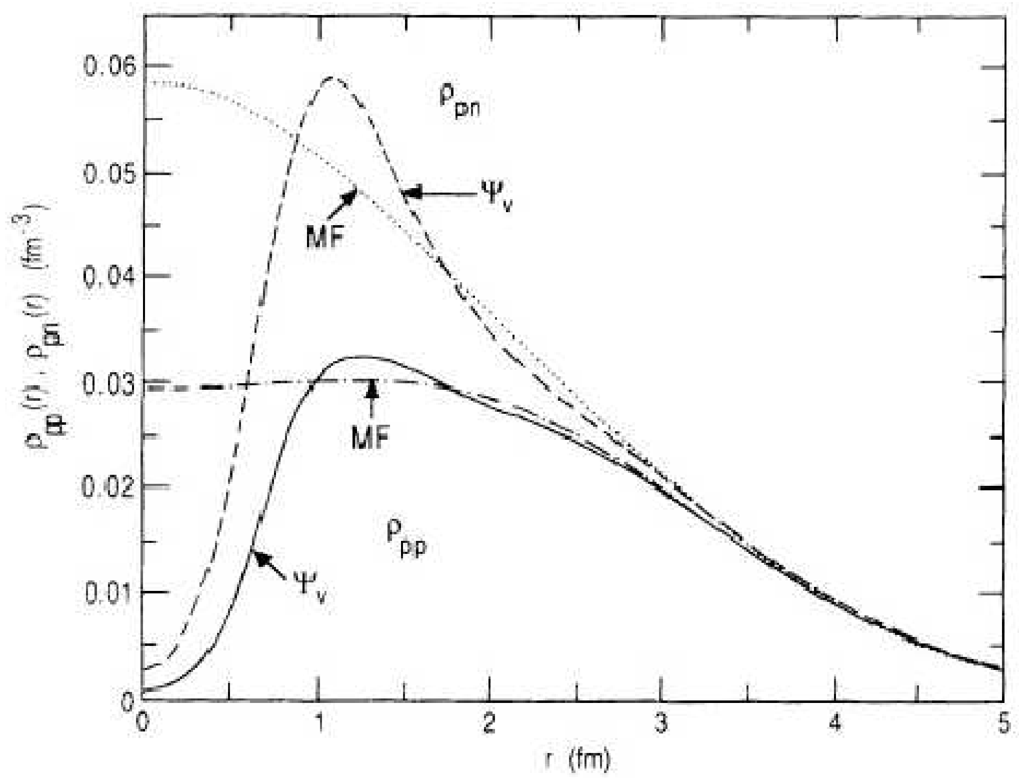


Figure 2: The two body density distribution within realistic and mean-field approaches for ^{16}O

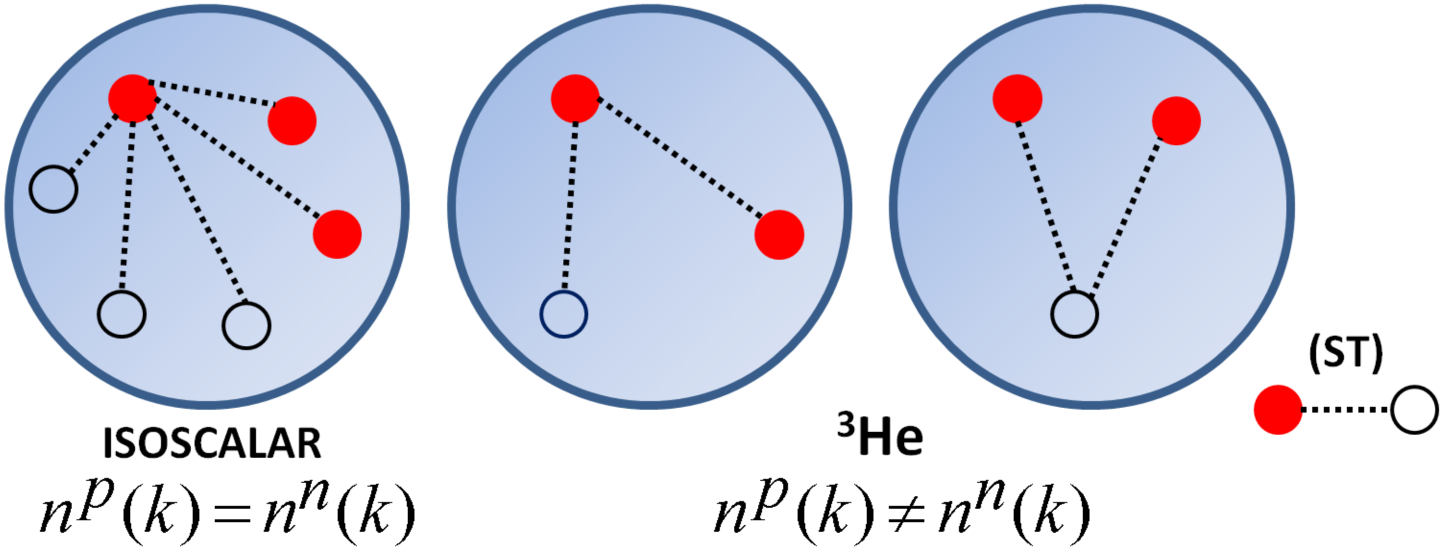
SRC IN CONFIGURATION SPACE: SUMMARY

- SRC create the *correlation hole,* generated by the cooperation of the *short-range repulsive interaction* and the *intermediate-range tensor attraction* . The basic features of the correlation hole are independent of the mass $A \Longrightarrow$ universality of SRC.

- SRC modify the spin-isospin content of the wave function.

- How can we investigate the existence and the properties of the correlation hole ? To this end we have to shift to momentum space. What do we expect? We expect: (i) an increase of nucleon high momentum components, and (ii) peculiar momentum configurations in the nuclear wave function..

THE NUMBER OF PAIRS IN SPIN-ISOSPIN STATES.



Pauli Principle: l+S+T-odd

Shell Model (IPM):

$A \leq 4$: $l-$even,(10),(01)–$A > 4$: $l-$even,(10),(01); $l =$ odd,(00),(11)

NN interaction creates states (00) and (11) also in $A \leq 4$ nuclei

The pair (ST) probabilities:

p-n pair: (3/4) [(10)+(00)] + (1/4)[(01) +(11)]

p-p (n-n) pair: (01) +(11)

The number of pairs in various (ST) states is then given by

$$N^{N_1N_2}_{(ST)} = \int d\boldsymbol{r}_{\mathbf{1}}\, d\boldsymbol{r}_2\, \rho^{N_1N_2}_{ST}(\boldsymbol{r}_1 = \boldsymbol{r}'_1; \boldsymbol{r}_2 = \boldsymbol{r}'_2)$$

The number of NN pairs in various spin-isospin (ST) states

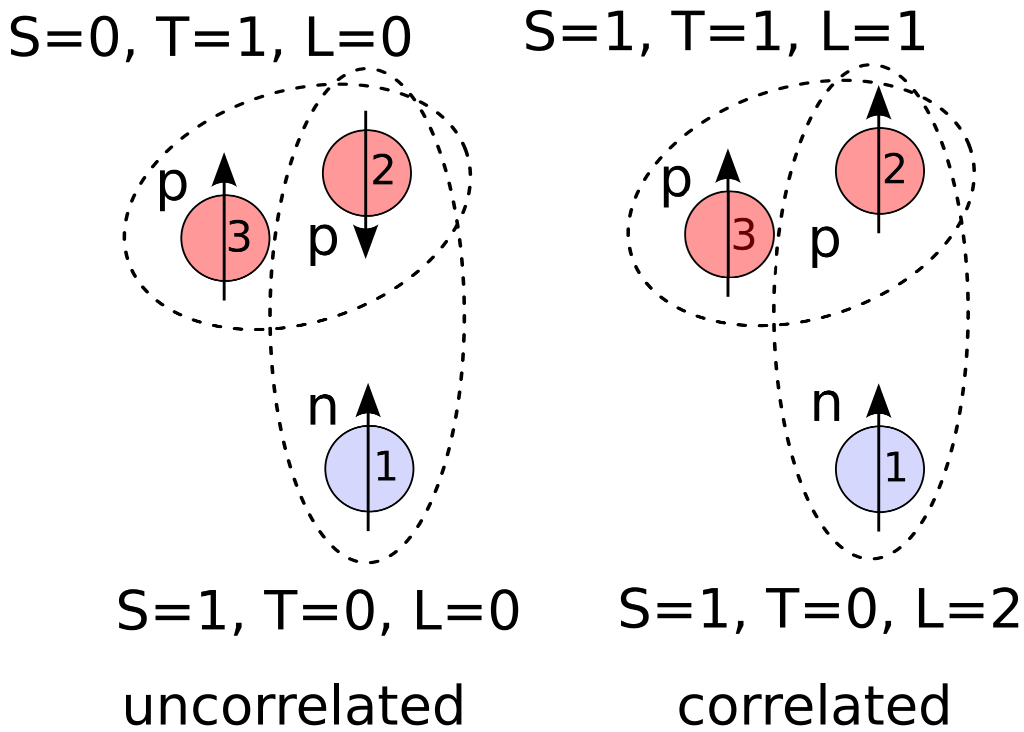
Nucleus		(ST)			
		(10)	(01)	(00)	(11)
^{2}H		1	-	-	-
^{3}He	IPM	1.50	1.50	-	-
	SRC (Present work)	1.488	1.360	0.013	0.139
	SRC (Forest et al, 1996)	1.50	1.350	0.01	0.14
	SRC (Feldmeier et al, 2011)	1.489	1.361	0.011	0.139
^{4}He	IPM	3	3	-	-
	SRC (Present work)	2.99	2.57	0.01	0.43
	SRC (Forestet al,1996)	3.02	2.5	0.01	0.47
	SRC (Feldmeier et al, 2011)	2.992	2.572	0.08	0.428
^{16}O	IPM	30	30	6	54
	SRC (Present work)	29.8	27.5	6.075	56.7
	SRC (Forest et al, 1996)	30.05	28.4	6.05	55.5
^{40}Ca	IPM	165	165	45	405
	SRC (Present work)	165.18	159.39	45.10	410.34

- NN interaction doesn't practically affect the state (10) but appreciably reduces the state (01) giving rise to a "visible" content of the (11) state; this is due to a three-body mechanism originating from the tensor force.

THE THREE-BODY MECHANISM

H. Feldemeier, W. Horiuchi, T. Neff, Y. Suzuki

Phys. Rev. C84, 054003 (2011)



IPM: only L=0 (10), (01) states are possible

Correlated particles: tensor interaction in the p-n pair in L=2 can induce a spin flip in the p-p pair with creation of a state L=1, (11) of the pair. Three-body effect.

(i) *increase of the high momentum content of the wave function*

Mean-field (shell model) wave function

$$\Phi_0(1,2,\ldots,A) = \hat{A}\prod_i^A \phi_{\alpha_i}(x_i) \equiv \Phi_{0p0h} \quad \alpha_i > \alpha_F, \phi_{\alpha_i} = 0$$

Correlated wave function

$$\Psi_0(1,2,\ldots,A) = C_{0p0h}\,\phi_{0p0h} + C_{1p1h}\,\Phi_{1p1h} + C_{2p2h}\,\Phi_{2p2h} + \ldots$$

$$SRC \Longrightarrow \sum_{n=2}^{\infty} C_{npnh}\Phi_{npnh}$$

Thus :

SRC populate states (n particle-n hole) with momentum much higher than the Fermi momentum $k_F \simeq 1.4 fm^{-1}$!!!

(ii) *SRC generate peculiar wave function configurations*

Momentum conservation

$$\sum_{1}^{A} \vec{k}_i = 0$$

Consider a nucleon with high momentum $\vec{k}_1$

In a mean-field configuration

$$\vec{k}_1 \simeq -\sum_{2}^{A} \vec{k}_i \qquad \vec{k}_i \simeq \frac{\vec{k}_1}{A}$$

In a two-nucleon correlation configuration

$$\vec{k}_1 \simeq -\vec{k}_2 \qquad \vec{K}_{A-2} = \sum_{3}^{A} \vec{k}_i \simeq 0 \quad \vec{k}_{rel} \simeq \vec{k}_1 \quad \vec{K}_{CM} = -\vec{K}_{A-2} \simeq 0$$

SRC :HIGH relative and LOW CM momenta of a pair.

Frankfurt, Strikman, Phys. Rep. 1988

THE HIGH MOMENTUM COMPONENTS IN THE ONE-BODY MOMENTUM DISTRIBUTION

$$\rho(\boldsymbol{r}_1, \boldsymbol{r}'_1) = \int \Psi_0^*(\boldsymbol{r}_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A)\, \Psi_0(\boldsymbol{r}'_1, \boldsymbol{r}_2 \ldots, \boldsymbol{r}_A) \prod_{i=2}^{A} d\boldsymbol{r}_i$$

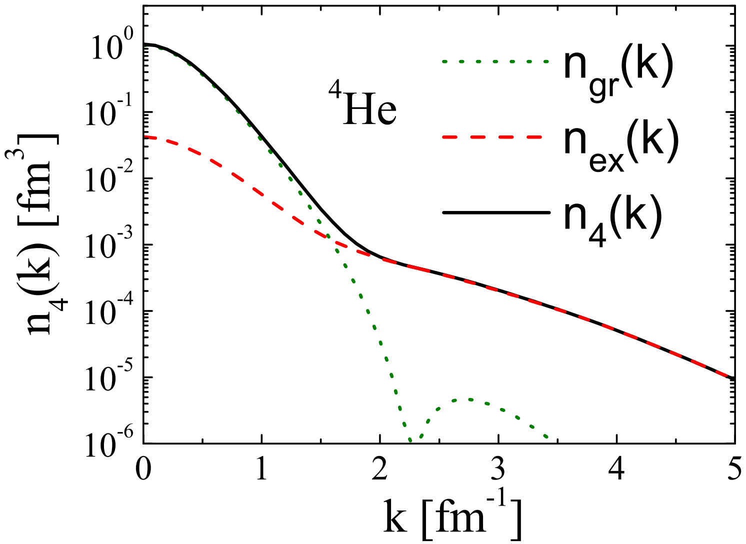
$$n(\boldsymbol{k}) = \int e^{-i\,\boldsymbol{k}\cdot(\boldsymbol{r}_1 - \boldsymbol{r}'_1)} \rho(\boldsymbol{r}_1, \boldsymbol{r}'_1) d\boldsymbol{r}_1 d\boldsymbol{r}'_1$$

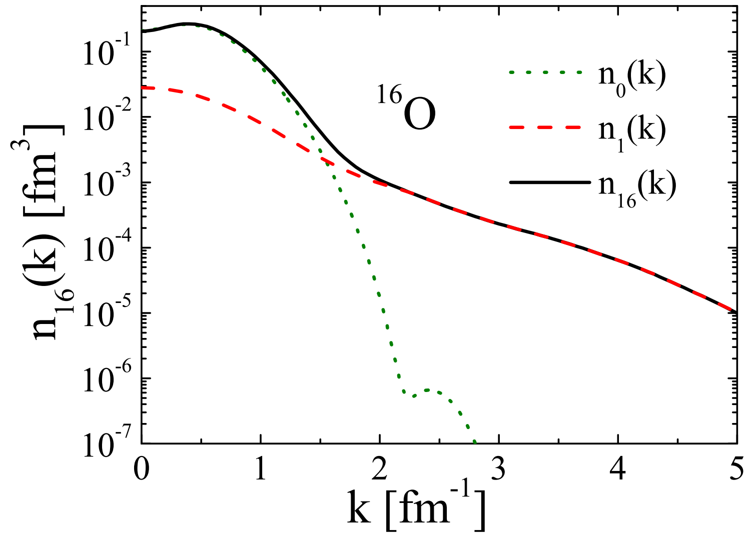
$$n_A(\boldsymbol{k}_1) = \sum_{ST} n_A^{(ST)}(\boldsymbol{k}_1) =$$

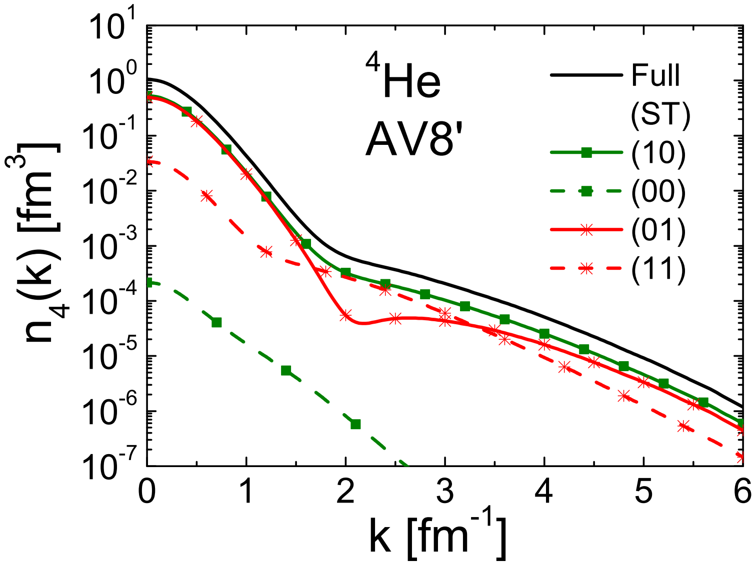
$$= \int d\boldsymbol{r}_1\, d\boldsymbol{r}'_1 e^{i\,\boldsymbol{k}_1\cdot(\boldsymbol{r}_1 - \boldsymbol{r}'_1)} \sum_{ST} \int d\boldsymbol{r}_2 \rho_{ST}^{N_1 N_2}(\boldsymbol{r}_1, \boldsymbol{r}'_1; \boldsymbol{r}_2)$$

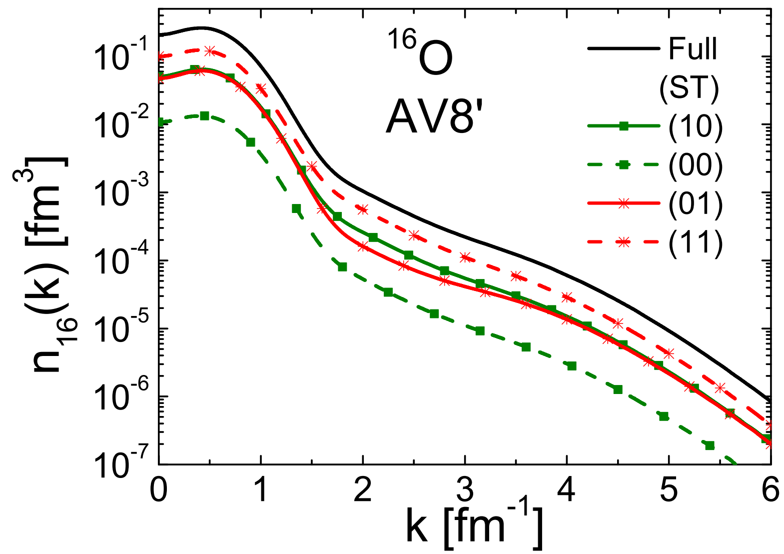
Alvioli, CdA, Kaptari, Mezzetti, Morita,

arXiv:1211.0134v1[nucl-th] Phys. Rev. (in print)

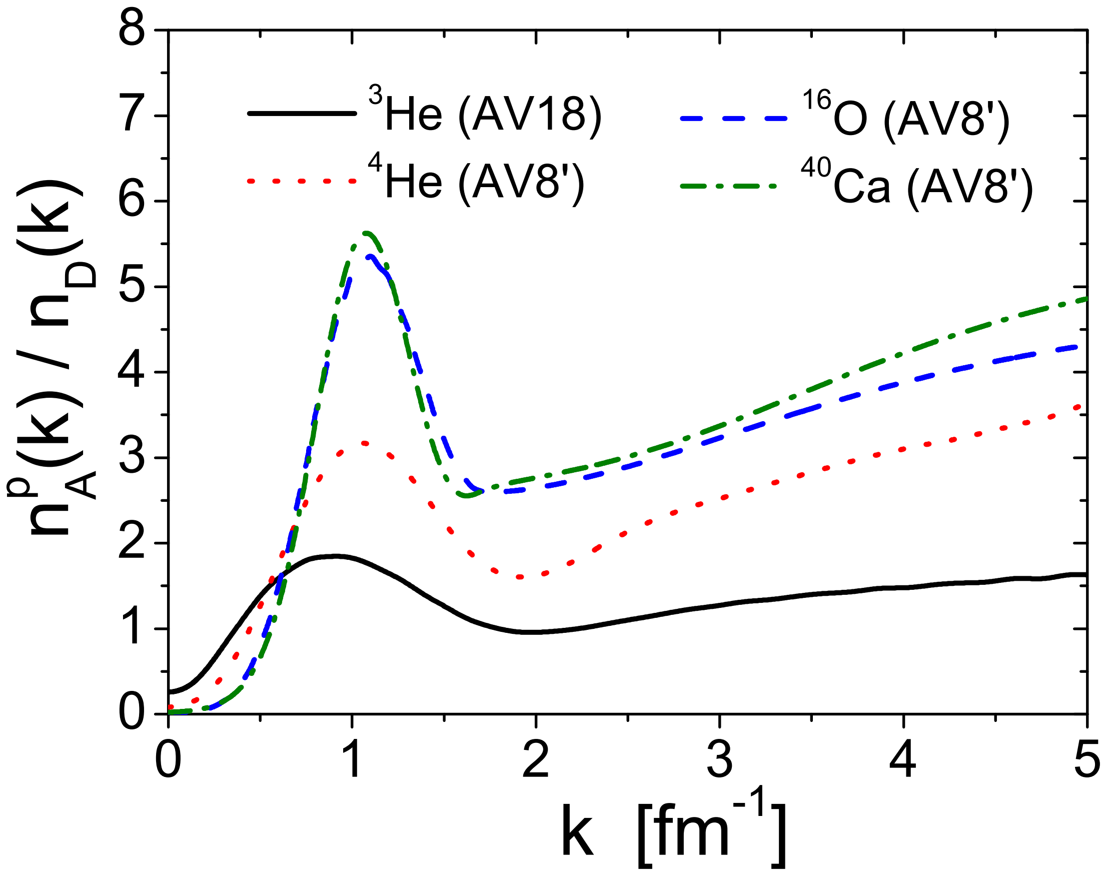

^{4}He
$n_{gr}(k)$
$n_{ex}(k)$
$n_4(k)$
$n_4(k)$ [fm^3]
k [fm^{-1}]


^{16}O
$n_0(k)$
$n_1(k)$
$n_{16}(k)$
$n_{16}(k)$ [fm^3]
k [fm^{-1}]


^{4}He
AV8'
Full
(ST)
(10)
(00)
(01)
(11)
$n_4(k)$ [fm^3]
k [fm^{-1}]

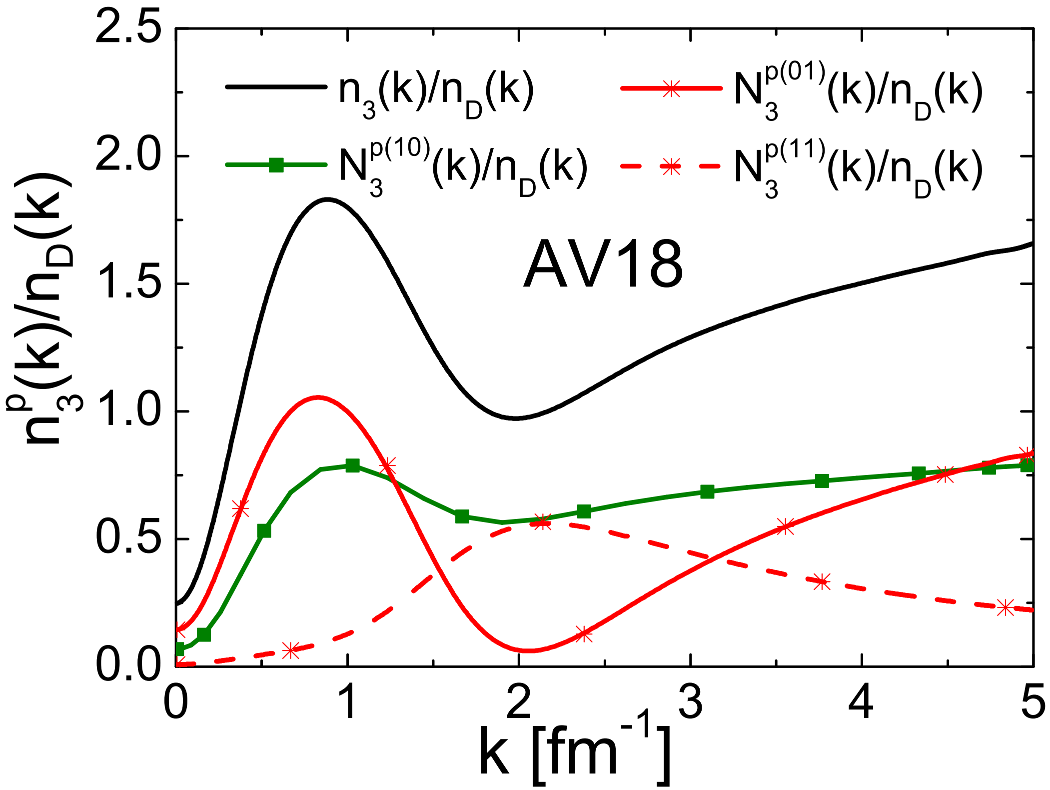

^{16}O
AV8'
Full
(ST)
(10)
(00)
(01)
(11)
$n_{16}(k)$ [fm^3]
k [fm^{-1}]

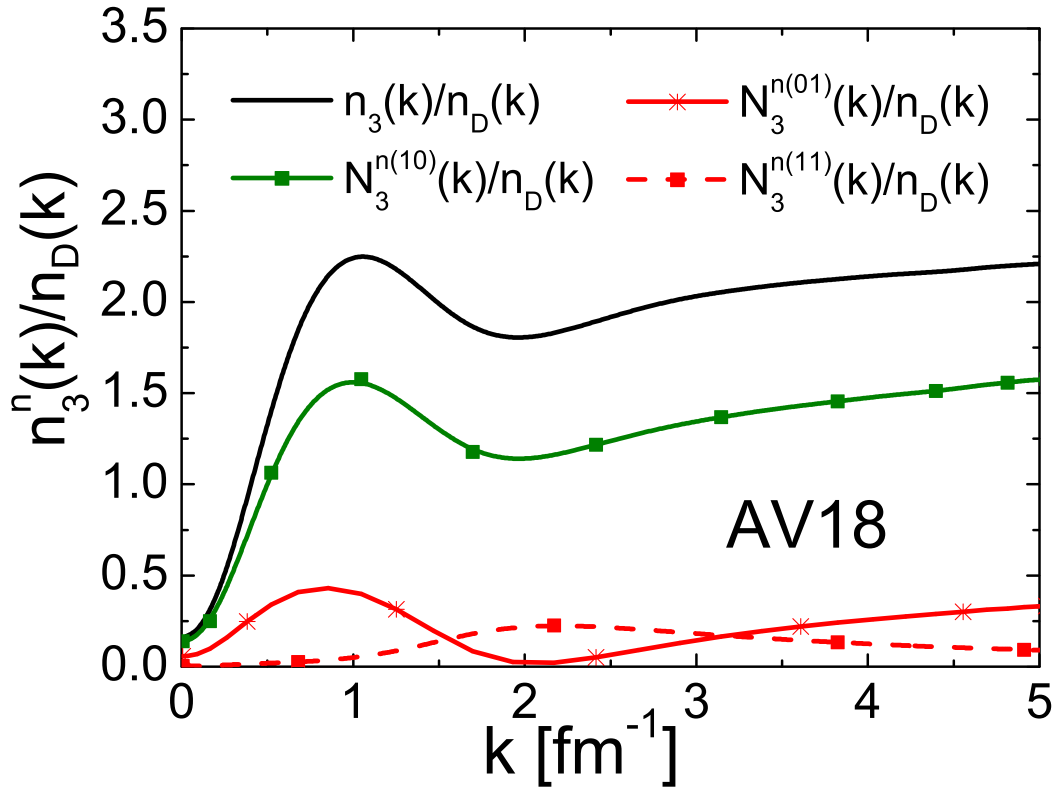
The ratio $n_A(k)/n_D(k)$ according to recent calculations



The increase of the ratio with k originates from the spin-isospin dependence of the momentum distributions and from the CM motion of the pair in the nucleus.

The proton and neutron momentum distributions in ^3He





A proton is correlated with one p-n and one p-p pair; a neutron with two n-p pair $\rightarrow$ Tensor dominance in neutron (proton) distributions in ^3He (^3H) and in neutron-rich nuclei.

TWO-BODY MOMENTUM DISTRIBUTIONS

$$\boldsymbol{k}_{rel} \equiv \boldsymbol{k} = \frac{1}{2}(\boldsymbol{k}_1 - \boldsymbol{k}_2) \qquad \boldsymbol{K}_{CM} \equiv \boldsymbol{K} = \boldsymbol{k}_1 + \boldsymbol{k}_2$$

1. $n(\boldsymbol{k}_1, \boldsymbol{k}_2) = n(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM}) = n(k_{rel}, K_{CM}, \theta) =$

$$= \frac{1}{(2\pi)^6} \int d\boldsymbol{r}\, d\boldsymbol{r}'\, d\boldsymbol{R}\, d\boldsymbol{R}'\, e^{-i\,\boldsymbol{K}\cdot(\boldsymbol{R}-\boldsymbol{R}')}\, e^{-i\,\boldsymbol{k}\cdot(\boldsymbol{r}-\boldsymbol{r}')} \rho^{(2)}(\boldsymbol{r}, \boldsymbol{r}'; \boldsymbol{R}, \boldsymbol{R}')$$

2. $n(k_{rel}, K_{CM} = 0)$

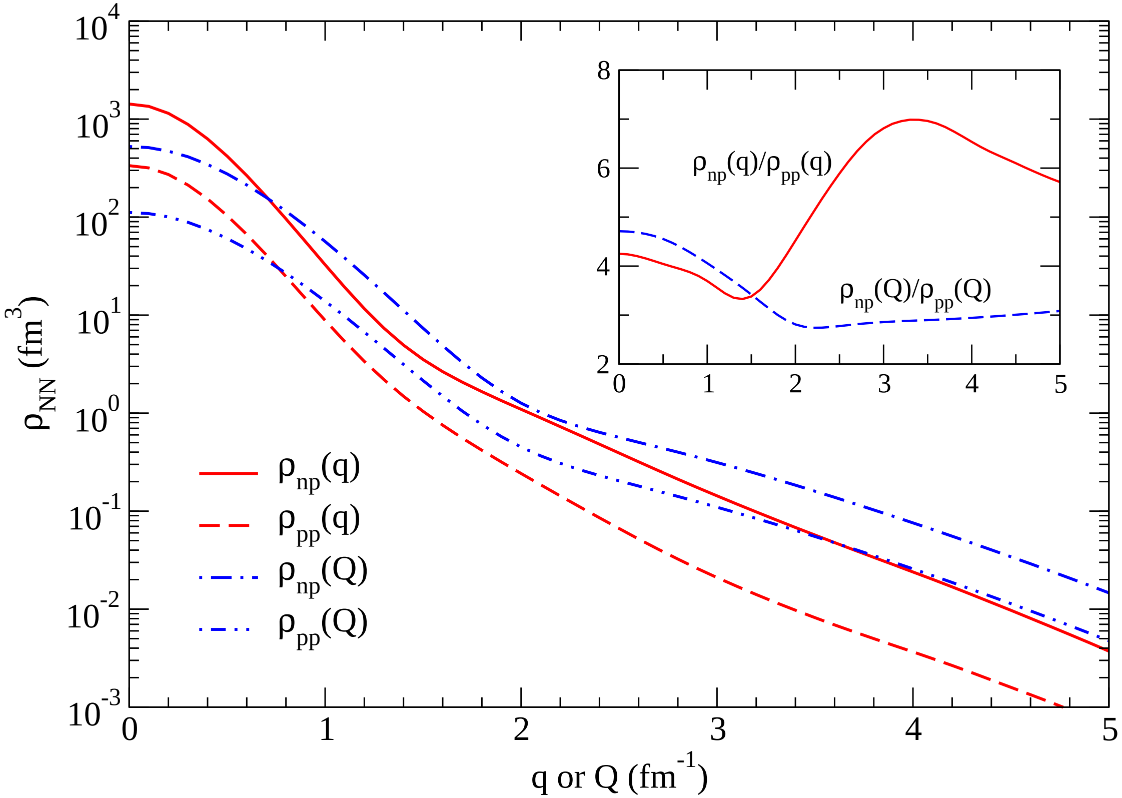
$$K_{CM} = 0 \qquad \Longrightarrow \qquad \boldsymbol{k}_2 = -\boldsymbol{k}_1,$$

back-to-back nucleons, like in the deuteron

3. $n_{rel}(k) = \frac{1}{(2\pi)^3} \int n(\boldsymbol{k}, \boldsymbol{K})\, d\boldsymbol{K}$ **4.** $n_{CM}(K) = \frac{1}{(2\pi)^3} \int n(\boldsymbol{k}, \boldsymbol{K})\, d\boldsymbol{k}$

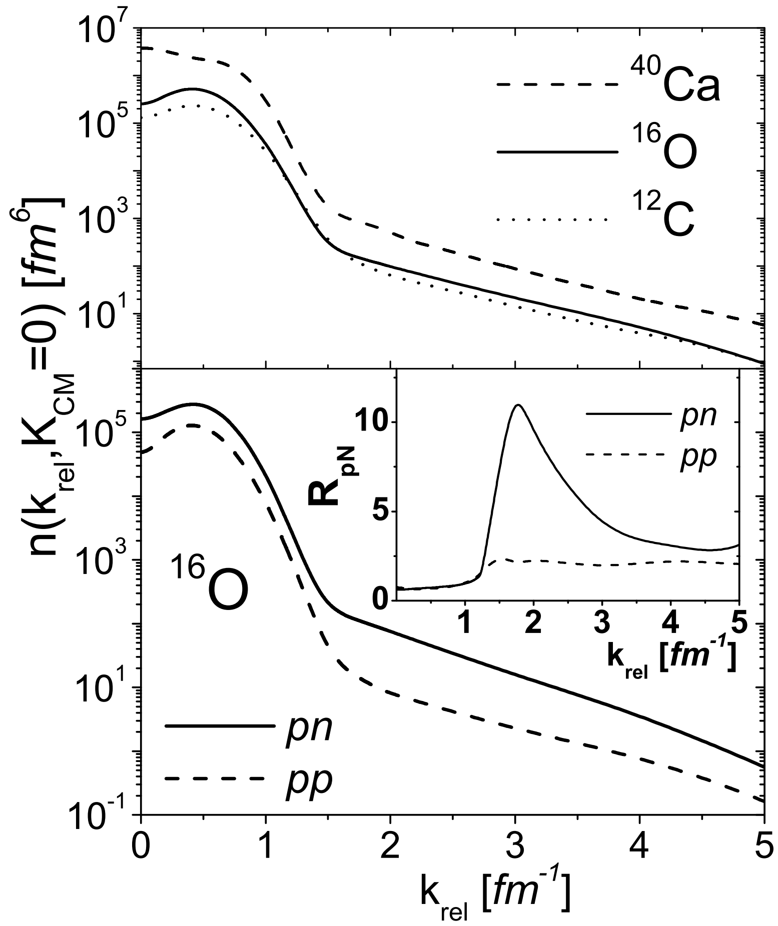
$n(k_{rel}), n(K_{CM})$ in FEW-NUCLEON SYSTEMS

Schiavilla et al Phys. Rev. Lett. 98(2007)132501 $\quad q \equiv \mathbf{k}_{rel} \quad Q \equiv \mathrm{K}_{CM}$



TENSOR DOMINANCE

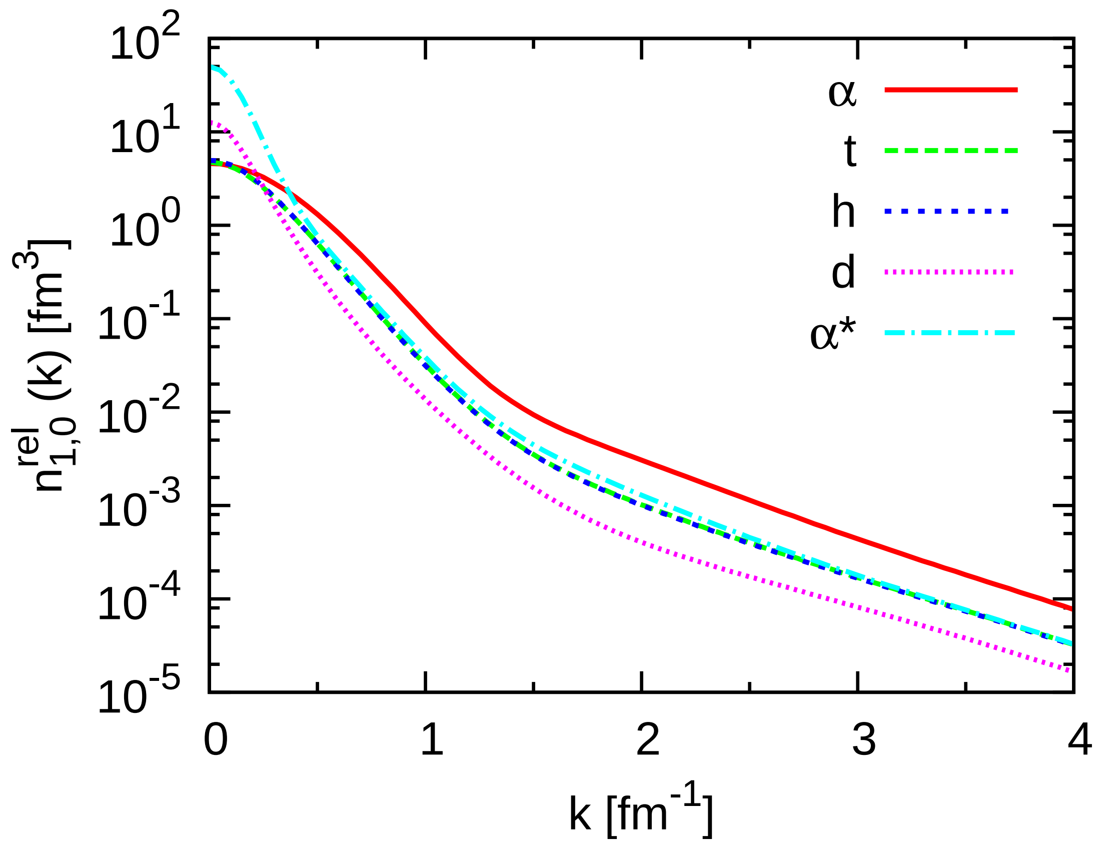
$n(k_{rel}, K_{CM} = 0)$ in COMPLEX NUCLEI



Alvioli, CdA, Morita Phys. Rev. Lett. 100 (2008)162503

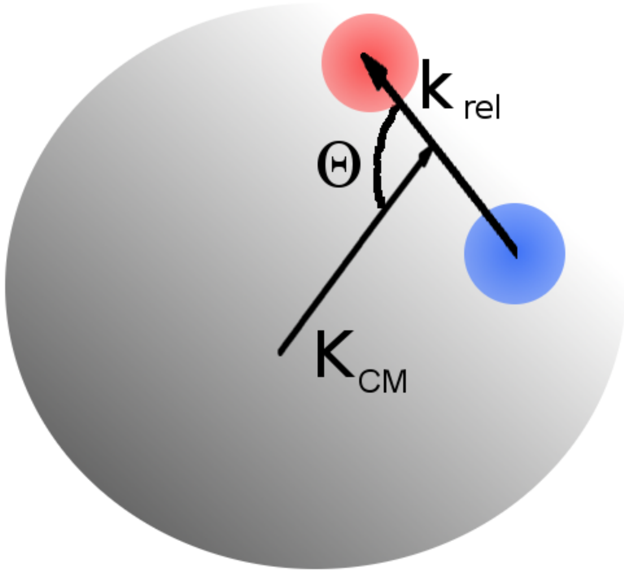
SPIN-ISOSPIN DEPENDENCE of $n_{rel}(k_{rel})$ in FEW-NUCLEON SYSTEMS

H. Feldmaier, W. Horiuchi, T. Neff, Y. Suzuki, Phys. Rev. (2011)



UNIVERSALITY: $n_{rel}^{A}(k_{rel}) \simeq C_A n_D(k)$ in (10) state

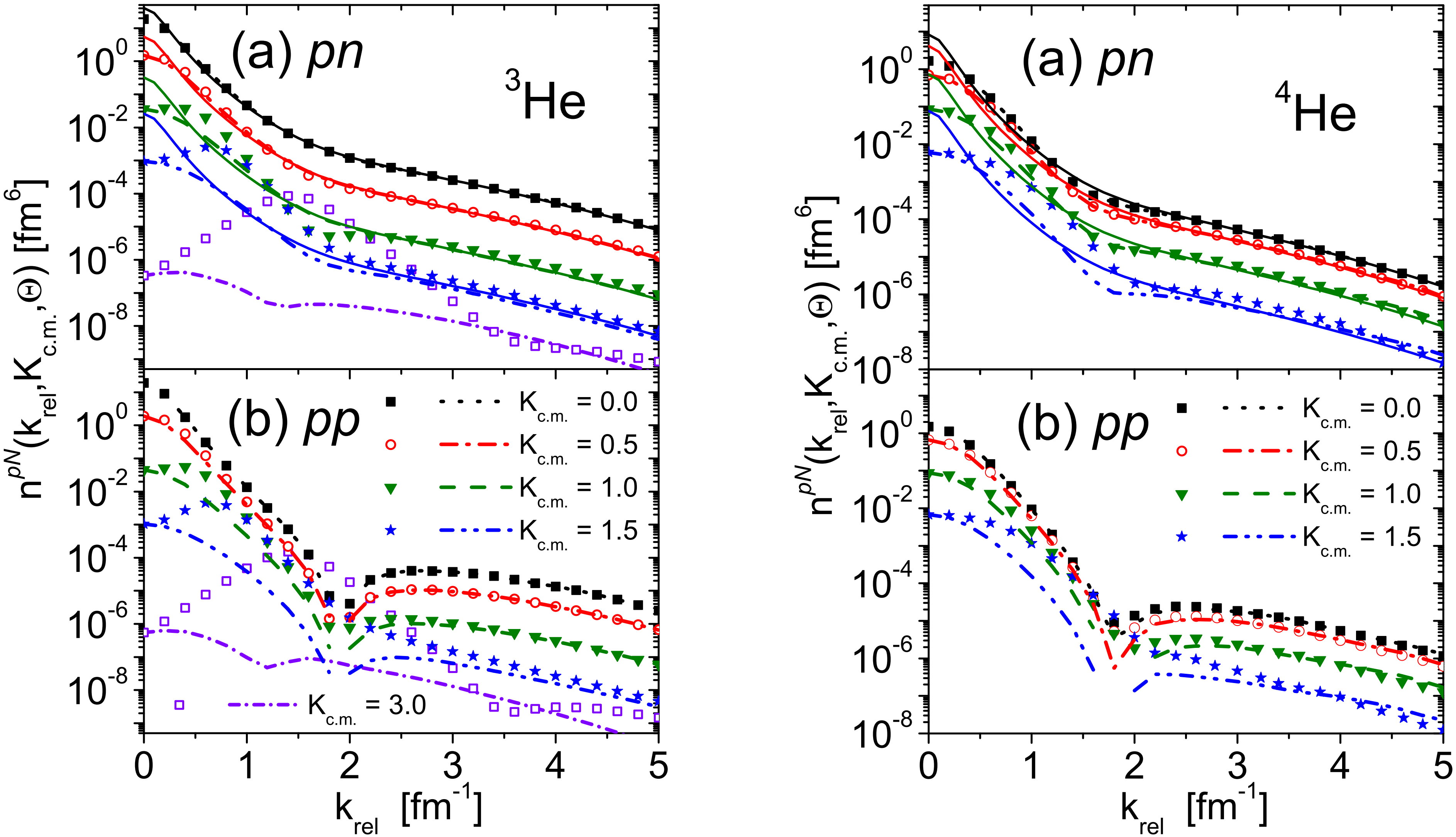
THE 3D PICTURE OF $n(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM}) = n(k_{rel}, K_{CM}, \Theta)$



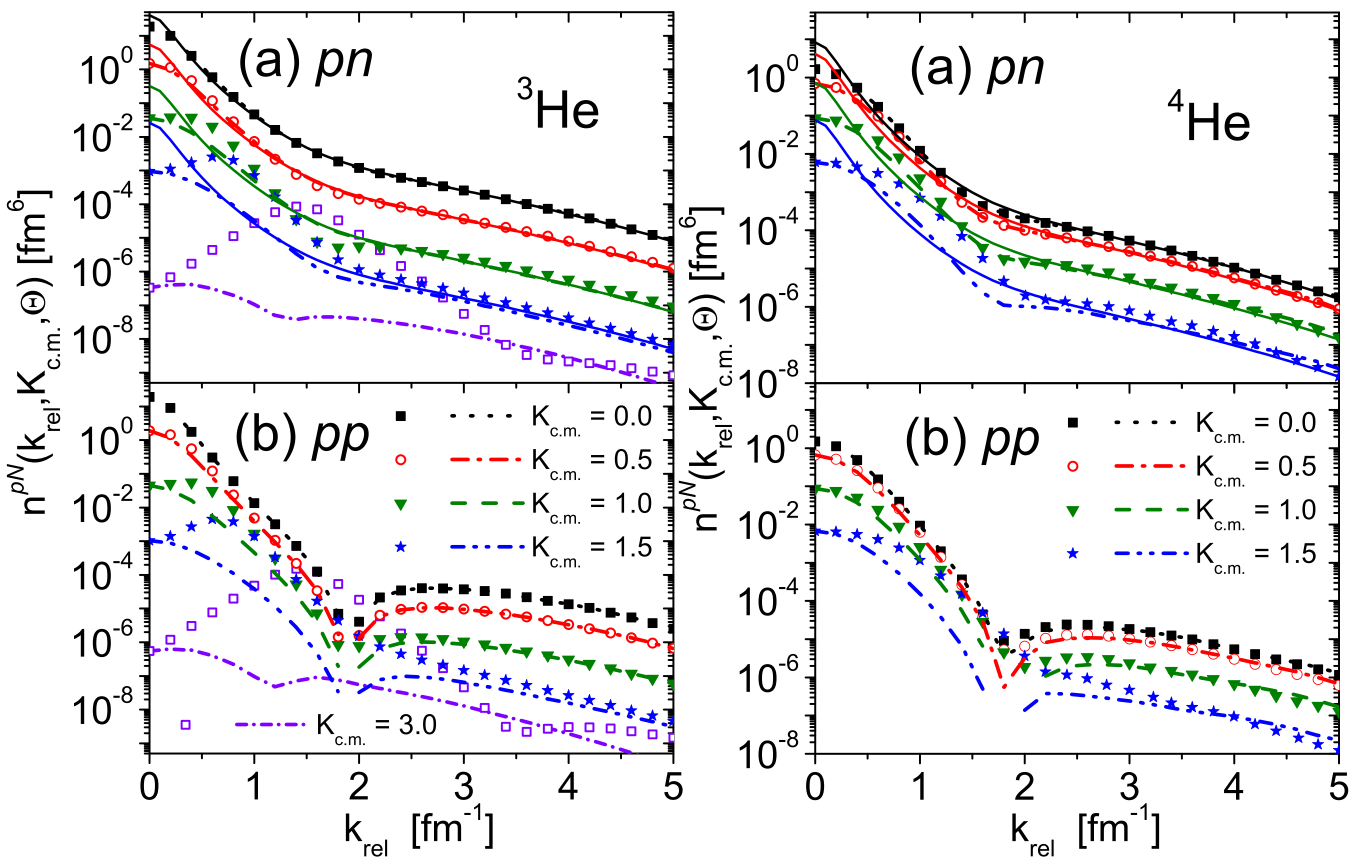
! VERY IMPORTANT !

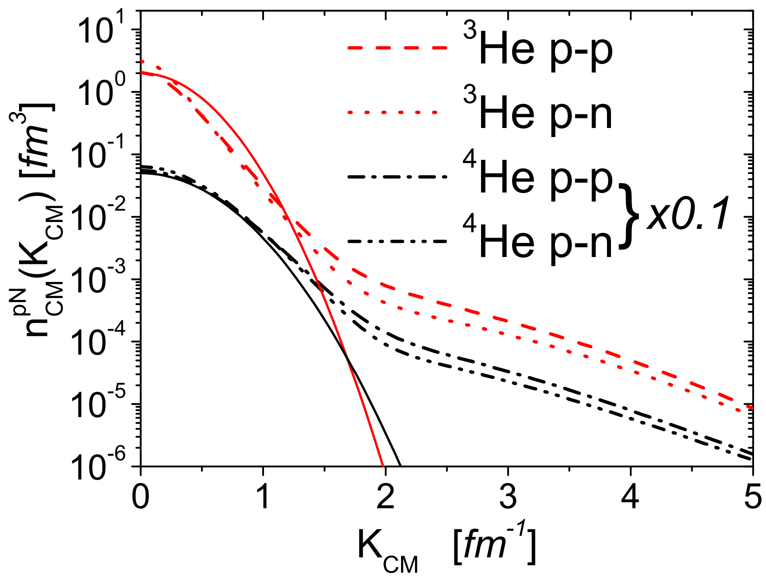
- **If** $n(k_{rel}, K_{CM}, \Theta)$ **is** Θ **independent, it means that** $n(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM}) = n(k_{rel})\, n(K_{CM})$ **i.e. the relative and CM motions factorize.**

$n(k_{rel}, K_{CM}, \theta)$ symbols-$\Theta = 90^o$, dashes-$\Theta = 180^o$, full-^2H.



Alvioli, CdA, Kaptari, Mezzetti, Morita, Scopetta, Phys. Rev. C85(2012)





at large values of k_{rel} and small values of K_{CM} we have :

$$n^{pn}(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM}) \Longrightarrow n^{pn}(k_{rel}, K_{CM}) \simeq n^{D}(k_{rel}) n_{CM}(K_{CM})$$

Factorization is proved by a rigorous many-body calculation

We demonstrated that in the region $\mathbf{k_{rel}} \geq \mathbf{k^{-}_{rel}}(\mathbf{K_{CM}}))$ factorization occurs.

$$\mathbf{k_1} + \mathbf{k_2} - \mathbf{K_{CM}} = \mathbf{0}, \quad \mathbf{k_{rel}} = (\mathbf{k_1} - \mathbf{k_2})/\mathbf{2}, \quad \mathbf{k_2} = -\mathbf{k_1} + \mathbf{K_{CM}}, \quad \mathbf{k_{rel}} = \mathbf{k_1} - \mathbf{K_{CM}}/\mathbf{2}$$

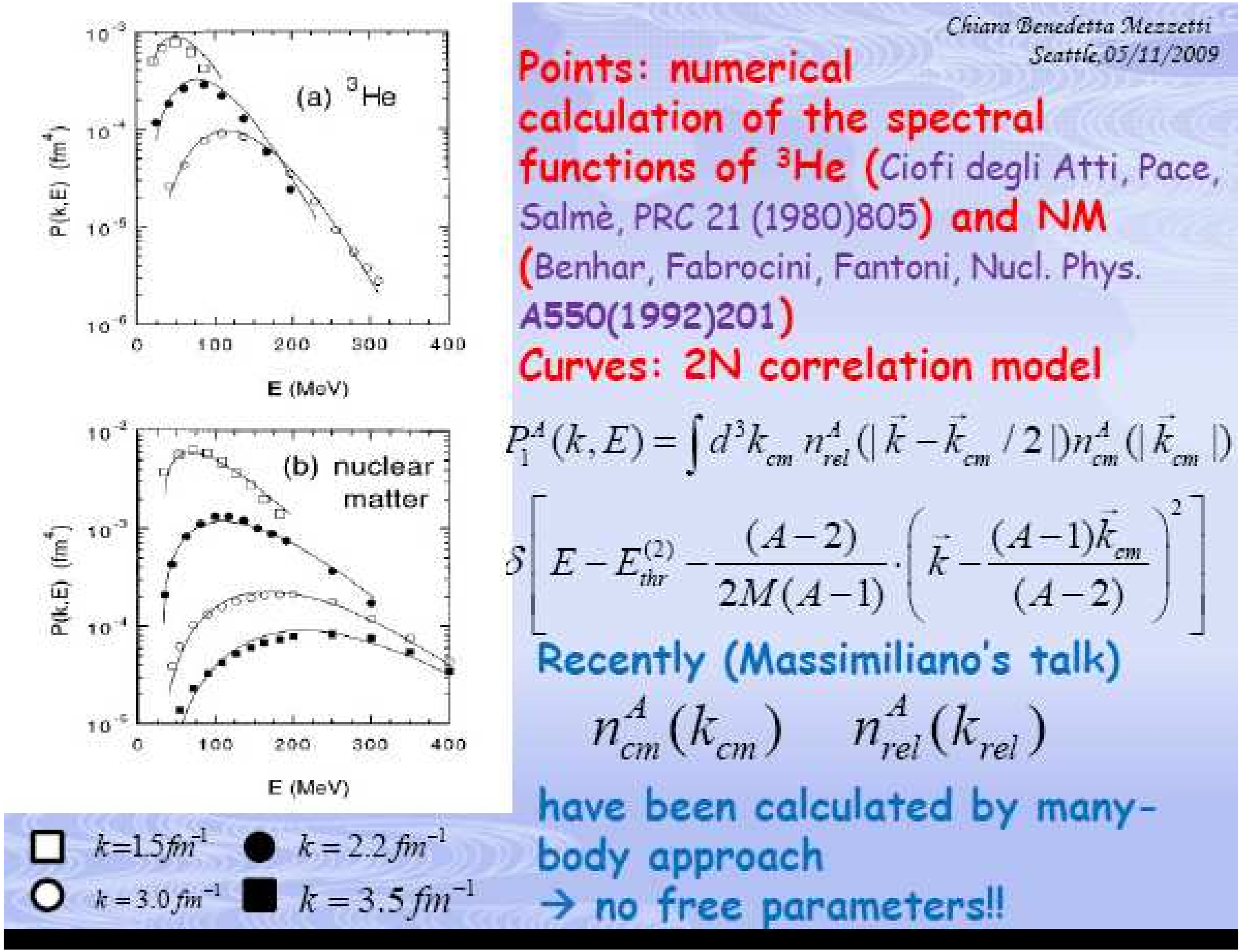
$$n_{pn}(k_{rel}, K_{CM}) \simeq n_D(k_{rel}) n_{CM}(K_{CM}) = n_D(|\boldsymbol{k}_1 - \frac{\boldsymbol{K}_{CM}}{2}|) n_{CM}(K_{CM})$$

which means

$$\begin{aligned} n^N(k_1) &\simeq \int n_D(|\boldsymbol{k}_1 - \frac{\boldsymbol{K}_{CM}}{2}|) n^N_{CM}(K_{CM}) \, d\,\boldsymbol{K}_{CM} = \\ &= \int P^N(k_1, E^*_{A-1}) \, d\,E^*_{A-1} \end{aligned}$$

where $P^N(k_1, E^*_{A-1})$ is the NUCLEON SPECTRAL FUNCTION

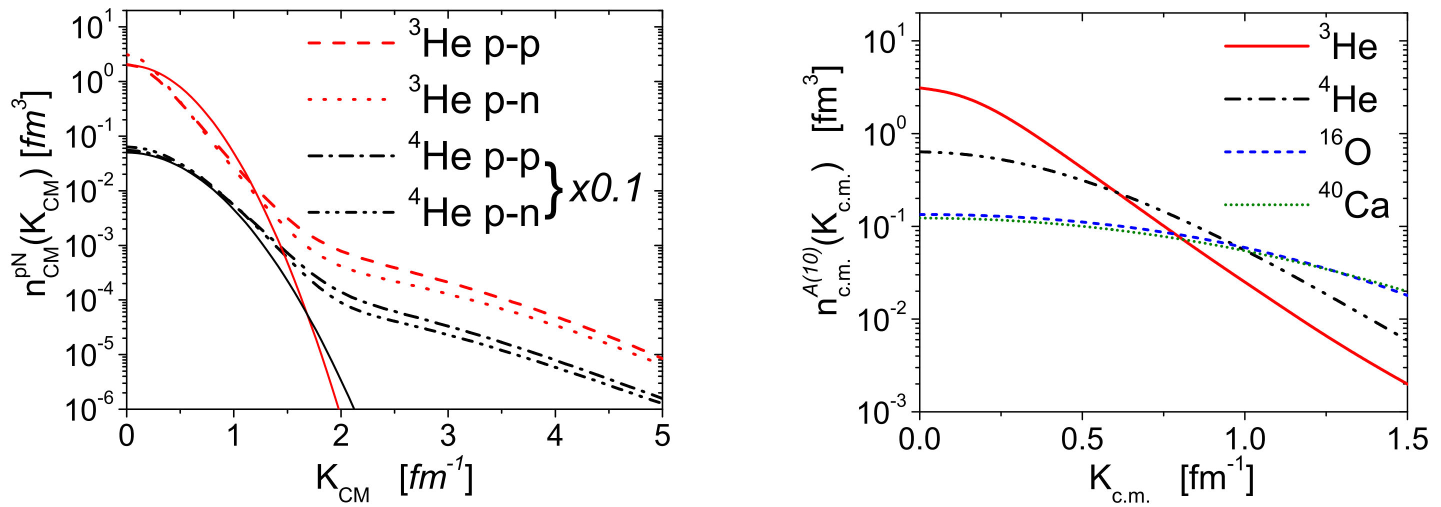
$$\begin{aligned} P^N(k_1, E^*_{A-1}) = \int n_D(|\boldsymbol{k}_1 - \frac{\boldsymbol{K}^N_{CM}}{2}|) n^N_{CM}(K_{CM}) d\,\boldsymbol{K}_{CM} \times \\ \times \, \delta \left(E^*_{A-1} - \frac{A-2}{2m_N(A-1)} \left[\boldsymbol{k}_1 - \frac{A-1}{A-2} \boldsymbol{K}_{CM} \right]^2 \right) \end{aligned}$$



CdA, Simula Nucl. Phys. 1996

The CM distribution of pn and pp pairs

$$n^{pN}_{CM}(K_{CM}) = \int d\,\boldsymbol{k}_{rel}\; n^{pN}(\boldsymbol{k}_{rel}, \boldsymbol{K}_{CM})$$



The low momentum part of $n_{CM}(K_{CM})$ for $A > 4$ agrees with a Gaussian $e^{-\alpha K^2_{CM}}$, in agreement with the convolution model where

$$\alpha = [3(A-1)/4(A-2)] \cdot [1/m_N < T_{SM} >]$$

(Theor. Prediction for $A = 12$: $\sigma = 139\ Mev/c$ (Nucl. Phys. 1966); Exp. value from $^{12}C(p,ppn)X$: $\sigma = 143 \pm 17\ MeV/c$) (PRL 2003).)

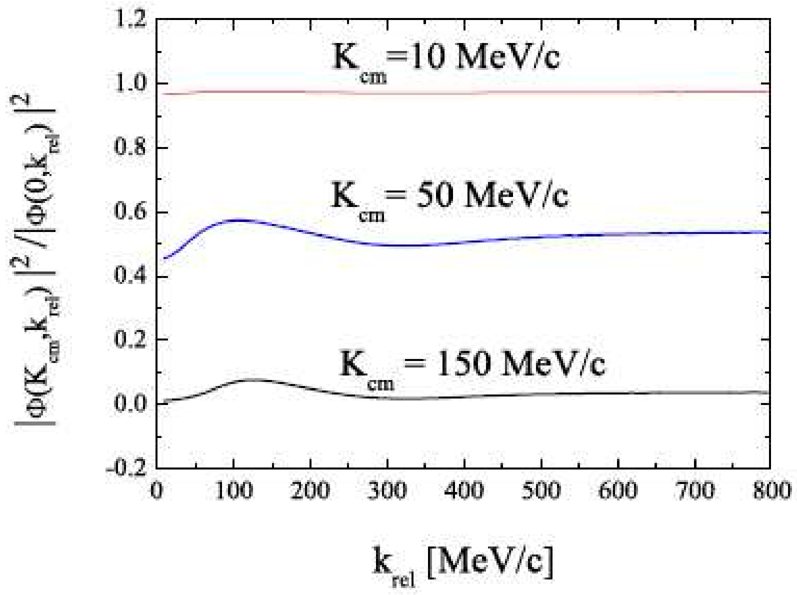
THE CONVOLUTION STRUCTURE OF $P(k, E)$ IS A GENERAL FEATURE OF THE SPECTRAL FUNCTION, RESULTING FROM SOME GENERAL PROPERTIES OF THE MANY-BODY WAVE FUNCTIONS IN MOMENTUM SPACE

^{3}He wf factorization: 2 - momentum space analysis

Towards the 2NC region, where $|\mathbf{K}_{cm}| << |\mathbf{k}_{rel}|$, if the factorization, and therefore the convolution model, holds, one should have

$$R = \frac{|M(\mathbf{K}_{cm}, \mathbf{k}_{rel})|^2}{|M(0, \mathbf{k}_{rel})|^2} \simeq \frac{n_{cm}(|\mathbf{K}_{cm}|)}{n_{cm}(|\mathbf{K}_{cm}| = 0)} = constant \cdot n_{cm}(|\mathbf{K}_{cm}|)$$

This behavior is found indeed: a clear signature of factorization in momentum space.



1

August, 30^{th} 2010

Short range correlations and wave function factorization in light and finite nuclei –

CdA, Kaptari, Morita, Scopetta, Few-Body Systems, 50(2011)243

ELSEVIER

Nuclear Physics A 604 (1996) 429–440

NUCLEAR PHYSICS A

The high momentum and energy behaviour of the nucleon spectral function of nuclear matter within the Brueckner–Bethe–Goldstone approach

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Received 14 February 1996

Abstract

The nuclear single-particle spectral function is considered in the region of high momentum and high removal energy. For these kinematical conditions, far away from the quasi-particle peak, the spectral function is expected to be dominated by nucleon–nucleon correlations. It has been previously argued that the spectral function can be written as a convolution between the two-body relative momentum distribution and the corresponding centre-of-mass distribution of the correlated pairs which characterize the structure of the ground state in this energy–momentum region. It is shown that the convolution model can be microscopically derived from the Brueckner–Bethe–Goldstone (BBG) expansion. At the same time, this result also allows us to establish a direct link between the spectral function and the defect function of the BBG theory. From a numerical comparison with the microscopic spectral function the convolution model turns out to be highly accurate in the relevant momentum and energy range.

3. The spectral function of nuclear matter within the BBG theory

In NM the spectral function corresponding to the nucleon self-energy $M(k,E) = V(k,E) + iW(k,E)$, is given by the well-known result [6]

$$P(k,E) = -\frac{1}{\pi}\mathrm{Im}\,\mathcal{G}(k,E) = \frac{1}{\pi}\frac{W(k,E)}{(-E - k^2/2m - V(k,E))^2 + W(k,E)^2}, \tag{9}$$

where $\mathcal{G}(k,E)$ is the single-particle Green function

$$\mathcal{G}(k,E) = \frac{1}{-E - k^2/2m - V(k,E) - iW(k,E)}. \tag{10}$$

It has to be noticed that the real, $V(k,E)$, and imaginary parts, $W(k,E)$, of the self-energy are highly off-shell in the considered energy and momentum ranges. We are interested in the region where E is much greater than the Fermi energy E_F. For high k and E, one finds

$$E + \frac{k^2}{2m} \gg |V(k,E)|, |W(k,E)|, \tag{11}$$

as can be seen from the results shown in Ref. [7], and the spectral function can thus

$$P(k,E) = \frac{\pi^2\rho^2}{16}\int\frac{d^3P}{(2\pi)^3}n_{\rm rel}(|\boldsymbol{k} - \tfrac{1}{2}\boldsymbol{P}|)n_{\rm cm}^{\rm FG}(\boldsymbol{P})$$
$$\times\delta\left(E - E_{\rm thr}^{(2)} - E^* - \frac{1}{2m}(\boldsymbol{P} - \boldsymbol{k})^2\right),$$

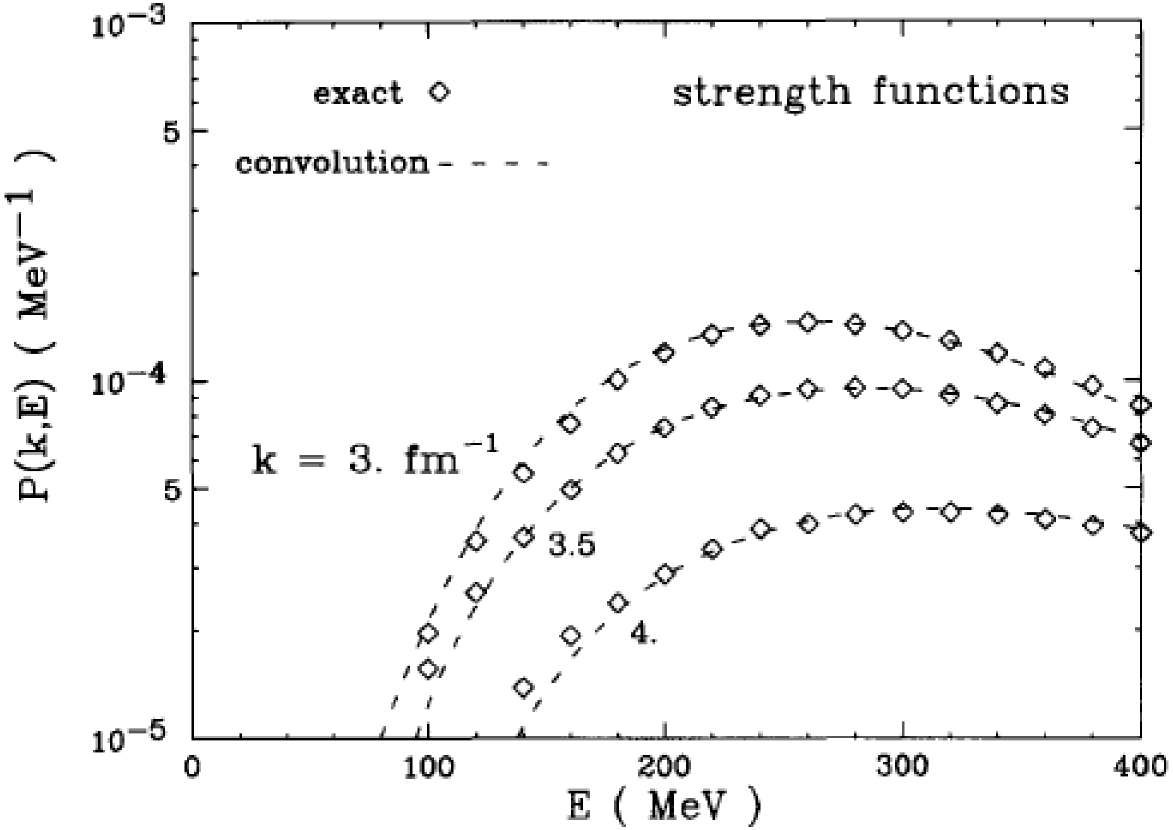
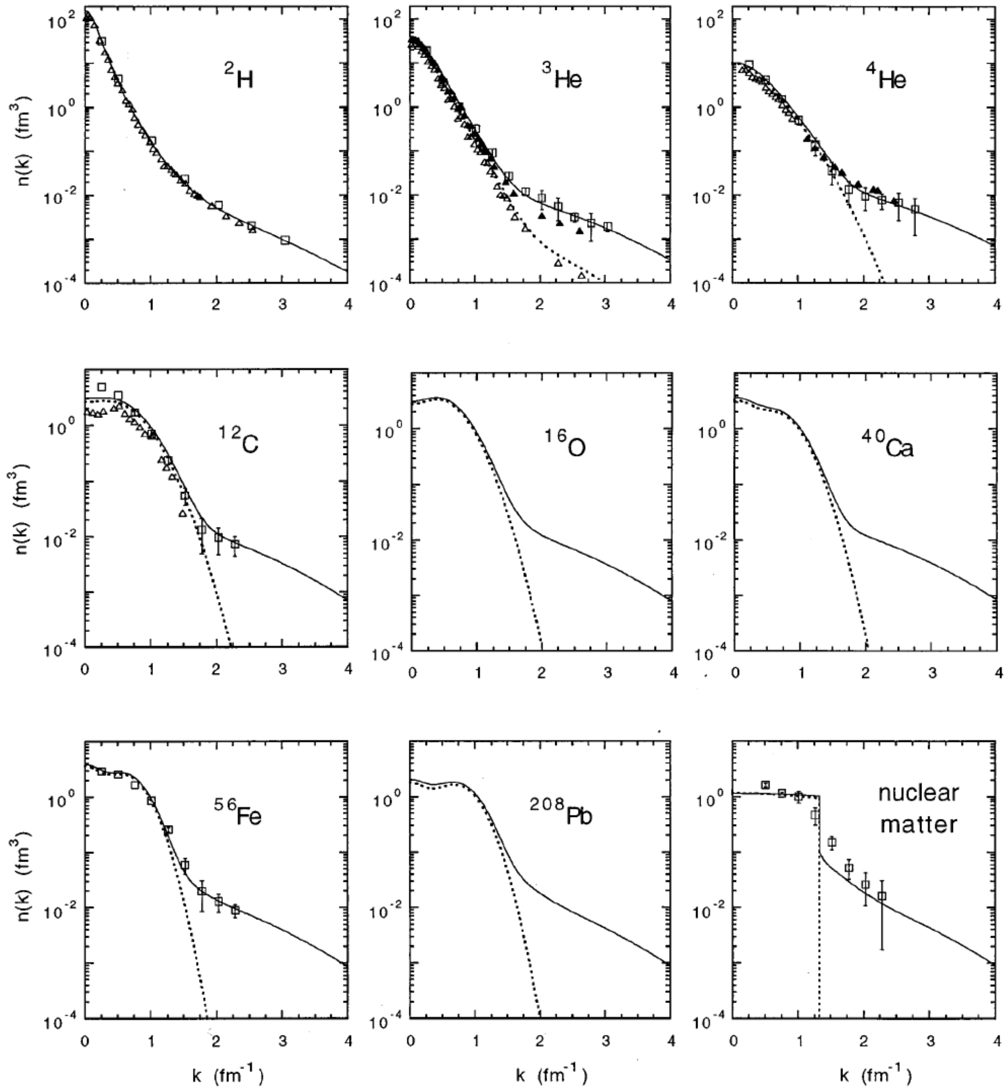


Fig. 4. Comparison between the SF obtained from the convolution model (dashed lines) and the one obtained from BBG theory (diamonds) for different values of the nucleon momentum k.

3 EXPERIMENTAL EVIDENCE OF SRC

3.1 The momentum distributions from inclusive $A(e, e')X$ processes



- Errors very large
- At high k errors much less than the difference between Mean-Field and correlated distributions
- Experimental data exist only for a limited range of A and low values of momenta.

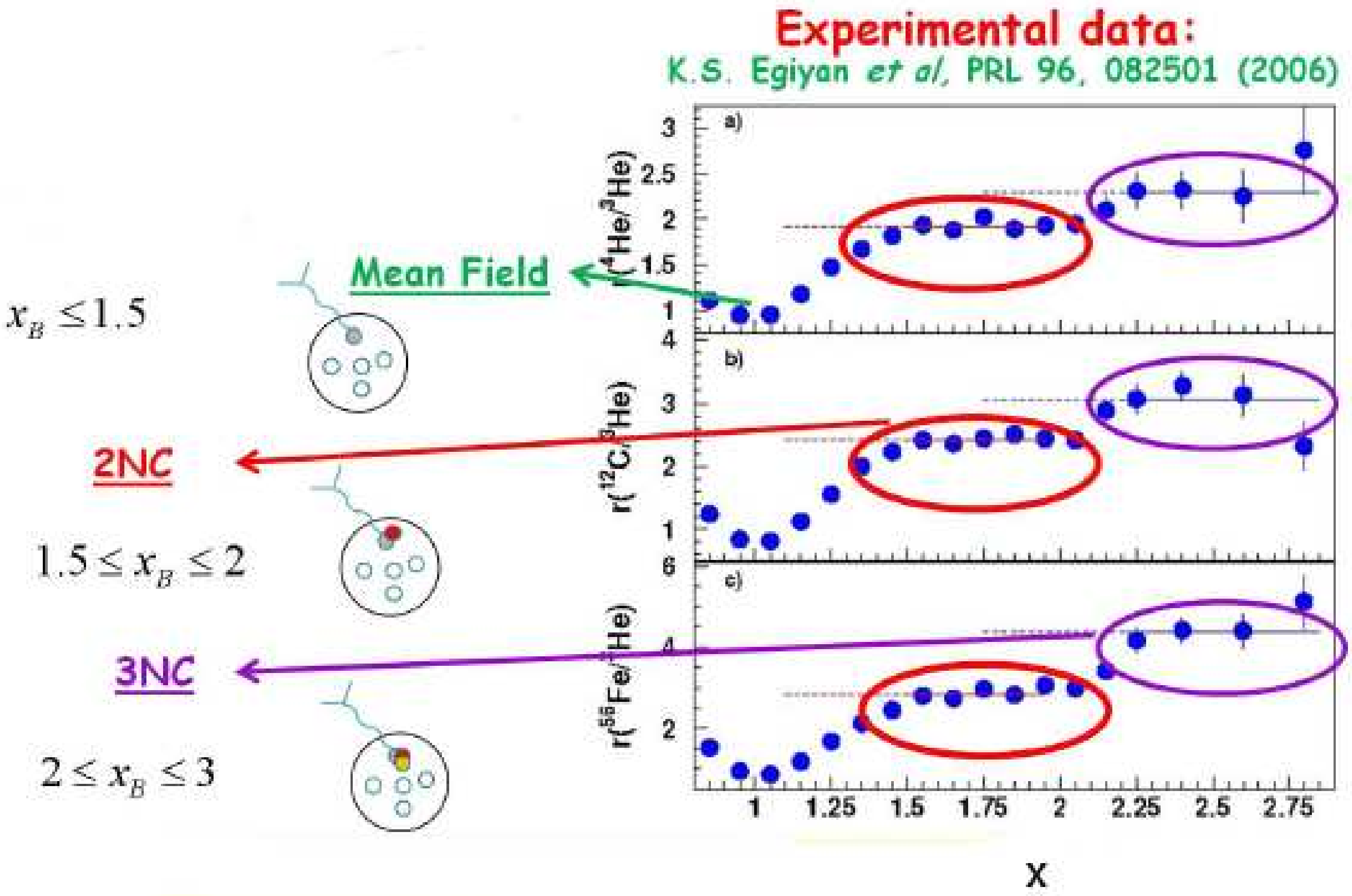
CdA, Pace, Salmè, Phys. Rev. C43 1141(1991)

See also a recent review: Arrington et al, Progr. Part. Nucl. Phys. 2012

3.2 The inclusive cross section ratio (a very useful quantity)

Original idea (Frankfurt, Strikman, Phys. Rep. 5 (1988) 235)

$$\sigma_A(x_B, Q^2) =\simeq \frac{A}{2}a_2(A)\sigma_2(1.5 < x_B < 2, Q^2)+\frac{A}{3}a_3(A)\sigma_3(2 < x_B < 3, Q^2)+\ldots$$



PHYSICAL REVIEW C, VOLUME 60, 024602

Linked cluster expansion for the calculation of the semi-inclusive $A(e,e'p)X$ processes using correlated Glauber wave functions

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(Received 2 February 1999; published 25 June 1999)

The distorted one-body mixed density matrix, which is the basic nuclear quantity appearing in the definition of the cross section for the semi-inclusive $A(e,e'p)X$ processes, is calculated within a linked cluster expansion based upon correlated wave functions and the Glauber multiple scattering theory to take into account the final state interaction of the ejected nucleon. The nuclear transparency for ^{16}O and ^{40}Ca is calculated using realistic central and noncentral correlations and the important role played by the latter is illustrated.
[S0556-2813(99)00208-3]

the cross section (1) becomes directly proportional to the distorted momentum distributions (8), i.e.,

$$n_D(\mathbf{k}_m) = (2\pi)^{-3} \int e^{i\mathbf{k}_m(\mathbf{r}-\mathbf{r}')} \rho_D(\mathbf{r},\mathbf{r}') d\mathbf{r} d\mathbf{r}', \quad (12)$$

where

$$\rho_D(\mathbf{r},\mathbf{r}') = \frac{\langle \Psi_A S_G^\dagger \hat{O}(\mathbf{r},\mathbf{r}') S_G' \Psi_A' \rangle}{\langle \Psi_A \Psi_A \rangle} \quad (13)$$

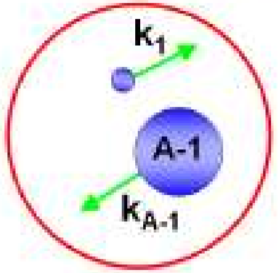
is the one-body mixed density matrix, and

$$\hat{O}(\mathbf{r},\mathbf{r}') = \sum_i \delta(\mathbf{r}_i - \mathbf{r}) \delta(\mathbf{r}_i' - \mathbf{r}') \prod_{j \neq i} \delta(\mathbf{r}_j - \mathbf{r}_j') \quad (14)$$

the one-body density operator. In Eq. (13) and in the rest of the paper, the primed quantities have to be evaluated at $\mathbf{r}'$

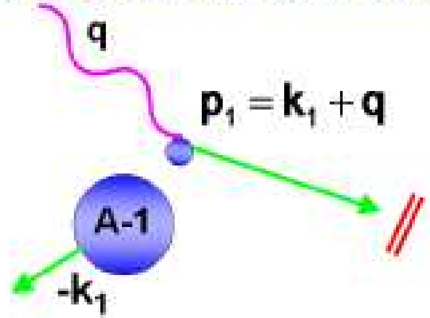
$$S_G(\mathbf{r}_1 \cdots \mathbf{r}_A) = \prod_{j=2}^{A} G(\mathbf{r}_1, \mathbf{r}_j) \equiv \prod_{j=2}^{A} [1 - \theta(z_j - z_1) \Gamma(\mathbf{b}_1 - \mathbf{b}_j)], \quad (7)$$

The (e,e'p) process on mean field and correlated nucleons.



Mean Field:

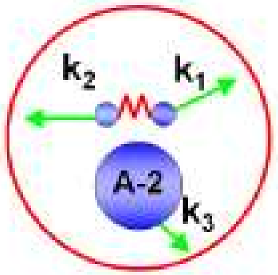
$$k_1 + k_{A-1} = 0$$



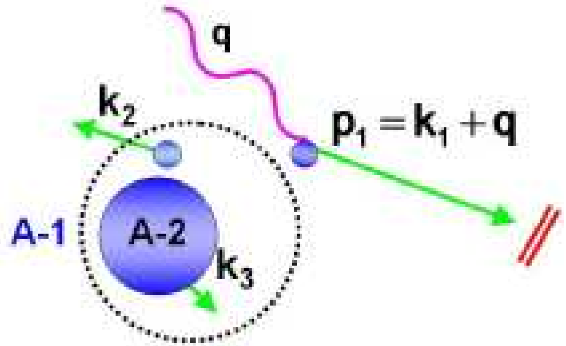
Correlations:

$$k_1 + k_2 + k_3 = 0$$

Simple model:



$$\begin{cases} k_2 \simeq -k_1 \quad k_3 \simeq 0 \quad E^*_{A-2} = 0 \\ E^*_{A-1} \simeq \frac{A-2}{A-1} \frac{k_1^2}{2\,m_N} \end{cases}$$

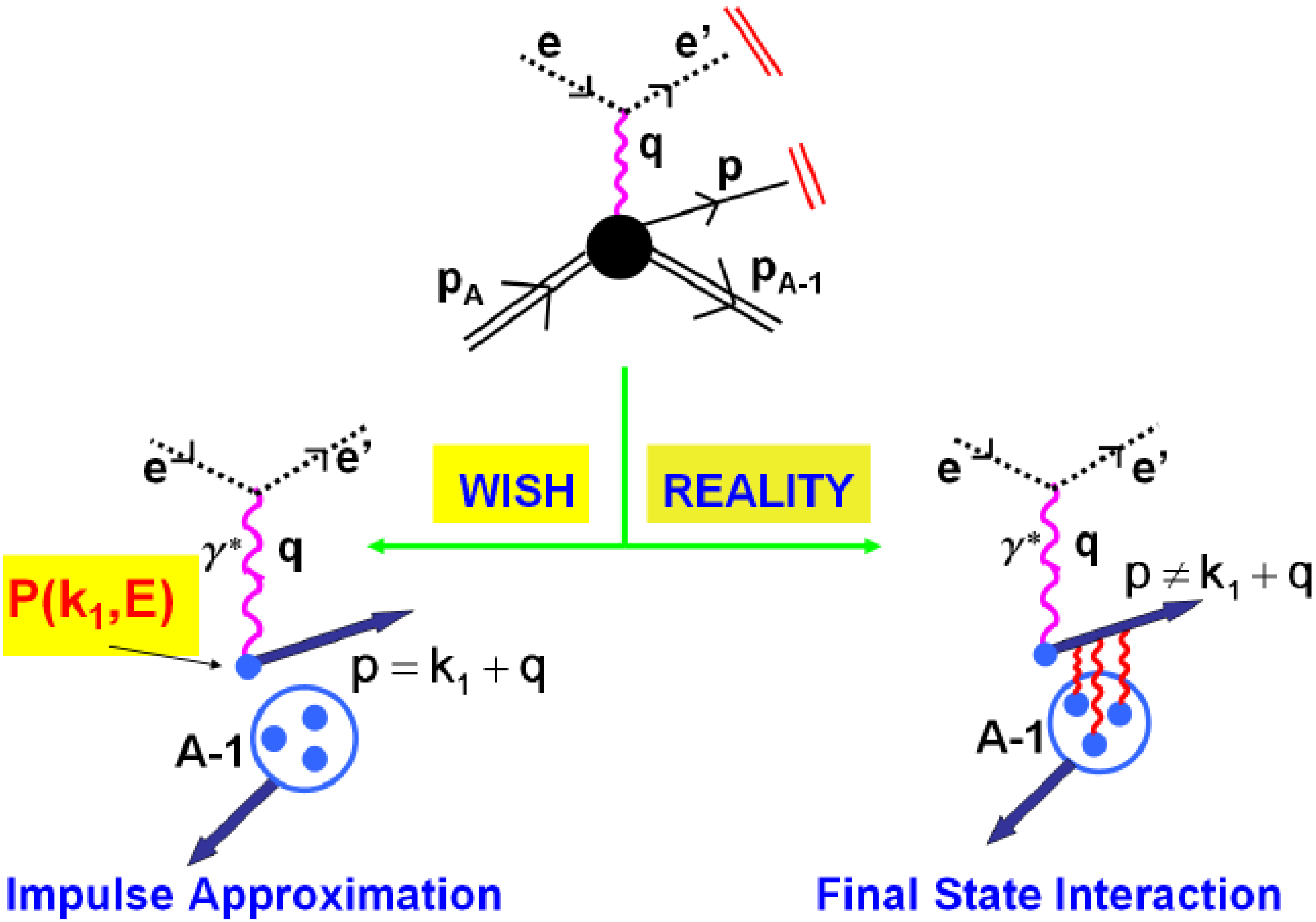


Realistic model:

$$\begin{cases} k_3 \neq 0 \qquad E^*_{A-2} \neq 0 \\ E^*_{A-1} = \frac{A-2}{2m_N(A-1)} \left[k_1 + \frac{A-1}{A-2} k_3\right]^2 + \bar{E}_{A-2} \end{cases}$$

C. Ciofi degli Atti 18 Valparaiso, February 2009

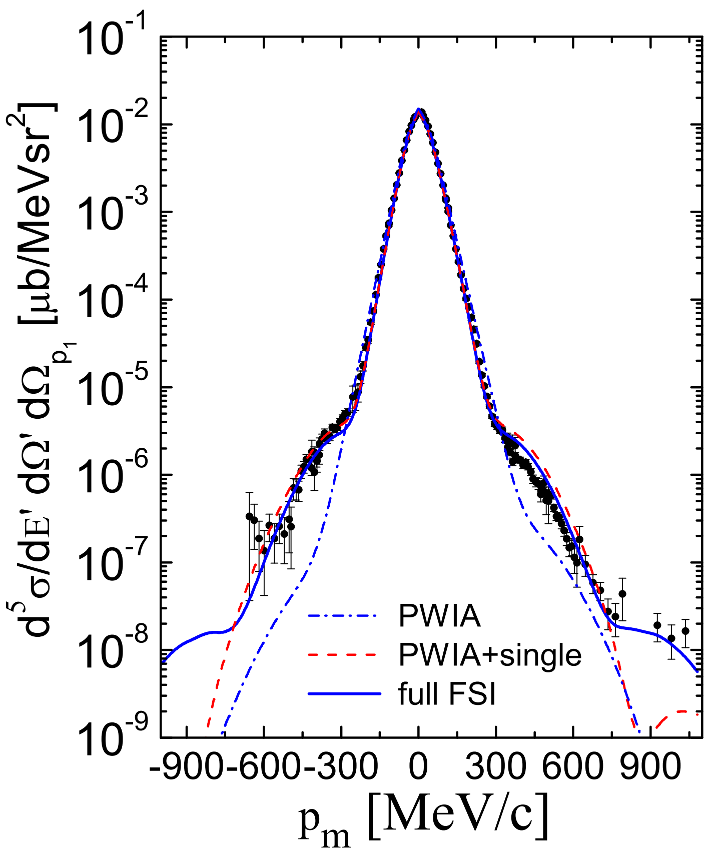
One important caveat

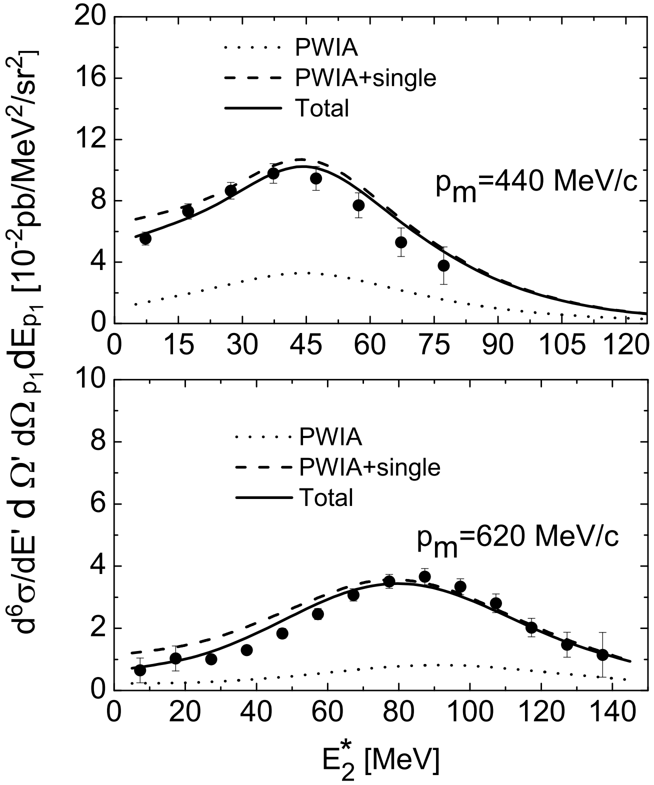


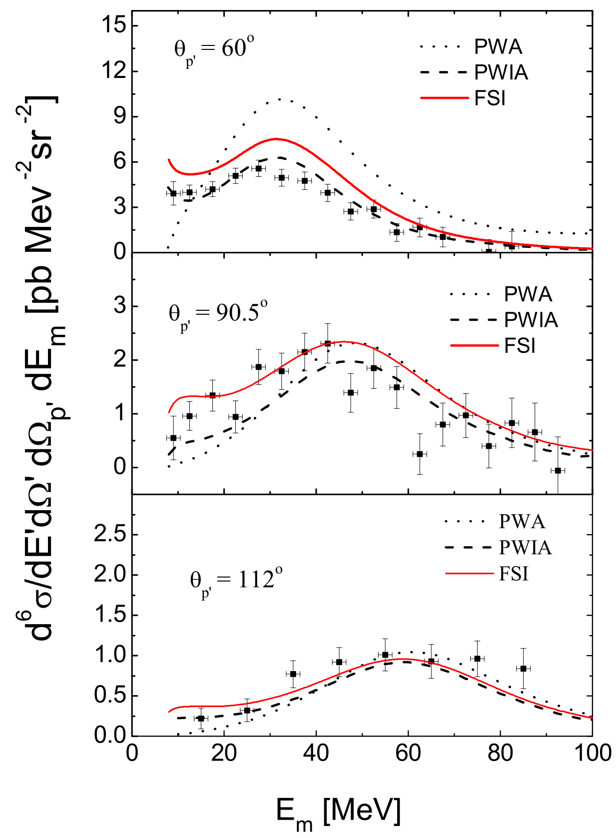
C. Ciofi degli Atti 19 Valparaiso, February 2009

JLAB (SACLAY) Experiments Phys. Rev. Lett. (2005)(1988)

$$e +^3 He \to e' + p +^2 H \qquad\qquad e +^3 He \to e' + p + (pn)$$



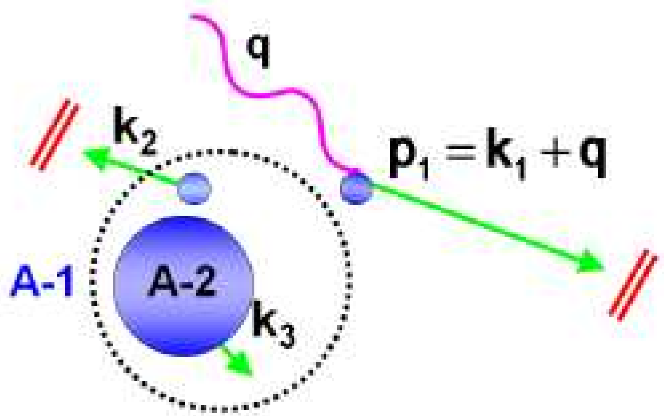




CdA, L.P. Kaptari, Phys. Rev. Lett. 95(2005); 100 (2008)

FSI under control. SRC peak observed. Agreement with other groups.

3.4 Exclusive two-body knock-out reactions A(a,a'2N)X a=(e,N) ⇒ *two-body nucleon spectral function.*



By detecting 2 Nucleons in the final state the initial pair correlation can be studied

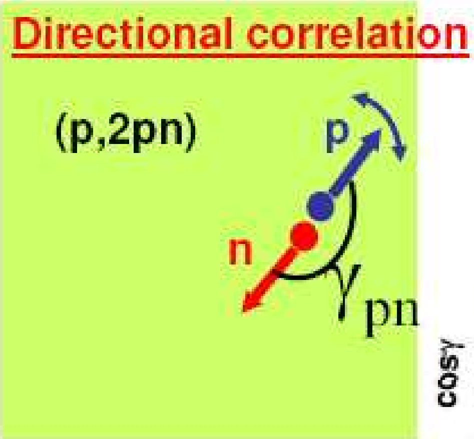
Triple coincidence experiment $A(a, a'NN)X \quad a = \{p, e\}$

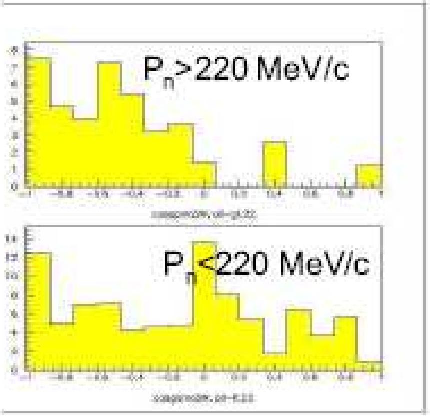
BNL and JLAB EXPERIMENTS

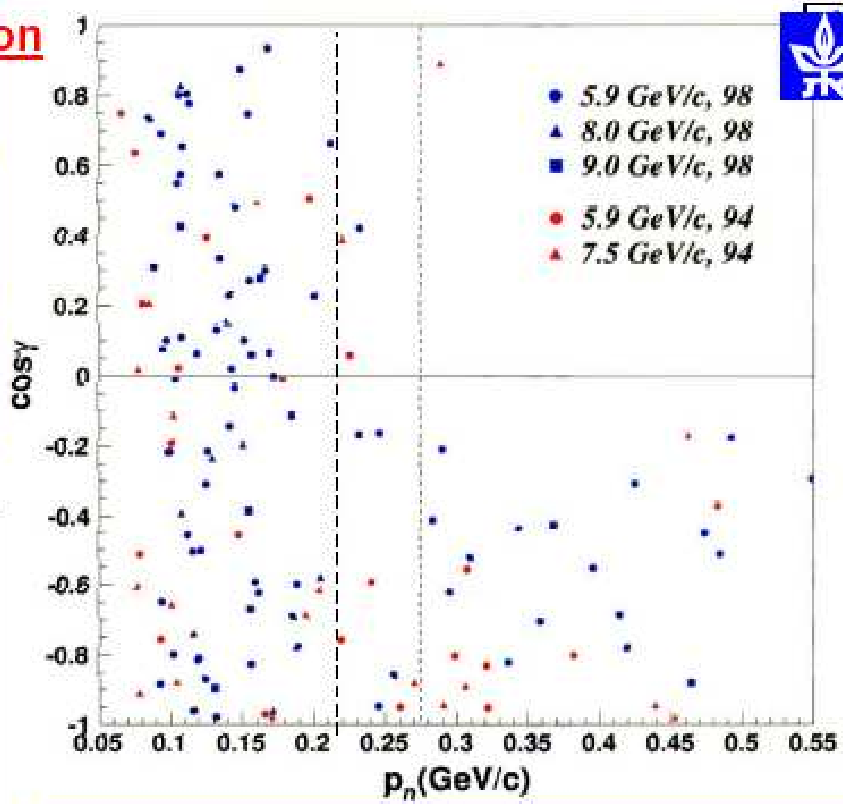
(Watson, Gilad, Piasetzky, & coworkers, this Workshop)

C. Ciofi degli Atti 22 Valparaiso, February 2009

$^{12}C(p,p'pN)X$ AGK BNL (2003); Piasetzky talk







The EVA/BNL collaboration

Experiment

Tang et al PRL 04231 (2003)

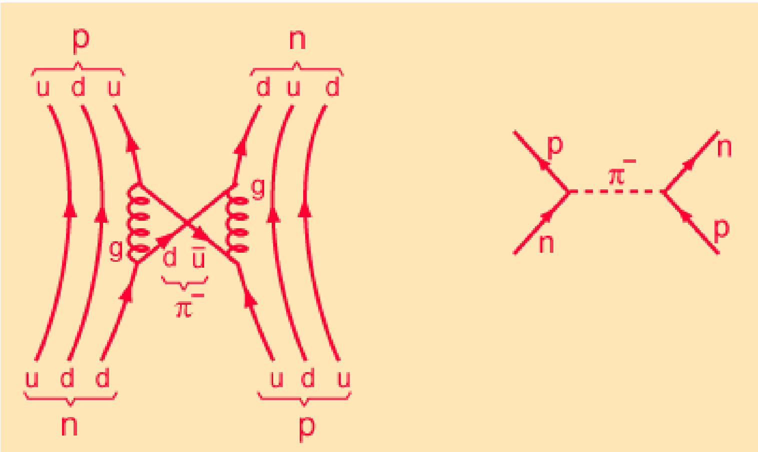
Analysis

Piasetzky, Sargsian, Frankfurt, Strikman, Watson

PRL 162504 (2006)

4 IMPACT OF SRC ON VARIOUS FIELDS OF PHYSICS

3.1.Transition from hadron to quark gluon descriptions of nuclei



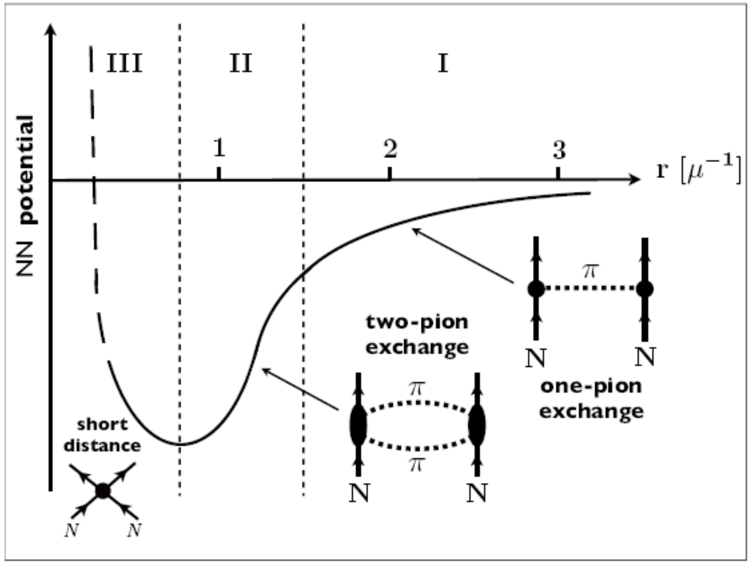


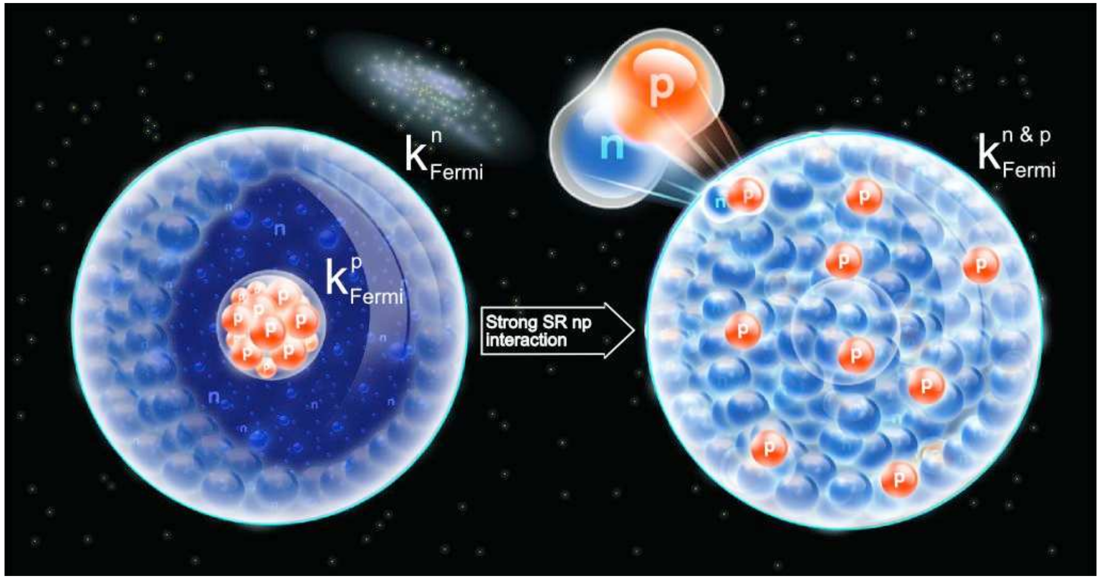
Fig. 2. Hierarchy of scales governing the nucleon-nucleon interaction (adapted from Taketani [5]). The distance r is given in units of the pion Compton wavelength, $\mu^{-1} \simeq 1.4$ fm.

Nucleon radius $< r^2 >^{1/2} \simeq 0.8 fm^{-1} \Rightarrow$ Nucleon overlap.

Adapted from: W. Weise, Nucl. Phys. A 805(2008)145c

3.2 Formation of cold dense nuclear matter in the laboratory and the structure of neutron stars

Implications for Neutron Stars



- At the core of neutron stars, most accepted models assume :~95% neutrons, ~5% protons
- Neglecting the np-SRC interactions, one can assume two separate Fermi gases
- Since np interaction is large compared to nn, n gas heats the p gas
- This could effect the upper limit on mass of neutron and allow the neutrons in the star decay

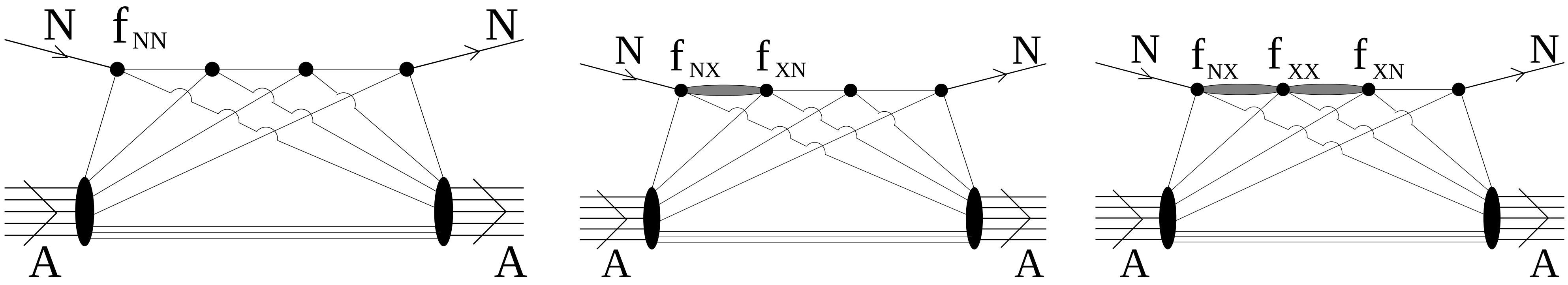
Sixth International Conference on Perspectives in Hadronic Physics — Jefferson Lab

See e.g. Frankfurt, Sargsian, Strikman Int. Jour. Mod. Phys.A (2008)

3.3 High energy hadron-Nucleus and Nucleus-Nucleus scattering

C.d.A, B. Kopeliovich *et al* Phys. Rev.(2009, 2010,2011,2012)

Glauber + Gribov Inelastic shadowing + SRC



(Glauber) (Inelastic Shadowing)

The exact expansion of $|\Psi_0|^2$ (Glauber, Foldy & Walecka):

$$|\Psi_0(\boldsymbol{r}_1,...,\boldsymbol{r}_A)|^2 = \prod_{j=1}^{A} \rho(\boldsymbol{r}_j) + \sum_{i<j=1}^{A} \boldsymbol{\Delta}(\boldsymbol{r}_\mathbf{i},\boldsymbol{r}_\mathbf{j}) \prod_{k\neq(il)}^{A-2} \rho(\boldsymbol{r}_k) +$$

$$+ \sum_{(i<j)\neq(k<l)} \boldsymbol{\Delta}(\boldsymbol{r}_\mathbf{i},\boldsymbol{r}_\mathbf{j})\,\boldsymbol{\Delta}(\boldsymbol{r}_\mathbf{k},\boldsymbol{r}_\mathbf{l}) \prod_{m\neq(i,j,k,l)}^{A-4} \rho_1(\boldsymbol{r}_m) + \ldots$$

$$\boldsymbol{\Delta}(\boldsymbol{r}_\mathbf{i},\boldsymbol{r}_\mathbf{j}) = \rho^{(2)}(\boldsymbol{r}_i,\boldsymbol{r}_j) - \rho^{(1)}(\boldsymbol{r}_i)\,\rho^{(1)}(\boldsymbol{r}_j);$$

$$\rho^{(1)}(\mathbf{r}_1) = \int |\Psi_0(\boldsymbol{r}_1,...,\boldsymbol{r}_A)|^2 \prod_{i=2}^{A} d\mathbf{r}_i\,;\ \rho^{(2)}(\mathbf{r}_1,\mathbf{r}_2) = \int |\Psi_0(\boldsymbol{r}_1,...,\boldsymbol{r}_A)|^2 \prod_{i=3}^{A} d\mathbf{r}_i$$

$$\int d\mathbf{r}_j\,\rho^{(2)}(\mathbf{r}_i,\mathbf{r}_j) = \rho^{(1)}(\mathbf{r}_i)\,;\ \int d\mathbf{r}_j \boldsymbol{\Delta}(\mathbf{r}_i,\mathbf{r}_j) = 0$$

$$\rho^{(1)}(\mathbf{r}) \equiv \rho(\mathbf{r})$$

R. J. Glauber, *High Energy Collision Theory, 1971*

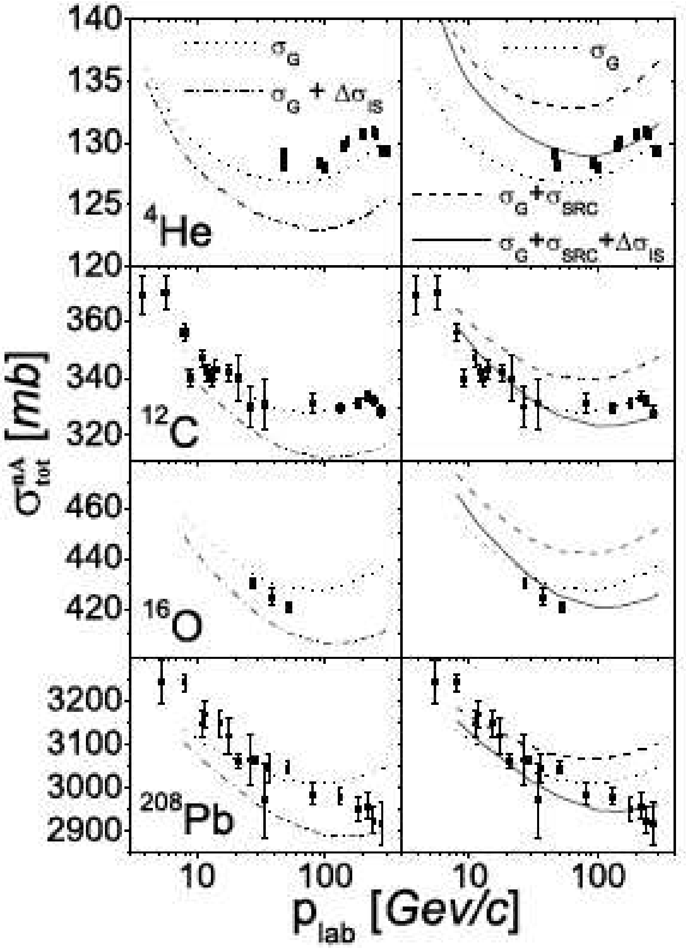
"Various types of correlations in positions and spin may exist between nucleons of an actual nucleus ... If the system being considered is spatially uniform an idea of the magnitude and nature of the effects due to pair correlations may be obtained by assuming that the range of NN force a is smaller than the range of correlations l_c and the nuclear radius R

$$l_c \gg a \text{ and } R \gg a$$

Because R is not vastly larger than a, and the correlation length l_c is not too different in magnitude from the force range, the approximations that follow from these conditions should only be used for rough estimates".

The total neutron − Nucleus cross section at high energies:

(M. Alvioli, C.d.A, et al Phys. Rev. C78(R),031601(2008))



- No free parameters!!
- Full SRC.
- Gribov inelastic shadowing at lowest order.
- Main result: SRC increase the opacity, Gribov IS decreases it, the two effects being of about the same order in this energy range.
- What about higher order Gribov corrections?.

Another recent calculation of the effects of SRC in high energy scattering processes:

"A Monte Carlo generator of nucleon configurations in complex nuclei including Nucleon-Nucleon correlations"

M. Alvioli, H.J. Drescher and M. Strikman,

Phys. Lett. (2009)

4. CONCLUSIONS

- NN SRC can be calculated *ab initio* with realistic NN interactions. They exhibit several universal (*independent of* A) features.

- robust evidence on the effects of NN SRC have been collected in the last few years both in few-nucleon systems and ^{12}C.

- NN SRC can provide basic information on the nature of the NN force. The experimental information so far obtained is in agreement with the current picture of phenomenological realistic NN interactions.

- SRC can have relevant effects on the structure of cold dense hadronic matter and high energy $h - A$ and $A - A$ scattering processes.

- The successful experimental study of NN SRC is a relatively new field of research that has to be continued, extending it to an increasing number of nuclei and to the investigation of the 3D structure of SRC (JLab, JPARC(?)).