How far can we push the impulse approximation picture ?

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    - Momentum distributions

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  - Inclusion of final state interactions in high energy nucleon knock out processes
  - The low momentum transfer regime

Single particle properties in interacting many-body systems

- ⋆ Overlaps are well (and *uniquely*) defined quantities for interacting many-body systems

$$\chi_n(\mathbf{r}_1) = \int d^3r_2 \ldots d^3r_\mathrm{A}\ \Psi_n^{\mathrm{A}-1}(\mathbf{r}_2 \ldots \mathbf{r}_A)^\dagger \Psi_0^{\mathrm{A}}(\mathbf{r}_1 \ldots \mathbf{r}_A)$$

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- ⋆ If $|\Psi_n^{\mathrm{A}-1}\rangle$ is a bound state χ_n carries information on single particle dynamics
- ⋆ Within the mean field picture $\chi_n \to \phi_n^{\mathrm{MF}}$, ϕ_n^{MF} being the n-th single particle orbital

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- ⋆ Assuming that the ground state of the target be fully understood, the extraction of the spectroscopic factors from nuclear cross sections

$$\sigma_A \propto \left| \langle \Psi_f | \, \hat{O} \, | \Psi_0^A \rangle \right|^2$$

implies assumptions on the structure of *both* the operator inducing the transition and the target final state.

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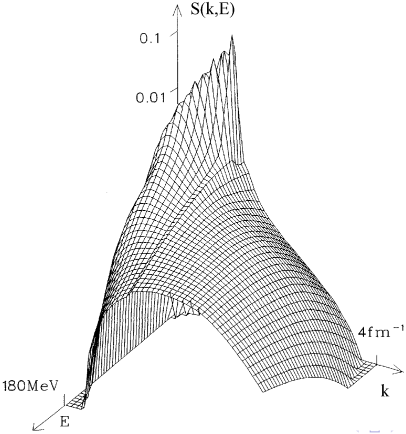
- ⋆ Note: Z_k *does not* coincide with the occupation number of the state $|\Phi^{1h}_{\mathbf{k}}\rangle$, $n(\mathbf{k})$, given by

$$n(\mathbf{k}) = \langle \Psi_0 | a^\dagger_{\mathbf{k}} a_{\mathbf{k}} | \Psi_0 \rangle = \sum_n \left|\langle \Phi^{n}_{\mathbf{k}} | a_{\mathbf{k}} | \Psi_0 \rangle\right|^2 = \int dE \ P(\mathbf{k}, E)$$

where $\{|\Phi^{n}_{\mathbf{k}}\rangle\}$, is the complete set of (A-1)-nucleon states of momentum $\mathbf{k}$

Spectral function of infinite nuclear matter

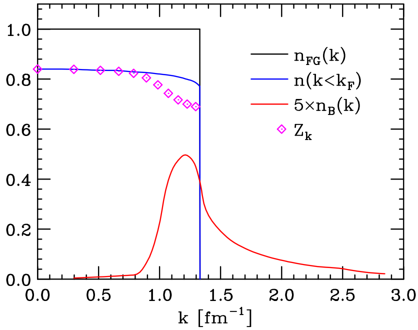
- ⋆ Results obtained using CBF perturbation theory and the U14+TNI hamiltonian (OB, A. Fabrocini and S.Fantoni, AD 1989)



Momentum distribution and spectroscopic factors

★ The momentum distribution can be split into quasi particle (pole) and and correlation (continuum) contributions (OB, A. Fabrocini and S. Fantoni, AD 1990)

$$n(\mathbf{k}) = \int dE\ P(\mathbf{k}, E) = Z_k + \int dE\ P_B(\mathbf{k}, E) = Z_k + n_B(\mathbf{k})$$



Occupation probability and spectroscopic factor

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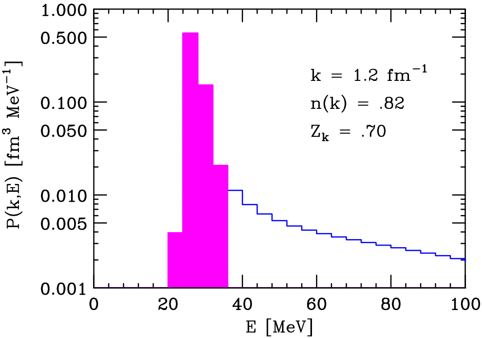
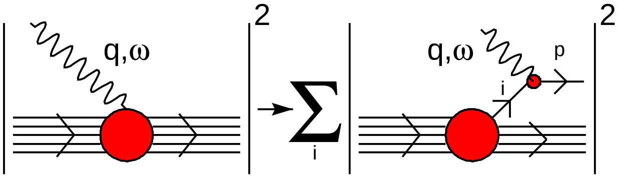


- integration over the peak region yields Z_k
- integration over the whole energy range yields $n(k)$

The impulse approximation (IA) paradigm*

★ At momentum transfer **q** such that $|\mathbf{q}|^{-1} \lesssim d$, d being the average nucleon-nucleon separation distance, replace



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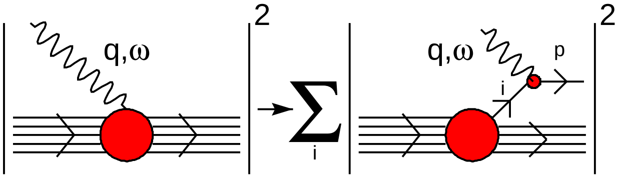

- ⋆ As a result, the x-section for knock out of a nucleon of momentum **p** and energy E_p takes the simple form

$$\sigma_A \propto P(\mathbf{p} - \mathbf{q}, \omega - E_p)$$

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Assumptions involved in the IA picture

- The operator inducing the transition is written as the sum of operators acting on individual *nucleons*

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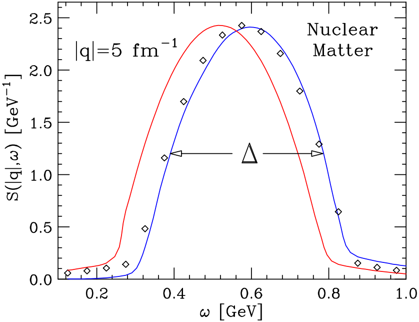
- Final state interactions (FSI) between the knocked out nucleon and the spectator particles are neglected

Momentum distribution vs spectral function

- ⋆ Minimal use of the underlying assumptions lead to expression of the IA nuclear cross section in terms of the spectral function (OB, A. Fabrocini and S. Fantoni, AD 2001)
- ⋆ The definition in terms of the momentum distribution involves a more extended use of the same assumptions, leading to the disappearance of the effect of the removal energy distribution.



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- ⋆ Coupling to collective excitations of the target nucleus.
- ⋆ Current conservation is violated.

Dynamical FSI

- Consider the transition matrix element of the process

$$e + A \to e' + p + (A-1)_\alpha$$

$$M_\alpha(\mathbf{p},\mathbf{q}) = \langle \Psi^{(-)}_{\alpha\mathbf{p}} | \hat{O}(\mathbf{q}) | \Psi_0 \rangle$$

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- ⋆ Isolate the contributions responsible for final state interactions in the nuclear hamiltonian

$$H_A = H_0 + H_{FSI} \quad , \quad H_0 = T_1 + H_{A-1}$$

where T_1 is the kinetic energy of the struck nucleon

Dynamical FSI (continued)

- Scattering state

$$|\Psi^{(-)}_{\alpha\mathbf{p}}\rangle = \Omega^{(-)}_{\mathbf{p}}|\Phi_{\alpha\mathbf{p}}\rangle$$

$$|\Phi_{\alpha\mathbf{p}}\rangle = |\mathbf{p}\rangle \otimes |\varphi_\alpha\rangle$$

$$T_1|\mathbf{p}\rangle = E_p|\mathbf{p}\rangle \ , \ H_{A-1}|\varphi_\alpha\rangle = E^\alpha_{A-1}|\varphi_\alpha\rangle$$

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- ⋆ Distortion (Möller) operator

$$\Omega^{(-)}_{\mathbf{p}} = \lim_{t\to\infty} \mathrm{e}^{iH_At}\mathrm{e}^{-iH_0t} = \lim_{t\to\infty} \widehat{T}\ \mathrm{e}^{-i\int_0^\infty dt' H_{FSI}(t')}$$

$$H_{FSI}(t) = \mathrm{e}^{iH_0t}H_{FSI}\mathrm{e}^{-iH_0t}$$

High energy (Glauber) approximation

(A) Eikonal approximation : the outgoing proton moves along a straight trajectory in the direction of $\mathbf{p}$, with constant velocity $\mathbf{v}$

(B) Frozen approximation : the spectator nucleons are seen as a collection of fixed scattering centers

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- ⋆ Under assumptions (A) & (B), the distortion operator can be rewritten in coordinate space as ($R \equiv \{\mathbf{r}_1, \ldots, \mathbf{r}_A\}$)

$$\Omega^{(-)}_{\mathbf{p}}(R) = P_z \frac{1}{A} \sum_{i=1}^{A} \left[1 - \sum_{j>i} \Gamma_p(i,j) + \sum_{k>j>i} \Gamma_p(i,j)\Gamma_p(1,k) - \ldots \right]$$

- ⋆ The z-ordering operator P_z prevents the occurrence of backward scattering.

High energy approximation (continued)

- ★ FSI interactions are driven by the coordinate space t-matrix Γ_p, related to the NN scattering amplitude f_p through

$$\Gamma_p(i,j) = \theta(z_j - z_i)\gamma_p(|\mathbf{b}_j - \mathbf{b}_i|)$$

$$\gamma_p(b) = -\frac{i}{2}\int \frac{d^2k_t}{(2\pi)^2}\, e^{i\mathbf{k}_t\cdot\mathbf{b}}\, f_p(k_t)$$

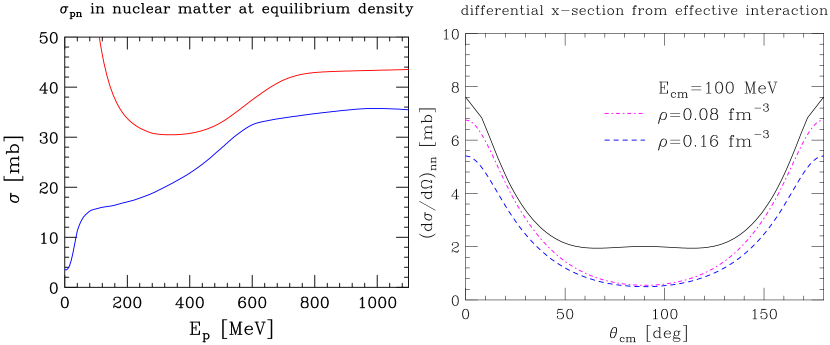
- ★ At large p, the *measured* free space $f_p(k_t)$ is generally parametrized in the for

$$f_p(k_t) = i\,\sigma(1 - i\alpha)e^{-\frac{1}{2}\frac{k_t^2}{B}}$$

where σ is the total NN cross section

High energy approximation (continued)

- ⋆ WARNING: NN scattering in the nuclear medium expected to be appreciably modified by, e.g., Pauli blocking and dispersive effects
- ⋆ Medium modifications consistently calculable (S. Pieper & V.R. Pandharipande, AD 1992, OB & M. Valli, AD 2007)



Local Density Approximation (LDA)

$$\Omega_{\mathbf{p}}^{(-)}(\mathbf{r}) = \frac{1}{\rho(\mathbf{r})} \int d^3\mathbf{r}_1 \ldots d^3\mathbf{r}_A |\Psi_0(\mathbf{r}_1 \ldots \mathbf{r}_A)|^2$$

$$\times \frac{1}{A} \sum_{i=1}^{A} \left[1 - \sum_{j>i} \gamma_{\mathbf{p}}(\mathbf{b}_i - \mathbf{b}_j)\theta(z_i - z_j) + \ldots \right] \delta(\mathbf{r} - \mathbf{r}_i)$$

$$g(\mathbf{r}_1, \mathbf{r}_2) = \frac{\rho(\mathbf{r}_1, \mathbf{r}_2)}{\rho(\mathbf{r}_1)\rho(\mathbf{r}_2)} \approx g_{NM} \left[|\mathbf{r}_1 - \mathbf{r}_2|, \rho_A \left(\frac{\mathbf{r}_1 + \mathbf{r}_2}{2} \right) \right]$$

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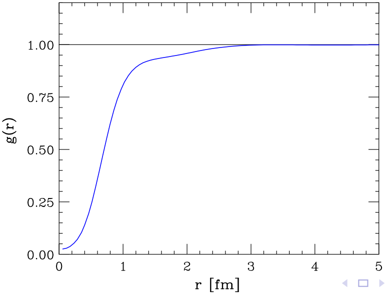


Transition amplitude including FSI effects

- Recall: within PWIA

$$M_\alpha(\mathbf{p}-\mathbf{q}) = \int d^3r_1 e^{i(\mathbf{p}-\mathbf{q})\cdot\mathbf{r}_1} \chi_\alpha(\mathbf{r}_1)$$

- In the presence of FSI

$$\chi_\alpha(\mathbf{r}) \to \psi_{\alpha\mathbf{p}}(\mathbf{r}) = \Omega^{(-)}_{\mathbf{p}}(\mathbf{r})\chi_\alpha(\mathbf{r})$$

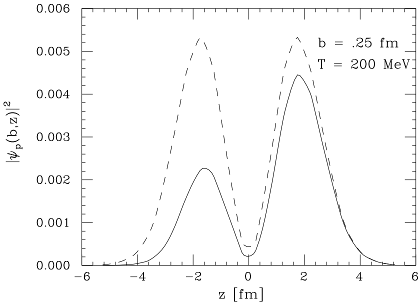
- Z_α is reduced by a transparency factor $T_{\alpha\mathbf{p}}$

$$Z_\alpha \to \widetilde{Z}_\alpha = \int \frac{d^3k}{(2\pi)^3} \left|\psi_{\alpha\mathbf{p}}(\mathbf{k})\right|^2 = T_{\alpha\mathbf{p}} Z_\alpha$$

- The momentum distributions $|\psi_{\alpha\mathbf{p}}(\mathbf{k})|^2$ is shifted with respect to $|\chi_\alpha(\mathbf{k})|^2$

Electron induced knock out of a p-shell proton from oxygen

- ⋆ $|\psi_p^{\mathbf{p}}(\mathbf{r})|^2$ vs $|\chi_p(\mathbf{r})|^2$



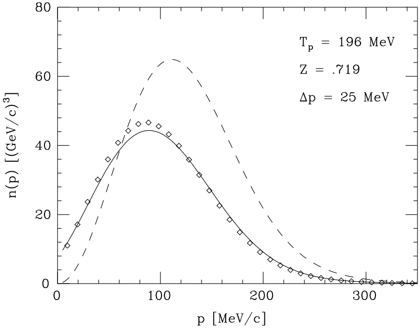
- ⋆ Spectroscopic factor and transparency

$$Z_p = \int d^3r \, |\chi_p(\mathbf{r})|^2 = .62 \quad , \quad T_p = \frac{1}{Z_p} \int d^3r \, |\psi_p^{\mathbf{p}}(\mathbf{r})|^2 = .72$$

Knock out of a p-shell proton from oxygen (continued)

- Momentum distribution:

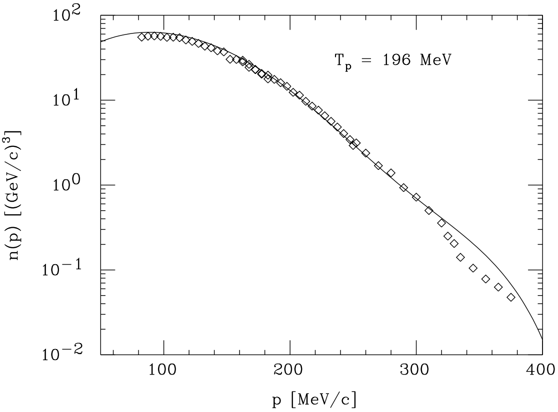
$$|\widehat{\psi}_p^{\mathbf{p}}(|\mathbf{p}-\mathbf{q}|)|^2 \approx \widetilde{Z}_p |\chi_p(|\mathbf{p}-\mathbf{q}| + \Delta_p)|^2$$



Mainz data: Blomqvist *et al*, PLB 344(95)85

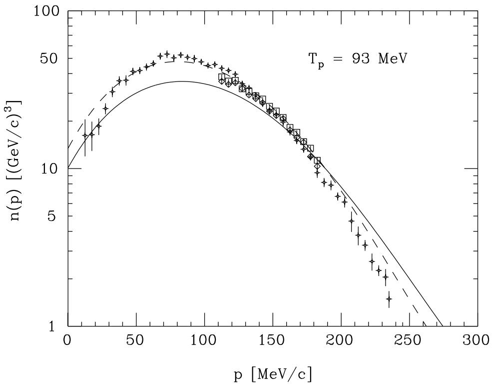
★

$$Z = 0.62 \ , \ \widetilde{Z}_{\mathbf{p}} = 0.72$$

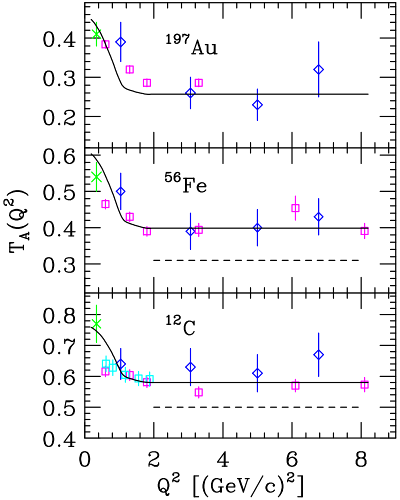


NIKHEF-K data: Leuschner *et al*, PRC 49(94)955)

- solid line: $\chi(\mathbf{r}) = \langle {}^{15}N(3/2)^{-}|a_{\mathbf{r}}|{}^{16}O\rangle \quad , \quad Z = 0.62$
- dashed line: $\chi(\mathbf{r}) = \sqrt{Z}\,\phi_{WS}(\mathbf{r}) \quad , \quad Z = 0.56$



Nuclear transparency (no FSI $\rightarrow T_A \equiv 1$)



- Nuclear transparency obtained from

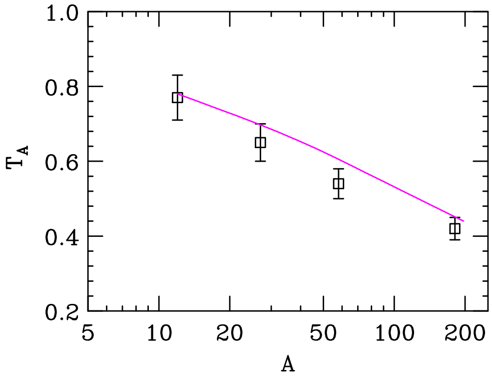
$$T_A = \frac{1}{A} \int d^3r \, \rho_A(\mathbf{r}) \, |\Omega_{\mathbf{p}}^{(-)}(\mathbf{r})|^2$$

  compared to MIT-Bates, SLAC and JLab data (D. Rohe *et al*, Phys. Rev. C 72(05)054602)

- Complicated pattern of correlation effects, leading to a sizable enhancement of the transparency

How low can the proton energy be ?

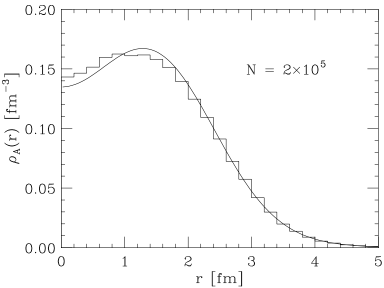
- ⋆ Compare theory to the A-dependence of nuclear transparency to a 200 MeV proton, measured at MIT

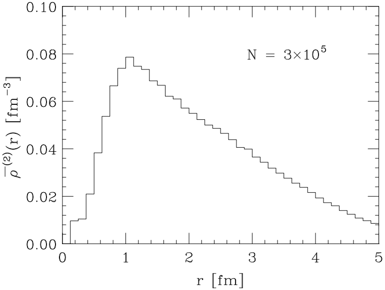


- ⋆ The high energy approximation appears to work down to surprisingly low energy

Implementig FSI in Monte Carlo simulations

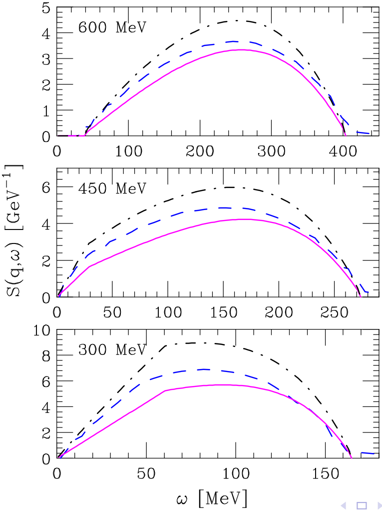
★ Distribution of the primary vertex and two-nucleon density obtained sampling the probability distributions associated with the ^{16}O wave function of Pieper *et al*





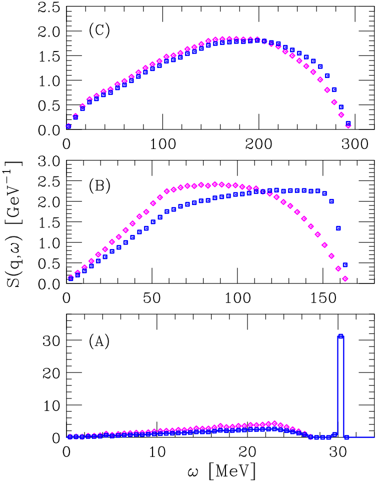
How far down can we go in momentum transfer ?

- ⋆ Compare IA ($P(\mathbf{p}, E)$, no FSI) to correlated Hartree-Fock response (A. Ankowski, OB and N. Farina, AD 2010)



Onset of collective excitations

★ Compare correlated Hartree-Fock to correlated Tamm Dancoff (OB and N. Farina, AD 2009): (A), (B), (C) = 0.3, 1.2, 2.4 fm^{-1}



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- The kinematical regime in which the assumptions underlying the IA picture can be safely applied must be carefully investigated.

Summary

- The IA provides a link between nuclear cross sections and single nucleon properties.
- The kinematical regime in which the assumptions underlying the IA picture can be safely applied must be carefully investigated.
- The IA can be seen as the zero-th order of a systematic approximation scheme, to be improved upon, *consistently* including effects such as FSI, antisymmetrization of the final state and coupling to collective excitations.