Role of short-range nuclear dynamics in neutrino-nucleus interactions

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MOTIVATION & OUTLINE

- ⋆ The interpretation of the flux-integrated νA cross section requires the understanding of a variety of reaction mechanism
- ⋆ Even at the level of 0π events, the occurrence of multi-nucleon emission poses non trivial problems for neutrino energy reconstruction
- ⋆ Correlations are a manifestation of short-range nuclear dynamics, *beyond the shell model*, now unanimously acknowledged as a leading mechanism driving two-nucleon emission
- ⋆ Despite many decades of experimental and theoretical efforts, correlations remain an elusive subject
- ⋆ In this talk, I will highlight few notions about correlations in nuclei, that seem to be overlooked in many ongoing studies, and try to clarify their role in νA interactions

A Long-Standing, and Largely Unresolved, Issue

- Reviews of Modern Physics **65**, 817 (1993)

Electron-scattering studies of correlations in nuclei

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The authors review theoretical estimates of spatial, spin, and isospin correlations among the nucleons in nuclei. The momentum distribution and spectral function of nucleons in nuclei are also discussed. The theoretical estimates are compared with the observed correlation effects in the inclusive scattering of electrons from nuclei, at energies ranging from a few hundred MeV to several GeV. The observed transparencies of nuclei to protons ejected in inclusive $e,e'p$ reactions are also compared with their theoretical estimates. Finally, the quenching of exclusive single-quasiparticle-type reactions, indicative of the overall strength of correlations in nuclei, is discussed. There appears to be a qualitative agreement between theory and experiment, but a firm quantitative understanding is still to be obtained.

- Electron-nucleus scattering experiments have long been recognised as a powerful tool to study correlation effects

DEFINING CORRELATIONS

- In coordinate space, the deviation from the mean-field approximation is measured by the ratio

$$R(x-y) = \frac{\varrho(x,y)}{\varrho(x)\varrho(y)}$$

where $\varrho(x)$ and $\varrho(x,y)$ are the one- and two-nucleon probability density

- Note that the above definition also applies to a non interacting Fermi gas, because the constituent particles are statistically correlated

$$R_{FG}(x-y) = 1 - \frac{1}{d}\ell^2(k_F|x-y|)$$

where d is the degeneracy of the momentum eigenstates and

$$\ell(z) = \frac{3}{z^3}\left[\sin z - z\cos z\right] \ , \ \lim_{z\to\infty} \ell(z) = 0$$

⋆ In momentum space, however

$$R(k-k') = \frac{n(k,k')}{n(k)n(k')} = 1 + \mathcal{O}(\frac{1}{N})$$

⋆ In the non interacting Fermi gas,

$$R_{FG}(k,k') = \theta(k_F-k)\theta(k_F-k')\left[1 - \frac{1}{N}\frac{\varrho}{d}(2\pi)^3\delta(k-k')\right] ,$$

⋆ A better and model independent characterisation of correlations can be obtained from the analysis of the two-point Green's function

$$\begin{aligned} G(k,E) &= \sum_n \frac{|\langle n|a^\dagger_{\mathbf{k}}|0\rangle|^2}{\omega-(E_0-E_n)-i\eta} + \sum_n \frac{|\langle n|a_{\mathbf{k}}|0\rangle|^2}{\omega-(E_n-E_0)+i\eta} \\ &= G_h(k,E) + G_p(k,E) \end{aligned}$$

The Lepton-Nucleus x-Section

- ⋆ Consider the x-section of the inclusive process $\ell + A \to \ell' + X$ at fixed beam energy

$$d\sigma_A \propto L_{\mu\nu} W_A^{\mu\nu}$$

  - ▸ $L_{\mu\nu}$ is fully specified by the lepton kinematical variables
  - ▸ The determination of the nuclear response

$$W_A^{\mu\nu} = \sum_X \langle 0 | J_A^{\mu\,\dagger} | X \rangle \langle X | J_A^{\nu} | 0 \rangle \delta^{(4)}(P_0 + k - P_X - k')$$

  involves

    - the ground state of the target nucleus, $|0\rangle$
    - all relevant hadronic final states, $|X\rangle$
    - the nuclear current operator ($q \equiv (\omega, \mathbf{q}) = P_X - P_0$)

$$J_A^{\mu}(q) = \sum_i j_i^{\mu} + \sum_{j>i} j_{ij}^{\mu} + \ldots$$

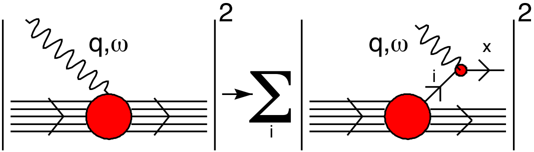
- ⋆ At low to moderate momentum transfer—typically $|\mathbf{q}| \lesssim 500$ MeV—the above quantities can be consistently obttained from a realistic a model of nuclear dynamics

Breakdown of the Non Relativistic Approximation

- the bad news: at large momentum transfer, the initial and final states and the current operator can no longer be described within a fully consistent framework
- the good news: in the kinematical regime in which

$$\lambda \sim \frac{\pi}{|\mathbf{q}|} \ll d_{\rm NN} \ ,$$

  where $d_{\rm NN}$ is the average NN distance in the target nucleus, nuclear scattering reduces to the incoherent sum of scattering processes involving individual nucleons
- Enter the Impulse Approximation (IA)



IMPULSE APPROXIMATION AND FACTORIZATION

- ⋆ The IA naturally leads to factorization of the nuclear transition amplitude. As a consequence the double differential cross section of the process $\ell + A \to \ell' + X$ can be written in the simple form

$$\frac{d^2\sigma_{\ell A}}{d\Omega_{\ell'} dE_{\ell'}} = \int d^3k \, dE \, P(\mathbf{k}, E) \, \frac{d^2\sigma_{\ell N}}{d\Omega_{\ell'} dE_{\ell'}} \ ,$$

  - the elementary cross section $d^2\sigma_{\ell N}$ can—at least in principle—be obtained from proton and deuteron data
  - the spectral function $P(k, E) = \mathrm{Im}\, G(k, E)/\pi$, describes the probability of removing a nucleon of momentum k from the target ground state, leaving the residual system with excitation energy E
  - factorization allows for a consistent treatment of all relevant reaction channels
  - corrections—arising mainly from final-state interactions (FSI) and two-body currents (MEC)—can be consistently taken into account

- ⋆ Within this scheme, nuclear dynamics is described by $P(k, E)$

Spectral Function of Hole States

- The analytic structure of the two-point Green's function—dictated by the Källèn-Lehman representations—is reflected by the spectral function

$$
\begin{aligned}
P(\mathbf{k}, E) &= P_{\text{pole}}(\mathbf{k}, E) + P_{\text{corr}}(\mathbf{k}, E) \\
&= \sum_{h \in \{F\}} Z_h |M_h(\mathbf{k})|^2 F_h(E - e_h) + P_{\text{corr}}(\mathbf{k}, E) \qquad (1)
\end{aligned}
$$

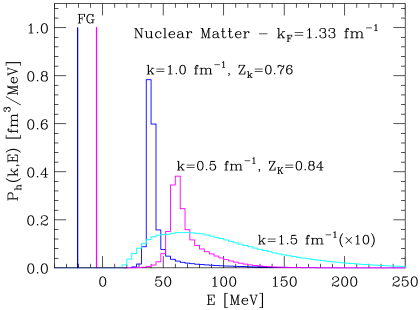
  - $Z_h M_h(\mathbf{k}) = \langle h | a_{\mathbf{k}} | 0 \rangle \quad , \quad Z_h < 1$
  - $F_h(E - e_h)$ sharply peaked around $E = e_h$
  - $P_{\text{corr}}(\mathbf{k}, E)$ is a *smooth* contribution arising from correlations

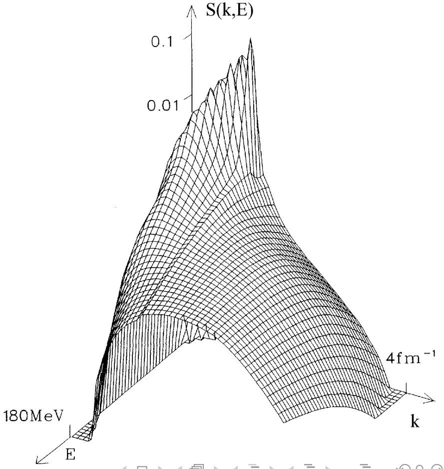
- In Mean Field Approximation
  - $M_h(\mathbf{k}) = \langle h | a_{\mathbf{k}} | 0 \rangle \to \phi_h(\mathbf{k})$, the shell-model wave funtion
  - $Z_h \to 1$, $F_h(E - e_h) \to \delta(E - e_h)$, $P_{\text{corr}}(\mathbf{k}, E) \to 0$

- The Mean Field Approximation is inherently unable to provide the correct normalisation of the cross section.

Spectral Function of Nuclear Matter

- Isospin-symmetric matter at equilibrium density





EARLY ELECTRON SCATTERING STUDIES OF CORRELATIONS

★ The $(e, e'p)$ cross section at large missing energy gives access to the correlation strength

- ^{3}He target

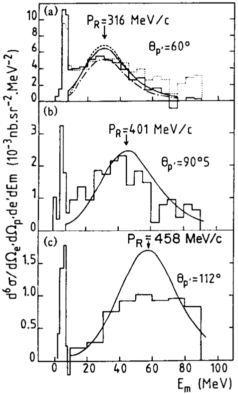
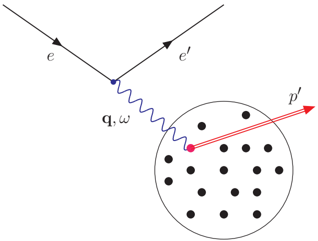


Fig. 5. Missing energy spectra form ^{3}He(e, e′p), showing evidence for an interaction on a two-nucleon correlated pair

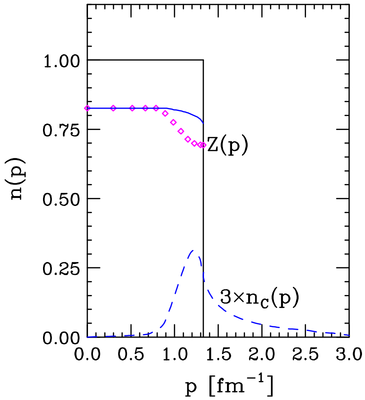
$$e + A \to e' + p + (A-1)$$



$$E_m = \omega - T_{\mathbf{p}'} - T_{A-1} \approx \omega - T_{\mathbf{p}'}$$

HIGH MISSING ENERGY AND HIGH MISSING MOMENTUM

- In spite of the observed correlation between high missing energy and high missing momentum, the widespread prejudice that all correlation strength resides at high momentum is not justified



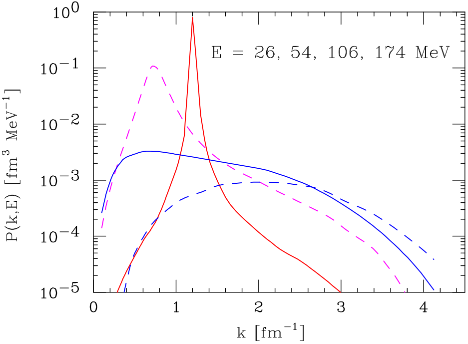
- Momentum distribution of uniform nuclear matter

$$n(k) = Z_k \theta(k_F - k) + n_c(k)$$

- The smooth correlation contribution extends across the Fermi surface

A CLOSER LOOK

- Momentum dependence of the nuclear matter spectral function at different values of E



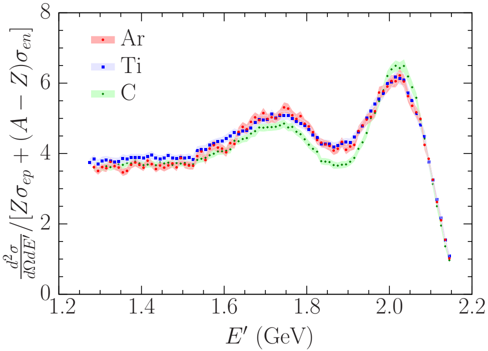
- At energies as large as 100 MeV an appreciable fraction of the correlation strength is located at $k < k_F$.
- A clear maximum at $k > k_F$ is only observed at very large E.

Impact on νA Interactions

- The inclusion of correlation effects is needed to describe multinucleon emission processes
- Pinning down correlations through measurements of the high-momentum components of the nuclear wave functions—an approach strongly advocated by the MIT group of Or Hen—does not appear to be a viable option
- The correlation strength can be unambiguously identified performing $(e, e'p)$ experiments in the regime of low missing energy, in which single nucleon knockout is the dominant reaction mechanism.
- The measured spectroscopic factors will provide a constraint to be met by any models of multinucleon emission
- This is the motivation of JLab experiment E12-14-012, aimed at measuring the spectral functions of Argon and Titanium

First Results from JLab E12-14-012

- (e, e') cross section at E =2.222 GeV and θ_e =15.541 deg
- Titanium data published in PRC **98**, 014617 (2018), Argon data published in PRC **99**, 054608 (2019). A paper reporting Aluminum data is under review.



- The results recently reported in arXiv:1907:01122v1 suggest that replacing the neutron spectral spectral function of $^{40}_{18}$Ar with the proton spectral function of $^{48}_{22}$Ti is quite a reasonable approximation

Thank you!

Backup slides