Understanging ν–nucleus interactions. Where we are, and why it matters

Omar Benhar

INFN and Department of Physics, "Sapienza" University
I-00185 Roma, Italy

IPPP/NuSTEC Topical Meeting on Neutrino-Nucleus Scattering
IPPP, Durham, April 18-20, 2017

Outline

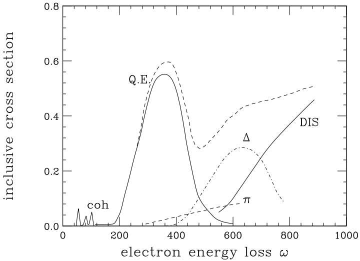
- *Varius, Multiplex, Multiformis*[1]
- Where we are: the issue of degeneracy
- Unraveling the nuclear cross section
- Impact on neutrino energy reconstruction
- Summary & Outlook

[1] Varius, Complex, Manifold. M. Yourcenar, *Memoirs of Hadrian* (Modern Library, New York, 1984)p.27

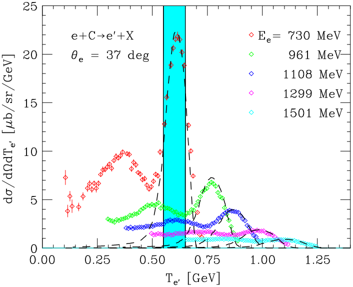
VARIUS, MULTIPLEX, MULTIFORMIS

⋆ eA *vs* νA x-section: the issue of flux average

- electron-nucleus scattering cross section at beam energy around 1GeV



- electron-carbon cross section at beam energy between ∼ 0.7 and ∼1.3 GeV.



⋆ The flux integrated cross section at fixed emission angle and kinetic energy of the outgoing lepton picks up contributions from different reaction mechanisms

The Lepton-Nucleus x-Nection

⋆ Double differential cross section of the process $\ell + A \to \ell' + X$ at fixed beam energy

$$\frac{d\sigma_A}{d\Omega_{k'} dk'_0} \propto L_{\mu\nu} W_A^{\mu\nu}$$

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

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

  requires the description of the target initial and final states, and of the nuclear current operator
- In the non-relativistic regime all elements can be consistently obtained from a realistic microscopic Hamiltonian, strongly constrained by phenomenology
- Accurate calculations of the cross section at momentum transfer $\lesssim 400$ MeV can be carried out using Quantum Monte Carlo techniques for targets of mass number $A \leq 12$

MODELLING $d\sigma_A$ AT LARGE MOMENTUM TRANSFER

⋆ In the kinematical regime in which the non-relativistic description breaks down, one has to resort to approximation schemes

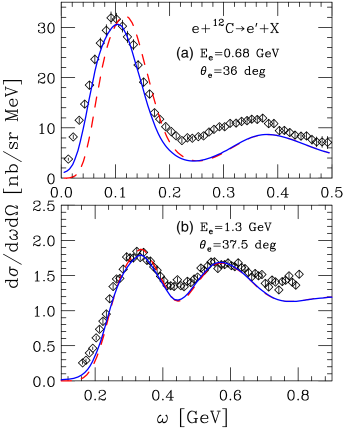
- independent particle model for the target ground state, supplemented with diagrammatic expansions based on somewhat simplified models of nuclear dynamics (Valencia model, see Juan's talk; Martini *et al* model)
- y-scaling and superscaling analysis of electron scattering data, allowing to obtain the νA cross section from a universal scaling function (originally developed by Donnelly, McCarthy and Sick, recently extended by Megias et al)
- factorization ansatz and spectral function formalism, allowing to decouple ground state dynamics—which can be accurately treated within nuclear many-body theory —from the elementary electroweak interaction vertex (OB et al)
- Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) formalism (see Ulrich's talk)

Where We Are

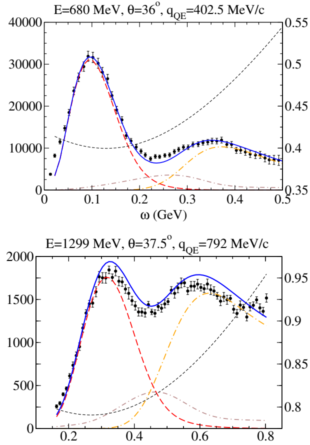
- ⋆ Over the ~ 15 years since the first NuINT Workshop—the post Fermi gas age—a number of models taking into account both the dynamcs of strong interactions and the variety of reaction mechanisms contributing to the nuclear cross section have been developed
- ⋆ Electron scattering data, mainly inclusive cross sections, have been exploited to assess the validity of the some of proposed models
- ⋆ Several models have achieved the degree of maturity required for a meaningful comparison between their predictions and the measured neutrino-nucleus cross sections

^{12}C(e, e'): FACTORIZATION *vs* SUPERSCALING

- N. Rocco *et al*



- Megias *et al*

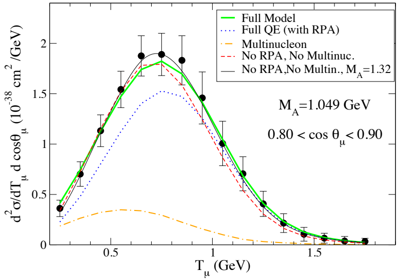


⋆ Mechanisms other than single nucleon knock-out—leading to the appearance of 2p2h final states—play a significant role

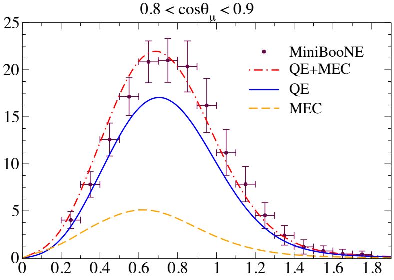
$^{12}C(\nu_\mu, \mu^-)$: VALENCIA MODEL *vs* SUPERSCALING

- ⋆ Comparison to the flux-integrated cross section measured by the MiniBooNE collaboration

- ▶ Nieves *et al*



- ▶ Megias *et al*



- ⋆ The degeneracy issue: calculation based on different approximations and including different reaction mechanisms yield similar results

UNRAVELING THE NUCLEAR CROSS SECTION

- ⋆ An accurate description of the 2p2h sector, providing $\sim 20\%$ of the nuclear cross section is only relevant to the extent to which the remaining $\sim 80\%$, arising from processes involving 1p1h final states, is fully understood

- ⋆ $(e, e'p)$ experiments, in which the scattered electron and the outgoing proton are detected in coincidence, have provided a wealth of information on single nucleon knock-out processes, associated with 1p1h final states, as well as clear-cut evidence of the coupling between the 1p1h and 2p2h sectors

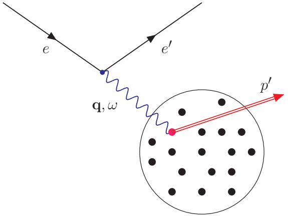
- ⋆ The large database of $(e, e'p)$ cross sections—measured mainly at Saclay, NIKHEF-K and Jefferson Lab—can be exploited to test the theoretical approaches employed to study neutrino-nucleus interaction, and assess their predictive power

THE $(e, e'p)$ REACTION

- Consider the process

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

in which both the outgoing electron and the proton, carrying momentum p', are detected in coincidence, and the recoiling nucleus can be left in a any (bound or continuum) state $|n\rangle$ with energy E_n



- In the absence of final state interactions (FSI)—which can be taken into acount as corrections—the the *measured* missing momentum and missing energy can be identified with the momentum of the knocked out nucleon and the excitation energy of the recoiling nucleus, $E_n - E_0$

$$\mathbf{p}_m = \mathbf{p}' - \mathbf{q} \quad , \quad E_m = \omega - T_{\mathbf{p}'} - T_{A-1} \approx \omega - T_{\mathbf{p}'}$$

$(e, e'p)$ Cross Section and Nuclear Spectral Function

- In the absence of FSI (to be discussed at a later stage)

$$\frac{d\sigma_A}{dE_{e'} d\Omega_{e'} dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- Káллën-Lehman representation of the spectral function

$$P_(\mathbf{p}_m, E_m) = P_{\rm MF}(\mathbf{p}_m, E_m) + P_{\rm corr}(\mathbf{p}_m, E_m)$$

- In the kinematical region corresponding to knock-out from the shell-model states ($E_m \lesssim 50$ MeV and $|\mathbf{p}_m| \lesssim 250$ MeV)

$$P_{\rm MF}(\mathbf{p}_m, E_m) = \sum_{\alpha \in \{F\}} Z_\alpha \, |\phi_\alpha(\mathbf{p}_m)|^2 \, F_\alpha(E_m - \epsilon_\alpha)$$

- According to the nuclear shell model

$$Z_\alpha \to 2j_\alpha + 1 \quad , \quad F_\alpha(E_m - \epsilon_\alpha) \to \delta(E_m - \epsilon_\alpha)$$

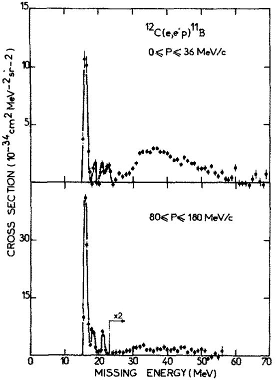
Pinning Down the 1p1h Sector

- At moderate missing energy—typically $E_m \lesssim 50$ MeV—the recoiling nucleus is left in a bound state
- The final state is a 1p1h state of the A-nucleon system
- The missing energy spectrum exhibits spectroscopic lines, corresponding to knock out from the shell model states. However the normalization of the shell model states is suppressed with respect to the predictions of the independent particle model.
- The momentum distributions of nucleons in the shell model states can be obtained measuring the missing momentum spectra at fixed missing energy
- Consider ${}^{12}\mathrm{C}(e, e'p)^{11}\mathrm{B}$, as an example. The expected 1p1h final states are

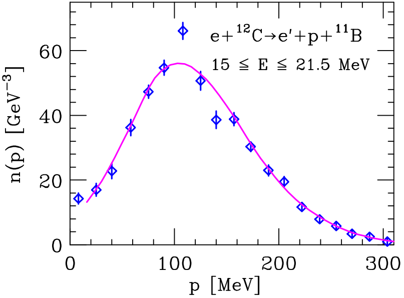
$$|{}^{11}\mathrm{B}(1/2^-),\ p\rangle \ , \ |{}^{11}\mathrm{B}(3/2^-),\ p\rangle \ , \ldots$$

$C(e, e'p)$ AT MODERATE MISSING ENERGY

- Missing energy spectrum of ^{12}C measured at Saclay (Mougey et al, 1976)



- P- state momentum distribution. Solid line: LDA spectral function (OB et al, 1994)

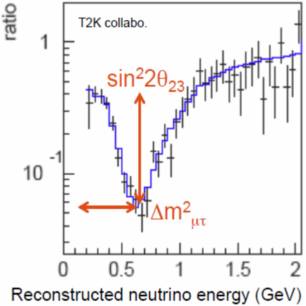


⋆ The description of the nuclear ground state based on the independent particle model fails to account for the measured spectroscopic factors

The Issue of Neutrino Energy Reconstruction

- Oscillation probability after traveling a distance L (two neutrino flavors, for simplicity)

$$P_{\alpha\to\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



- The energy of the incoming neutrino, E_ν is not precisely known, and must be reconstructed on a event-by-event basis using the information carried by the observed final state particles

Kinematic Neutrino Energy Reconstruction

- In the charged current quasi elastic (CCQE) channel, assuming single nucleon single knock out, the relevant elementary process is

$$\nu_\ell + n \to \ell^- + p$$

- The *reconstructed* neutrino energy is

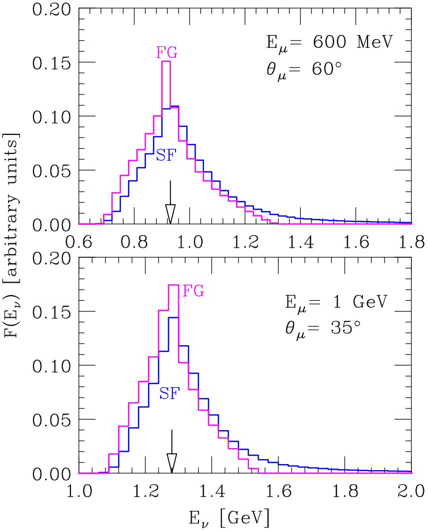
$$E_\nu = \frac{m_p^2 - m_\mu^2 - E_n{}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n{}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_n| \cos\theta_n)} ,$$

  where $|\mathbf{k}_\mu|$ and θ_μ are measured, while $\mathbf{p}_n$ and E_n are the *unknown* momentum and energy of the interacting neutron

- Existing simulation codes routinely use $|\mathbf{p}_n| = 0$, $E_n = m_n - \epsilon$, with $\epsilon \sim 20$ MeV for carbon and oxygen, or the predictions of the Fermi gas model

RECONSTRUCTED NEUTRINO ENERGY IN THE CCQE CHANNEL

- Neutrino energy reconstructed using 2×10^4 pairs of $(|\mathbf{p}|, E)$ values sampled from LDA (SF) and Fermi gas oxygen spectral functions
- The average value $\langle E_\nu \rangle$ obtained from the realistic spectral function turns out to be shifted towards larger energy by ~ 70 MeV



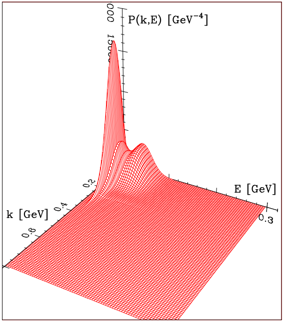
Summary & Outlook

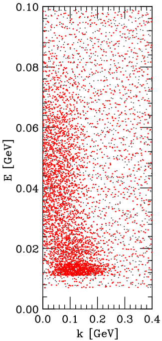
- ⋆ A number of advanced models of the electroweak nuclear cross section are being developed and tested
- ⋆ The degeneracy between models based on different physics must be resolved. The availablity of electron scattering data in exclusive channels will play a critical role in this context.
- ⋆ A necessary next step will be the consistent extension to the inelastic sector, required for the analysis of experiments using higher energy neutrino beams
- ⋆ **Breaking News:** Jlab experiment E12-12-14-012 just measured the $\mathrm{Ar}, \mathrm{Ti}(e, e'p)$ cross section. These data will allow the detrmination of the spectral function needed for the analysis of both ν and $\bar{\nu}$ interactions in liquid argon detectors

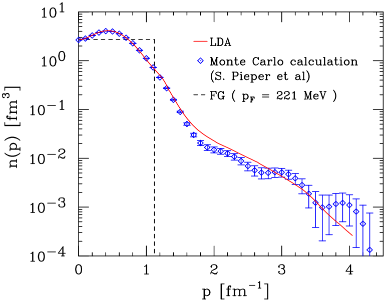
Backup slides

SPECTRAL FUNCTION OF ^{16}O

- The spectral function of medium-mass nuclei has obtained combining $(e, e'p)$ data and results of accurate nuclear matter calculations within the Local Density Approximation (LDA)



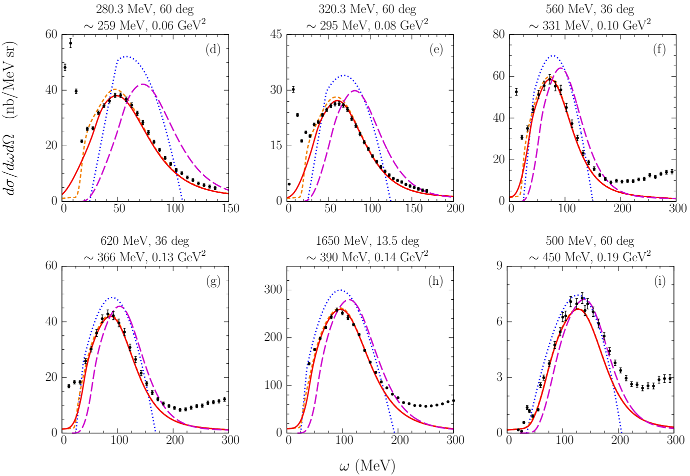




- shell model states account for $\sim 80\%$ of the strenght
- the remaining $\sim 20\%$, arising from NN correlations, is located at high momentum and large removal energy ($\mathbf{k} \gg k_F, E \gg \epsilon$)

Spectral function formalism

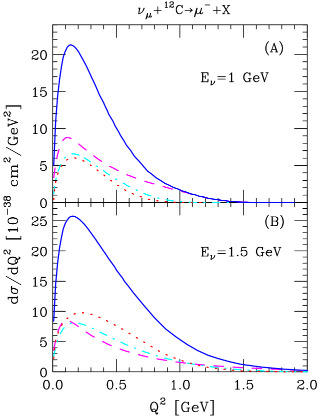
- $e + {}^{12}\mathrm{C} \to e' + X$ cross section computed within the impulse approximation and including final state interactions.

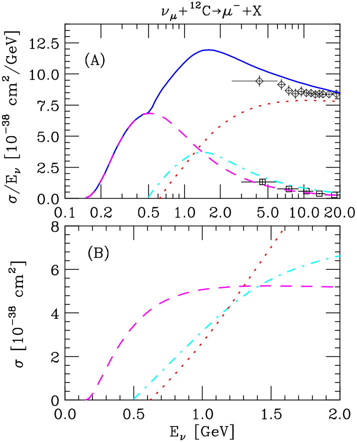


A. Ankowski *et al*, PRD **91** 033005, (2015)

Extension to the Inelastic Sector

- ⋆ Factorization ansatz and LDA spectral function (Vagnoni et al)

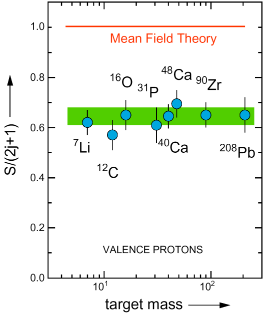




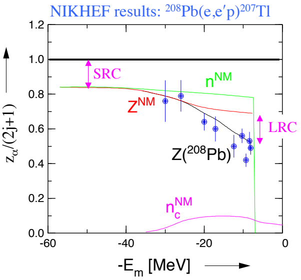
Quenching of the 1p1h Strength

⋆ Nucleon-nucleon correlations move strength from the 1p1h sector to the 2p2h sector

- Spectroscopic factors of valence states (Lapikas, 1993)



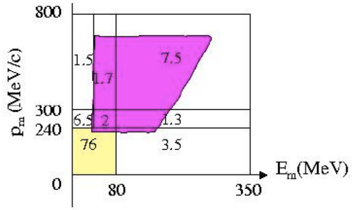
- Spectroscopic factors of the shell model states of ^{208}Pb (OB et al, 1991)

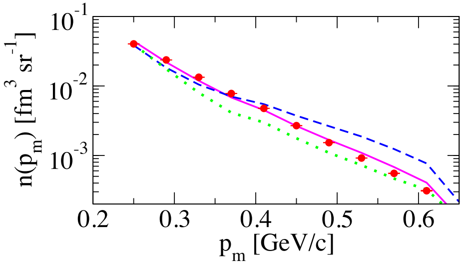


⋆ Short range correlations account for a large fraction of the observed quenching

Measured Correlation Strength

- The correlation strength in the 2p2h sector has been investigated by the JLAB E97-006 Collaboration using a carbon target



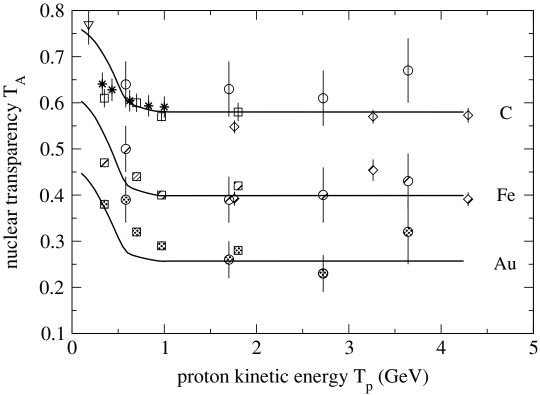


- Measured correlation strength (Rohe et al, 2005)

Experiment	0.61 ±0.06
Greens function theory [3]	0.46
CBF theory [2]	0.64
SCGF theory [4]	0.61

Calorimetric Neutrino Energy Reconstruction

- The effects of final state interactions (FSI), whose importance can be gauged studying the nuclear transparency to protons, significantly affect neutrino energy reconstruction based on calorimetric analyses (Ankowski)
  - Rohe et al



The E12-14-012 Experiment at Jefferson Lab

- ⋆ The reconstruction of neutrino and antineutrino energy in liquid argon detectors will require the understanding of the spectral functions describing both protons and neutrons
- ⋆ The $\mathrm{Ar}(e, e'p)$ cross section only provides information on proton interactions. The information on neutrons can be obtained from the $\mathrm{Ti}(e, e'p)$, exploiting the pattern of shell model levels