Unraveling the ν-Nucleus Cross-Section

Omar Benhar

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

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Outline

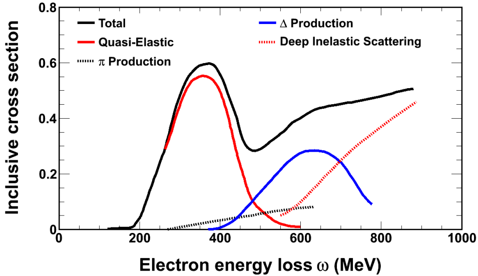
- The riddle of the flux integrated neutrino-nucleus cross section
- The issue of degeneracy between different models of the *inclusive* cross section in the 0π channel
- Exploit *exclusive* channels to resolve the degeneracy
- The $(e, e'p)$ cross section and the nuclear spectral function
- The $Ar, Ti(e, e'p)$ experiment at Jefferson Lab
- Summary & outlook

The Issue of Flux Average

- The energy-transfer dependence of the cross section of the process

$$e + A \to e' + X$$

at fixed beam energy and electron scattering angle displays a complex landscape.

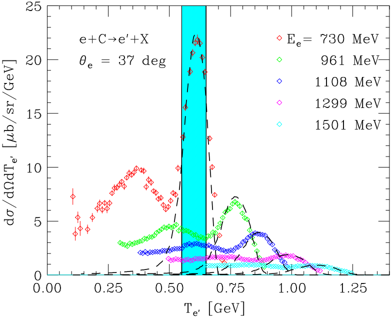


- The contributions of the main reaction mechanisms—involving both nuclear and nucleon structure—can be clearly identified

⋆ In neutrino interactions, e.g.

$$\nu_\mu + A \to \mu^- + X$$

the energy of the incoming particle is spread according to a broad distribution, and different reaction mechanisms contribute to the cross section at fixed muon energy and emission angle



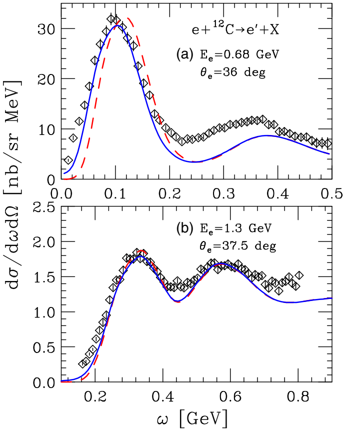
⋆ This feature clearly emerges from the analysis of the available electron-scattering data

Where We Are

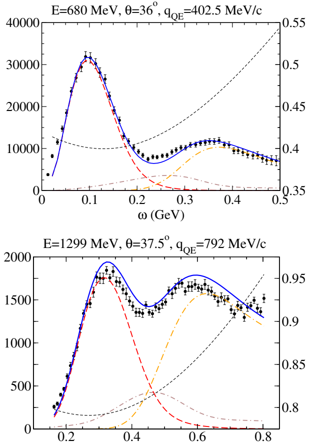
- ⋆ Even if we restrict ourselves to the 0π sector, the interpretation of the signals measured by neutrino detectors require the understanding of the different reaction mechanisms contributing to the neutrino-nucleus cross section: single-nucleon knock out, coupling to meson-exchange currents (MEC), and excitation of collective modes
- ⋆ Over the ~ 15 years since the first NuINT Workshop—that we may characterize as the post Fermi-gas age—a number of more advanced models have been developed
- ⋆ Electron scattering data, mainly *inclusive* cross sections, have been exploited to derive or validate 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
- ⋆ Very accurate results have been also obtained from Quantum Monte Carlo calculations. However, this approach is is inherently non relativistic, and its applicability is limited

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

- N. Rocco *et al*



- Megias *et al*

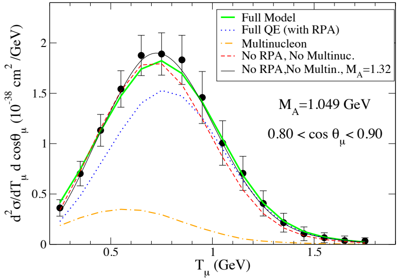


★ Mechanisms other than single nucleon knock-out and leading to the appearance of 2p2h final states (ground state correlations, final state interactions and coupling to MEC) play a significant role

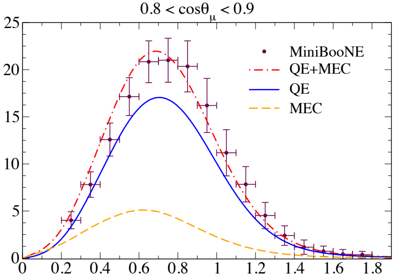
$^{12}C(\nu_\mu, \mu^-)$: Valencia Model *vs* Superscaling

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

▸ Nieves *et al*



▸ Megias *et al*



⋆ The degeneracy issue: The result of Nieves et al show a significant contribution arising from the excitation of nuclear collective modes (RPA), which is not included in the approach of Megias et al

UNRAVELING THE NEUTRINO-NUCLEUS CROSS SECTION

- ⋆ An accurate description of the 2p2h sector and collective excitations, providing a $\sim 20\%$ contribution to 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. The ability of the models to explain single-nucleon knock out needs to be assessed

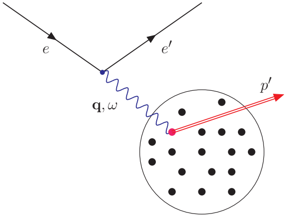
- ⋆ Fifty years of $(e, e'p)$ experiments, in which the scattered electron and the outgoing proton are detected in coincidence, have provided a wealth of information on single nucleon knock-out processes, associated with 1p1h final states, as well as clear-cut evidence of the coupling between the 1p1h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

- ⋆ The large database of $(e, e'p)$ cross sections—measured mainly at Saclay, NIKHEF-K and Jefferson Lab—must 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)

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

- Kállën-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)

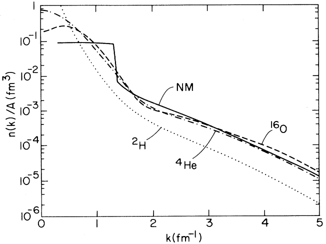
$$P_(\mathbf{p}_m, E_m) \approx P_{\rm MF}(\mathbf{p}_m, E_m) = \sum_{\alpha \in \{F\}} Z_\alpha \, |\phi_\alpha(\mathbf{p}_m)|^2 \, F_\alpha(E_m - \epsilon_\alpha)$$

- According to the nuclear shell model

$$Z_\alpha \to \frac{2j_\alpha + 1}{Z} \ , \ F_\alpha(E_m - \epsilon_\alpha) \to \delta(E_m - \epsilon_\alpha) \ , \ P_{\rm corr}(\mathbf{p}_m, E_m) \to 0$$

$P(\mathbf{k}, E)$ Within The Local Density Approximation (LDA)

$$n(k) = \int dE \; P(\mathbf{k}, E)$$



- ⋆ Bottom line: the tail of the momentum distribution, arising from the continuum contribution to the spectral function, turns out to be largely A-independent for $A > 2$

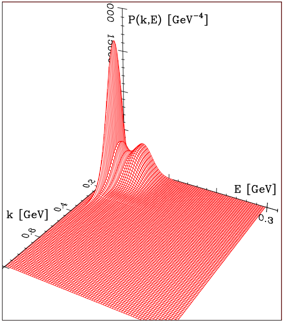
- ⋆ Spectral functions of complex (isospin symmetric) nuclei have been obtained within the local density approximation (LDA)

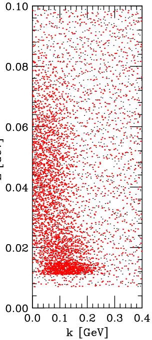
$$P_{\mathrm{LDA}}(\mathbf{k}, E) = P_{\mathrm{MF}}(\mathbf{k}, E) + \int d^3r \; \rho_A(r) \; P^{NM}_{corr}(\mathbf{k}, E; \rho = \rho_A(r))$$

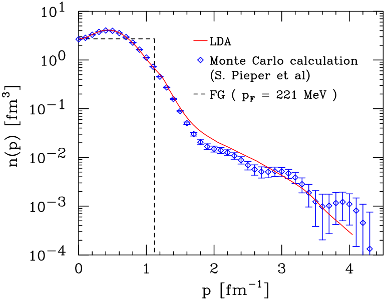
using the MF contributions extracted from $(e, e'p)$ data

- ⋆ The continuum contribution $P^{NM}_{corr}(\mathbf{k}, E)$ can be accurately computed in uniform nuclear matter at different densities

Oxygen Spectral Function







- FG model: $P(\mathbf{p}, E) \propto \theta(p_F - |\mathbf{p}|)\, \delta(E - \sqrt{|\mathbf{p}|^2 + m^2} + \epsilon)$
- 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 (more on this later)

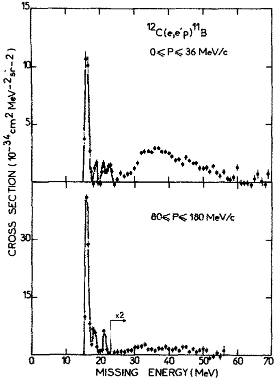
Pinning Down the 1p1h Sector

- 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

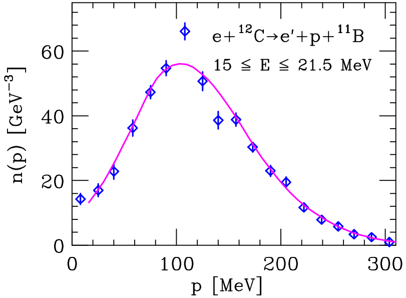
$$|^{11}\mathrm{B}(3/2^-),\ p\rangle \ , \ |^{11}\mathrm{B}(1/2^-),\ p\rangle \ , \ldots$$

$C(e, e'p)$ at Moderate Missing Energy

- Missing energy spectrum of ^{12}C measured at Saclay in the 1970s



- P- state momentum distribution. Solid line: LDA spectral function



DETERMINATION OF THE SPECTROSCOPIC FACTOR

- The spectroscopic factor of the p-state with $j = 3/2$ is obtained from

$$Z_p = \frac{Z}{(2j+1)} \int_{\Delta k} \frac{d^3k}{(2\pi)^3} \int_{\Delta E} dE \; P_{\rm LDA}(|\mathbf{k}|, E) = 0.64$$

with

$$Z_p = \int \frac{d^3k}{(2\pi)^3} \int dE \; P_{\rm LDA}(|\mathbf{k}|, E) = 1$$

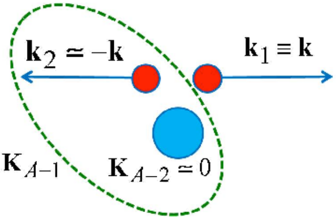
and

$$\Delta k \equiv [0\text{–}310] \text{ MeV} \quad , \quad \Delta E \equiv [15\text{–}22.5] \text{ MeV}$$

- The result obtained from the LDA spectral function—which is within 2 % of the experimental value—implies that dynamical effects not taken into account within the independent particle model reduce the average number of protons in the p-shell from $4 \to 2.5$

WHERE IS THE MISSING 1P1H STRENGTH?

- ⋆ The correlation strength in the 2p2h sector arises from processes involving high momentum nucleons, with $|\mathbf{p}_m| \gtrsim 400$ MeV. The relevant missing energy scale can be easily understood considering that momentum conservation requires

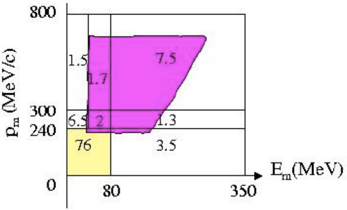


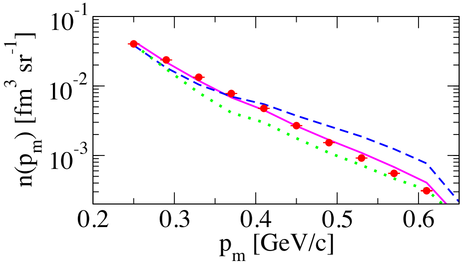
$$E_m = E_{\rm thr} + \sqrt{|\mathbf{p}_m|^2 + m^2} - m$$

- ⋆ Scattering off a nucleon belonging to a correlated pair entails a strong energy-momentum correlation

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

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

More $(e, e'p)$ Data is on its Way

- Jlab experiment E12-12-14-012 has measured the $\text{Ar}, \text{Ti}(e, e'p)$ cross section. These data will allow the determination of the spectral functions needed for the analysis of both ν and $\bar{\nu}$ interactions in liquid argon detectors

- Collaboration involving 38 physicists, including few theorists, from 8 institutions

- Approved by the Jefferson Lab PAC42 in July, 2014, with scientific grade A-

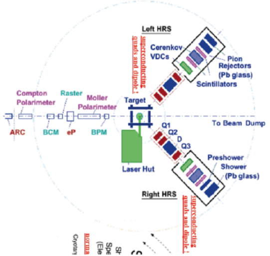
- Experimental readiness review passed in July, 2016

- Data taking in February-March 2017

JLab E12-14-012 Kinematics

Kinematic setups

	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\lvert\mathbf{q}\rvert$	p_m
	MeV	MeV	deg	MeV/c	deg	MeV/c	MeV/c
kin1	2222	1799	21.5	915	−50.0	857.5	57.7
kin3	2222	1799	17.5	915	−47.0	740.9	174.1
kin4	2222	1799	15.5	915	−44.5	658.5	229.7
kin5	2222	1716	15.5	1030	−39.0	730.3	299.7
kin2	2222	1716	20.0	1030	−44.0	846.1	183.9



kin1

Collected Data	Hours	Events(k)
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

kin3

Collected Data	Hours	Events(k)
Ar	13.5	73176
Ti	8.6	28423
Dummy	0.6	2948

kin2

Collected Data	Hours	Events(k)
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

kin4

Collected Data	Hours	Events(k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

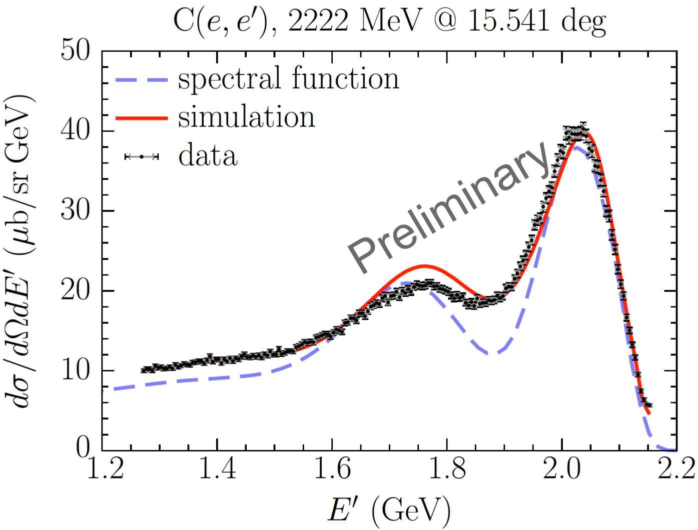
kin5

Collected Data	Hours	Events(k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

kin5 - Inclusive

Collected Data	Minutes	Events(k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

Preliminary $^{12}C(e, e')$ Results



Schedule

- ⋆ Inclusive cross sections of C and Ti analysed: December 2017
- ⋆ Inclusive cross section of Ar analysed: Early 2018
- ⋆ $(e, e'p)$ analysis: 2018
- ⋆ First data release: End of 2018
- ⋆ Spectral functions of Argon and Titanium: Mid 2019
- ⋆ Data release: End of 2019

Summary & Outlook

- A number of advanced models of the electroweak nuclear cross section the 0π sector have been developed and extensively tested
- The degeneracy between models based on different physics must be resolved. The available electron scattering data in exclusive channels can play a critical role in this context
- $(e, e'p)$ data at low missing energy and low missing momentum provide model independent information on single-nucleon knock out, which is known to provide the dominant contribution to the cross section in quasi-elastic kinematics
- The upcoming models of the Argon and Titanium spectral functions, based on the data collected by the JLab E12-14-012 experiment, will allow to pin down the contribution of single-nucleon knock out processes in neutron-rich nuclei, the description of which involves non trivial difficulties
- Note that, being an intrinsic property of the target, the spectral function is needed to obtain the nuclear cross sections in both the elastic and inelastic channels

Backup slides

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