Unraveling the ν-Nucleus Cross-Section

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Outline

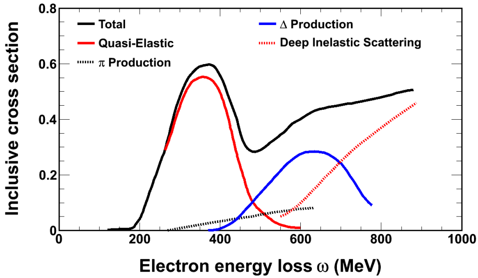
- The riddle of the *flux integrated* neutrino-nucleus cross section
- The issue of degeneracy between different models of the cross section in the 0π channel
- *Electron scattering* studies of *exclusive* channels can be exploited to resolve the degeneracy
- The $(e, e'p)$ cross section and the nuclear spectral function
- The $\mathrm{Ar}, \mathrm{Ti}(e, e'p)$ 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

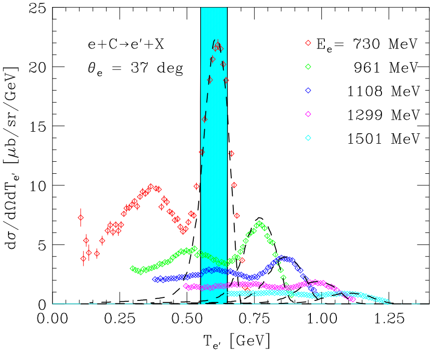


- A variety of reaction mechanisms—involving both nuclear and nucleon structure—can be clearly identified

- Owing to flux average, in neutrino-nucleus interactions, e.g.

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

different reaction mechanisms may contribute to the cross section at fixed muon energy and emission angle with comparable probability



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

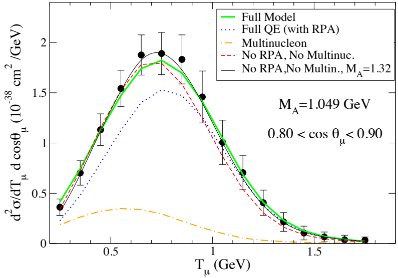
(My Own Take on) Where We Are

- Even considering the 0π sector only, the interpretation of the signals measured by neutrino detectors requires 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 develop and validate the proposed models
- Several models have achieved the degree of complexity required for a meaningful comparison between their predictions and the measured neutrino-nucleus cross sections

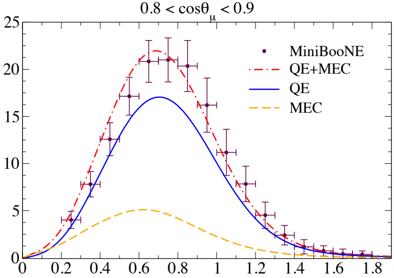
$^{12}C(\nu_\mu, \mu^-)$: Valencia Model *vs* Superscaling

⋆ The degeneracy issue: The models of Nieves *et al* and Megias *et al* provide comparable descriptions of MiniBooNE data

- Nieves *et al*



- Megias *et al*



⋆ However, the results of Nieves *et al* include a significant contribution arising from the collective nuclear excitations (RPA), not taken into acount in the approach of Megias *et al*

Unraveling the Neutrino-Nucleus Cross Section

- ⋆ An accurate description of MEC contributions and collective excitations, providing $\sim 20\%$ of the nuclear cross section, is only relevant to the extent to which the remaining $\sim 80\%$, arising from the single-nucleon knock out, is fully understood. The ability of the models to explain single-nucleon knock out needs to be assessed

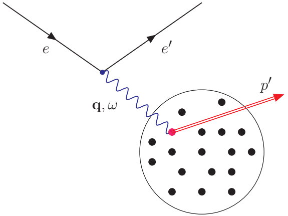
- ⋆ Fifty years of $(e, e'p)$ experiments, in which the scattered electron and the outgoing proton are detected in coincidence, have provided a wealth of information on single nucleon knock-out processes, associated with 1p1h final states, as well as clear-cut evidence of the coupling between the 1p1h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

- ⋆ The large database of $(e, e'p)$ cross sections—measured mainly at Saclay, NIKHEF-K and Jefferson Lab—can be exploited to test theoretical models of neutrino-nucleus interaction, and appraise 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, while the unobserved 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) between the knocked out proton and the residual nucleus—which can be taken into account as corrections—the *measured* missing momentum and missing energy can be identified with the initial proton momentum 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

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

- ⋆ 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

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

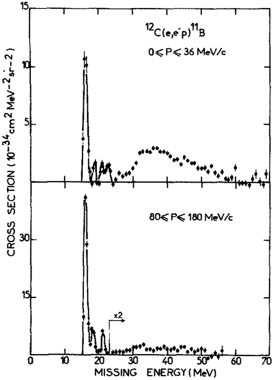
Pinning Down the 1p1h Sector

- 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

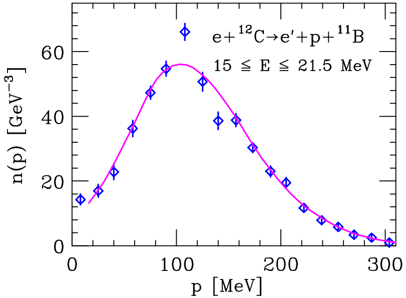
$$|^{11}\mathrm{B}(3/2^-),\ p\rangle\ ,\ \ |^{11}\mathrm{B}(1/2^-),\ p\rangle\ ,\ldots$$

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

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



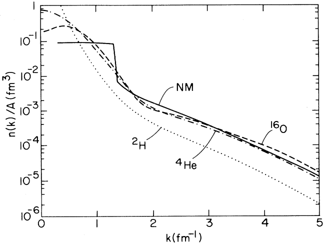
- *P*- state momentum distribution.



Modeling the Nuclear Spectral Function

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

- ⋆ 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)

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

  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

Determination of the Spectroscopic Factor

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

$$Z_p = \frac{(2j+1)}{Z} \int_{\Delta k} \frac{d^3k}{(2\pi)^3} \int_{\Delta E} dE \, P_{\rm expt}(|\mathbf{k}|, E) = 0.625$$

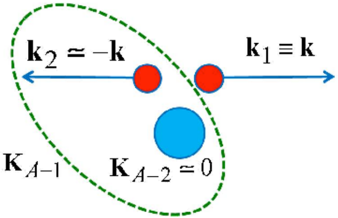
with and

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

- Models based on the mean field approximation predict $Z_p = 1$
- The deviation of Z_p from unity implies that dynamical effects not taken into account within the independent particle picture reduce the average number of protons occupying the $j = 3/2$ p-state from 4 to 2.5
- The result obtained from the LDA analysis is within 2% of the experimental value

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

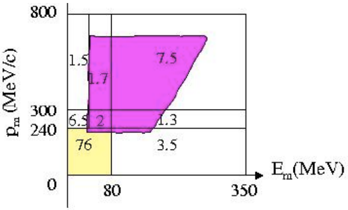


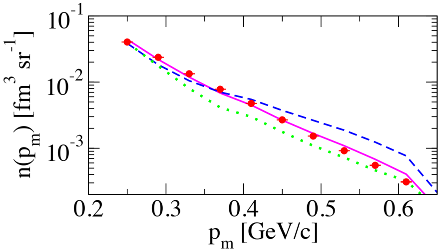
$$E_m = E_{\rm thr} + \sqrt{|\mathbf{p}_m|^2 + m^2} - m$$

- ⋆ 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





- ⋆ The correlation strength predicted by the LDA model, 0.64, turns out to be consistent with the experimental result, 0.61 ± 0.06

Detour: 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

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

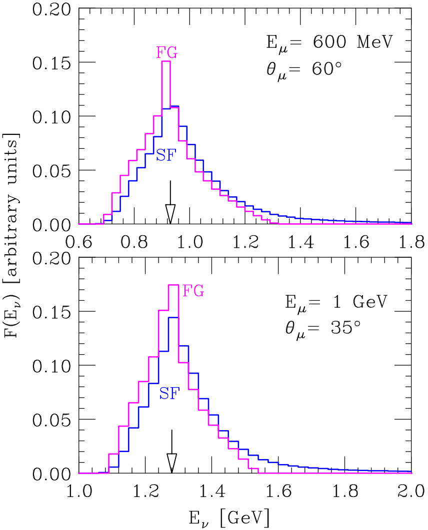
  where $|\mathbf{k}_\mu|$ and θ_μ are measured, while $\mathbf{p}_n$ and E_n are the *unknown* momentum and energy of the interacting neutron, distributed according to the spectral function

- ⋆ 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

- ⋆ 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



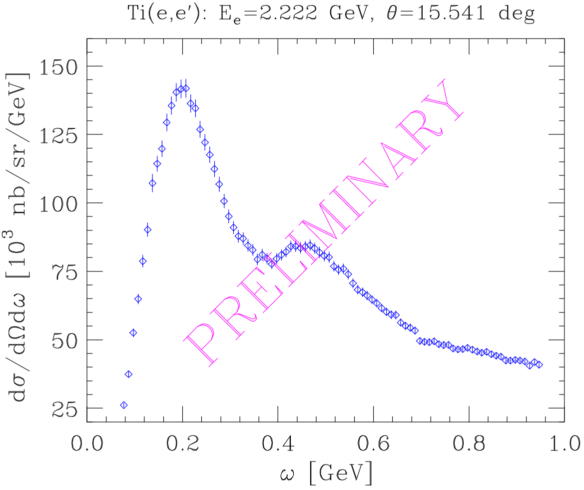
MORE $(e, e'p)$ DATA IS ON ITS WAY

- Jlab experiment E12-12-14-012 has measured the $\mathrm{Ar}, \mathrm{Ti}(e, e'p)$ 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 completed in March 2017

E12-14-012 Schedule

- ⋆ Inclusive cross sections of C and Ti analysed: December 2017
- ⋆ First data, including the first measurement of the $\mathrm{Ti}(e, e')$ cross section, submitted for publication by the end of February , 2018
- ⋆ 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
- ⋆ Final data release: End of 2019

First E12-14-012 Data (preliminary)



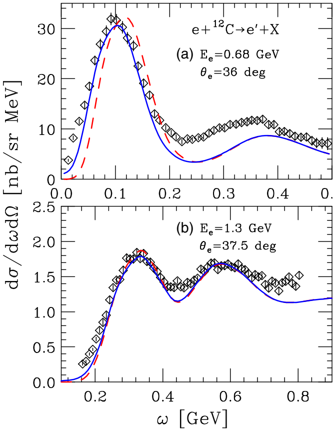
SUMMARY & OUTLOOK

- ⋆ 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 determination of the Argon and Titanium spectral functions, based on the JLab E12-14-012 data, will pave the way to the development of realistic models of ν and $\bar{\nu}$ interactions in liquid argon detectors
- ⋆ Note that, being an intrinsic property of the target, the spectral function is needed for neutrino energy reconstruction, and allows to obtain the nuclear cross sections in both elastic and inelastic channels

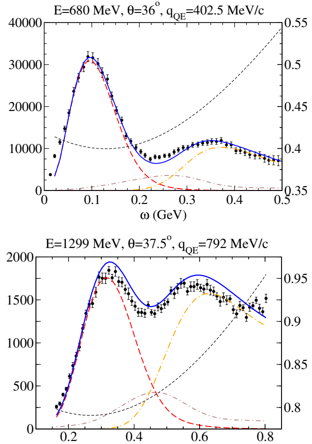
Backup slides

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

- N. Rocco *et al*

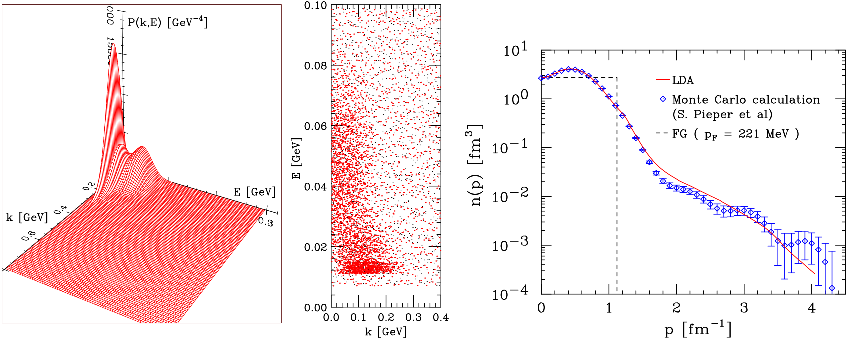


- Megias *et al*



⋆ 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

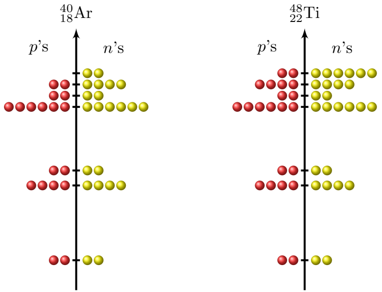
OXYGEN SPECTRAL FUNCTION



- ⋆ 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)

The E12-14-012 Experiment at Jefferson Lab

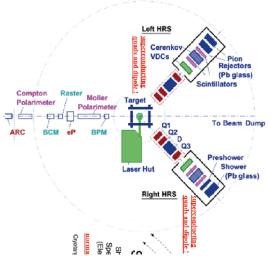
- ⋆ The reconstruction of neutrino and antineutrino energy in liquid argon detectors will require the understanding of the spectral functions describing both protons and neutrons
- ⋆ The $\mathrm{Ar}(e, e'p)$ cross section only provides information on proton interactions. The information on neutrons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



JLAB E12-14-012 KINEMATICS

Kinematic setups

	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\|\mathbf{q}\|$	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

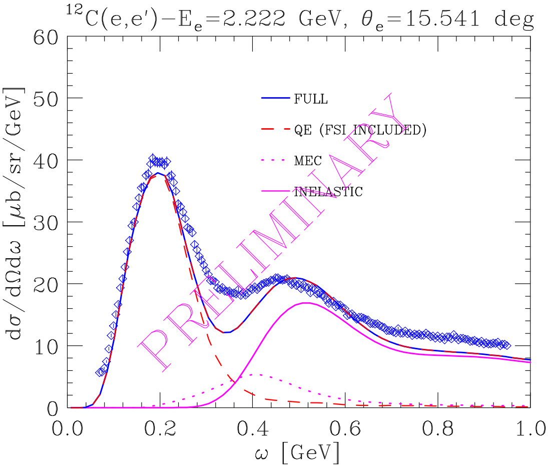
kin5

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

FIRST E12-14-012 DATA (PRELIMINARY)



⋆ Theoretical model based on the spectral function formalism. No adjustable parameters involved.

Extension to the Inelastic Sector

- ⋆ Factorization ansatz and LDA spectral function