Neutrino-nucleus scattering in the quasi-elastic region

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LDRD

NUCLEI Nuclear Computational Low-Energy Initiative
www.computingnuclei.org

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Outline

- Motivations
- The nuclear Hamiltonian and the method
- Electron scattering
- Neutrino scattering
- Conclusions

Motivation

At "nuclear" energies, understanding neutrino-nucleus interactions very challenging and important!

Understanding Nuclei:

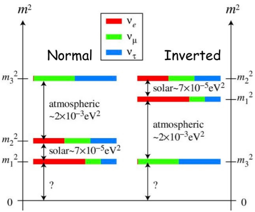
- Nuclear interactions and structure
- Exotic nuclei - neutron rich
- Electroweak processes

Relevance:

- Neutrino scattering in nuclei (neutrino oscillation experiments)
- Neutrinoless Double Beta Decay
- Neutrino interactions in supernovae and neutron stars, nucleosynthesis

Motivation

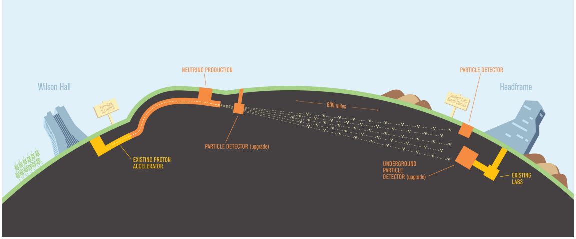
DUNE - Deep Underground Neutrino Experiment - to measure neutrino oscillations and CP violation



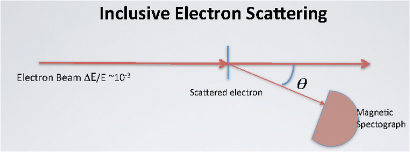
Simplified 2 flavors evolution (CP violation non included):

$$P_{\alpha\rightarrow\beta}=\sin^2(2\theta_{\alpha\beta})\sin^2\left(1.267\frac{\Delta m^2_{\alpha\beta}L}{E}\frac{GeV}{eV^2km}\right)$$

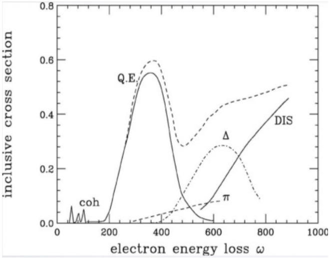
Need to know E!



Electron energy easy to know:



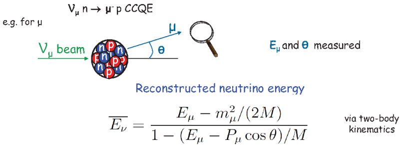
Electron scattering in nuclei:



Benhar, Day, Sick, RMP (2008)

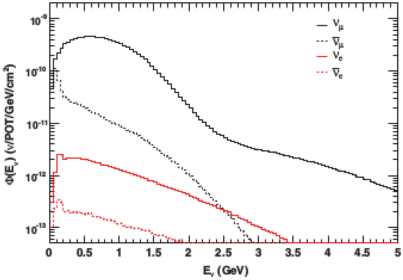
Introduction: neutrino energy and cross-section

E_ν difficult to reconstruct. Example: CCQE process



Neutral current process even more difficult.

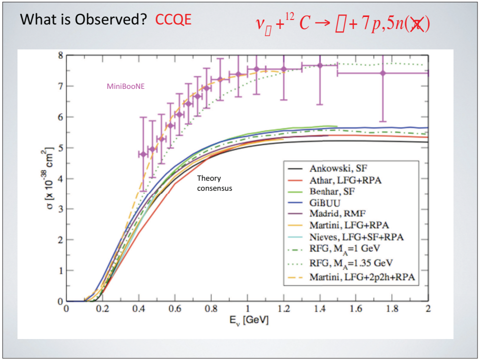
Simulation of neutrino energy distribution:



MiniBooNE Coll., PRD (2009)

Knowledge of cross-section
$+$ near detector
$=$ determination of E_ν

... but calculation of the cross-section not easy.
Experimental vs theory disagreement:



Currents inconsistent with the Hamiltonian.

Nucleon-nucleon correlations and two-body processes approximately accounted for. These models do not describe electron-scattering!!!

Nuclear Hamiltonian

Model: non-relativistic nucleons strongly interacting with a nucleon-nucleon (NN) and three-nucleon interaction (TNI).

$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{A}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

v_{ij} NN fitted on scattering data and TNI to properties of light nuclei.

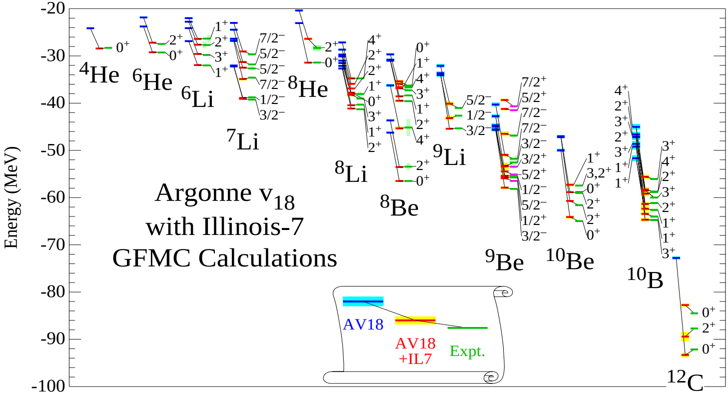
Quantum Monte Carlo methods used to solve the many-body Schroedinger equation in imaginary time t:

$$H\,\psi(\vec{r}_1 \ldots \vec{r}_N) = E\,\psi(\vec{r}_1 \ldots \vec{r}_N) \qquad \psi(t) = e^{-H\,t}\psi(0)$$

Ground-state extracted in the limit of $t \to \infty$.

No more details! Ask if interested...

Light nuclei spectrum computed with GFMC

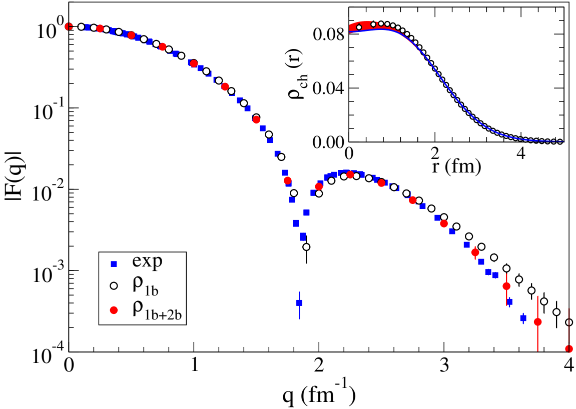


Carlson, Gandolfi, Pederiva, Pieper, Schiavilla, Schmidt, Wiringa, RMP (2015)

Also radii, densities, matrix elements, ...

Charge form factor of ^{12}C

$$|F(q)| = \langle\psi|\rho_q|\psi\rangle \qquad \rho_q = \sum_i \rho_q(i) + \sum_{i<j} \rho_q(ij)$$



Lovato, Gandolfi, Butler, Carlson, Lusk, Pieper, Schiavilla, PRL (2013)

Inclusive scattering

Electron scattering:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}\epsilon'\mathrm{d}\Omega}\right)_{\nu/\overline{\nu}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_M \left[\frac{Q^4}{q^4} R_L(q,\omega) + \left(\frac{Q^2}{2q^2} + \tan^2\frac{\theta}{2}\right) R_T(q,\omega)\right]$$

R_T and R_L transverse and longitudinal response functions.

Neutrino scattering:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}\epsilon'\mathrm{d}\Omega}\right)_{\nu/\overline{\nu}} = \frac{G^2}{2\pi^2} k'\epsilon' \cos^2\frac{\theta}{2}\left[R_{00}(q,\omega) + \frac{\omega^2}{q^2} R_{zz}(q,\omega) - \frac{\omega}{q} R_{0z}(q,\omega) + \left(\tan^2\frac{\theta}{2} + \frac{Q^2}{2\,q^2}\right) R_{xx+yy}(q,\omega) \mp \tan\frac{\theta}{2}\sqrt{\tan^2\frac{\theta}{2} + \frac{Q^2}{q^2}}\, R_{xy}(q,\omega)\right]$$

R_{00}, R_{zz}, R_{0z}, R_{xx+yy}, and R_{xy} neutrino response functions.

R_{xy} is important for ν vs $\bar{\nu}$ processes.

Response functions

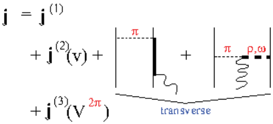
$$R(q,\omega) = \sum_n \langle \Psi | j^\dagger(q) | n \rangle \langle n | j(q) | \Psi \rangle \delta(\omega - E_n + E_0)$$
$$= \int \mathrm{d}t \langle \Psi | j^\dagger(q) \exp[i(H-\omega)t] j(q) | \Psi \rangle$$
$$= \int \mathrm{d}t \, E(q,\tau)$$

Using QMC we can calculate **exactly** $E(q,\tau)$

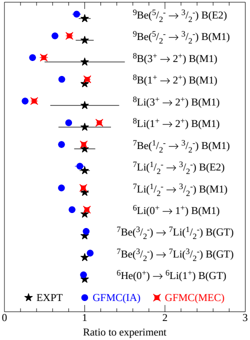
Ingredients:

- Hamiltonian H
- Ground-state Ψ (H)
- Currents described by the electroweak operators $\mathbf{j}(q)$, constructed consistently with H.

Two-body processes

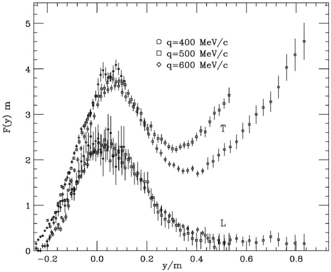


Low-momentum, transitions:



Pastore *et* al, PRC 2014

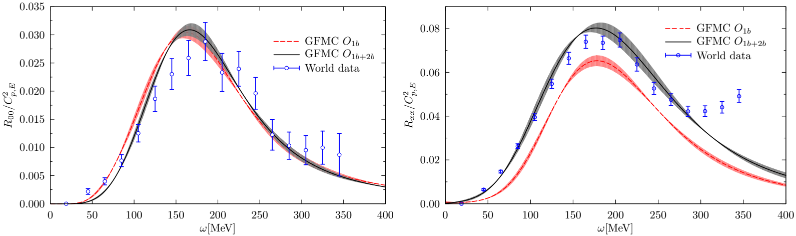
High-momentum, e^- scattering: rescaled longitudinal vs transverse electromagnetic response in ^{12}C



Benhar, Day, Sick, RMP (2008)

Without two-body processes, the longitudinal and transverse response is about the same

Electromagnetic longitudinal and transverse response functions of ^{12}C (q=570 MeV)

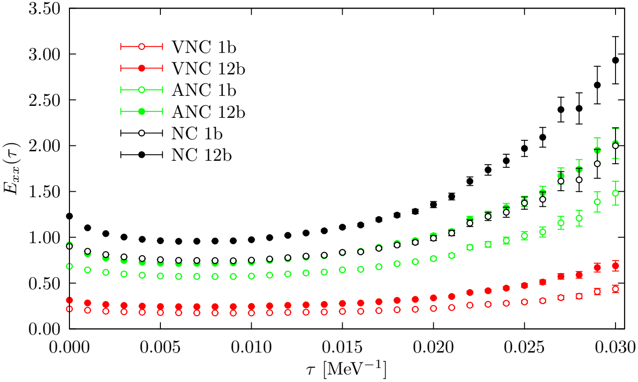


Lovato et al., PRL (2016).

Role of two-body currents very important (as expected).

Euclidean electroweak response functions of ^{12}C

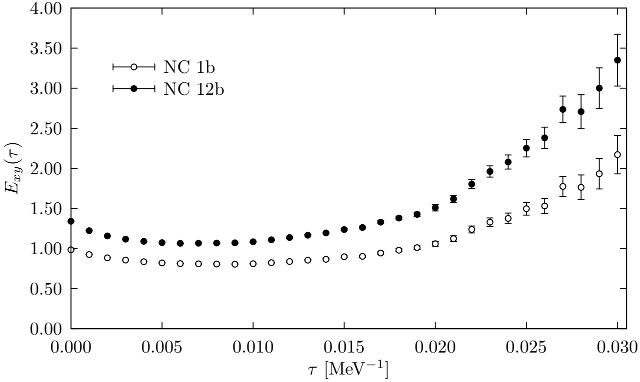
Transverse vector, axial, and neutral current euclidean response functions, with one- and two-body operators. ^{12}C, q=570 MeV



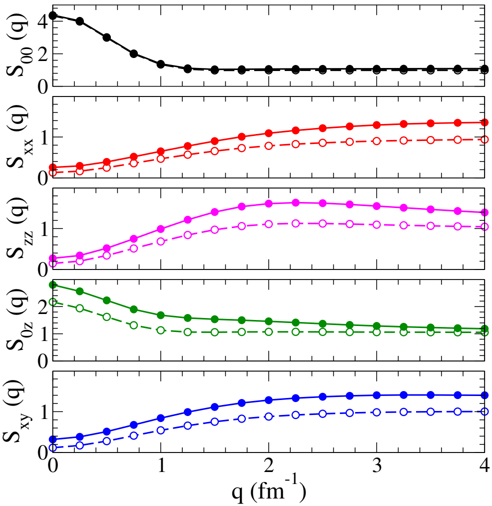
Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRC (2015)

Euclidean electroweak response functions of ^{12}C

R_{xy} term responsible for ν vs $\bar{\nu}$ response. ^{12}C, q=570 MeV



Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRC (2015)



Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRL (2014).

Two-body operators enhance sum-rules up to 50%.

Summary and future work

Conclusions:

- Electron scattering in ^{12}C calculated using GFMC. Good agreement with experiments. One- and two-body vector currents tested.
- Two-body axial currents show a similar enhancement in Euclidean response functions and sum rules.
- Interference terms are very important.

In progress/future work:

- Calculation of real time Euclidean neutral current response functions.
- Implementation of charge changing weak currents.
- Extension to larger nuclei.

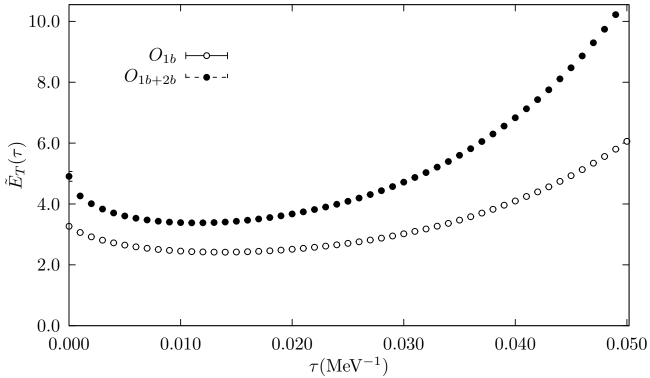
Acknowledgments:

- Joe Carlson (LANL)
- A. Lovato, S. Pieper (ANL)
- R. Schiavilla (Jlab/ODU)

Extra slides

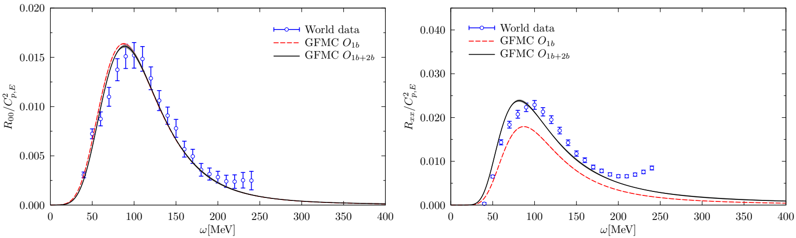
Euclidean response

Transverse electromagnetic (euclidean) response functions of ^{4}He (q=500 MeV)



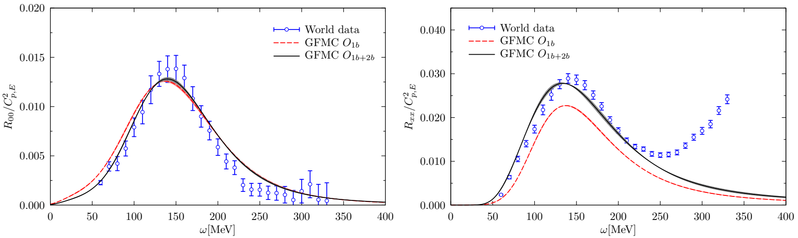
Note: results multiplied by $\exp(\tau q^2/2m)$

Longitudinal and transverse electromagnetic response functions of ^{4}He (q=400 MeV)



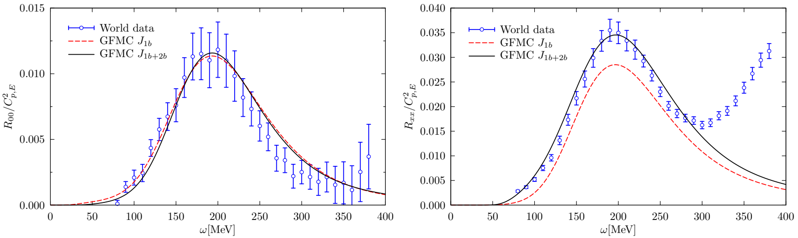
Note: results multiplied by $\exp(\tau q^2/2m)$

Longitudinal and transverse electromagnetic response functions of ^{4}He (q=500 MeV)



Note: results multiplied by $\exp(\tau q^2/2m)$

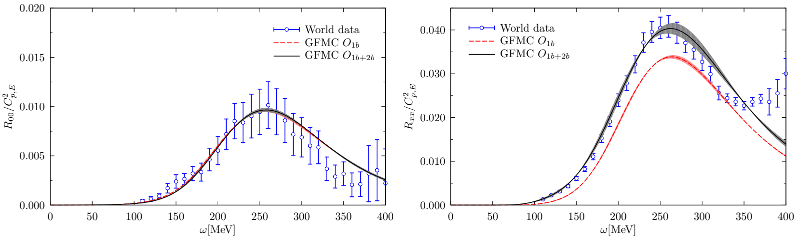
Longitudinal and transverse electromagnetic response functions of ^{4}He (q=600 MeV)



Note: results multiplied by $\exp(\tau q^2/2m)$

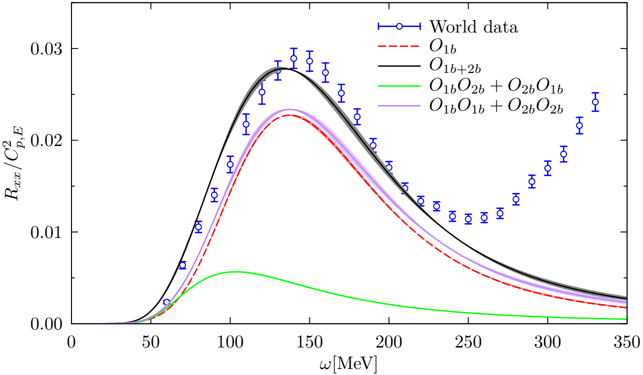
Longitudinal and transverse response response

Longitudinal and transverse electromagnetic response functions of ^{4}He (q=700 MeV)



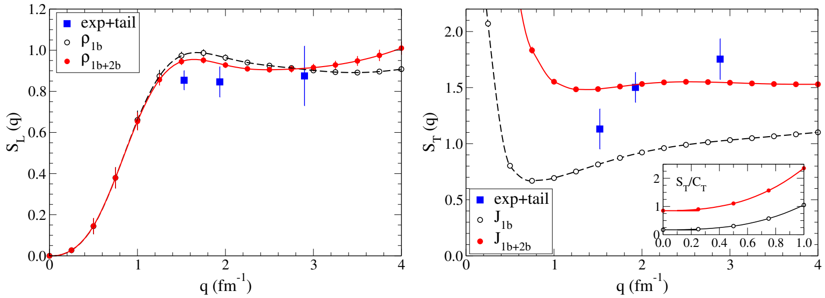
Note: results multiplied by $\exp(\tau q^2/2m)$

Transverse electromagnetic response functions of ^{4}He (q=500 MeV).
Role of the interference:



Note: results multiplied by $\exp(\tau q^2/2m)$

Sum rules: $S_{L,T}(q) = C_{L,T} \int R_{L,T}(\omega, q) d\omega$

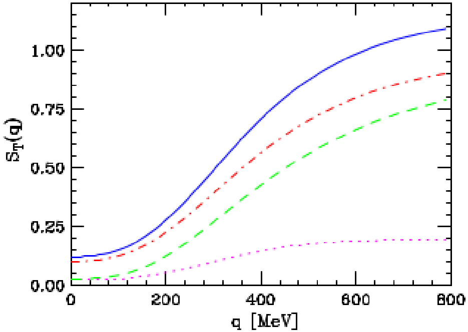


$$S_L(q) = C_L \left(\langle \psi | \rho_q^\dagger \rho_q | \psi \rangle - |\langle \psi | \rho_q | \psi \rangle|^2 \right) \qquad S_T(q) = C_T \langle \psi | \vec{J}_q^\dagger \vec{J}_q | \psi \rangle$$

Lovato, Gandolfi, Butler, Carlson, Lusk, Pieper, Schiavilla, PRL (2013)

MEC currents (two-body operators) very important in S_T sum-rule.

Transverse sum rule of ^{12}C



- Full response, $(j_1 + j_2)^\dagger (j_1 + j_2)$
- $j_1^\dagger j_1 + j_2^\dagger j_2$
- $j_1^\dagger j_1$
- interference

Benhar, Lovato, Rocco, PRC (2015)