Nucleon emission off nuclei induced by neutrino interactions

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Main Nuclear Effects

- Pauli blocking: Fermi Gas
- Fermi motion: Fermi Gas
- Correlations in excited states: RPA
- Nucleon binding: Nucleon spectral functions (hole states)
- Final State Interactions: Nucleon spectral functions (particle states)
- Nucleon rescattering: Monte Carlo propagation
Self-energy of the Gauge Boson

Many Body expansion of

\[ \Pi^{\nu\rho}_{W,Z^0,\gamma}(q,\rho) \]

Absorption by \textbf{one Nucleon}, 2N,\ldots

Real and virtual meson (\(\pi, \rho, \cdots\)) production

Excitation of \(\Delta\) or higher resonances
\[ W^+ n \rightarrow p \]
\[ W^+ N \rightarrow \Delta, N^* \]
\[ W^+ N \rightarrow N \pi, N\rho, ... \]
\[ W^{+N} N \rightarrow NN \]
\[ \sum_{N < F} W^+ \]

\[ \Delta, N^* \]

\[ \pi, \rho, ... \]
\[ W^+ n \rightarrow p \]
\[ W^+ N \rightarrow \Delta, N^* \]
\[ W^+ N \rightarrow N \pi, N\rho, ... \]

\[ W^+ NN \rightarrow NN \]

\[ \Delta, N^* \]
\[ \pi, \rho, ... \]

\[ \sum_{N,N' < F} W^+ \]

\[ 2 \]
\[ W^+ n \rightarrow \pi, \rho, \ldots \]

\[ W^+ N \rightarrow \Delta, N^* \]

\[ W^+ N \rightarrow N \pi, N\rho, \ldots \]

\[ W^+ N N \rightarrow NN \]

\[ W^+ N \rightarrow \Delta, N^* \]

\[ \Delta, N^* \rightarrow \pi, \rho, \ldots \]

\[ \sum_{N, N' < F} \]

\[ W^+ \rightarrow N, N' \]

\[ N', \pi, \rho, \ldots \]
\[ \begin{align*}
W^+ n & \rightarrow p \\
W^+ N & \rightarrow \Delta, N^* \\
W^+ NN & \rightarrow NN \\
W^+ N & \rightarrow N \pi, N\rho, ... \\
\end{align*} \]
Main features of the model

We work in nuclear matter and get results via LDA
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We work in nuclear matter and get results via LDA but include whole range of nuclear corrections

- Long (RPA) and short range correlations
- $\Delta(1232)$ degrees of freedom
- Final State Interactions (FSI)
- Nucleon Rescattering (Semi-inclusive Observables)

J. Nieves, J.E. Amaro, M. Valverde, Phys. Rev. C

J. Nieves, M. Valverde, M. J. Vicente Vacas Phys. Rev. C
The Impulse Approximation

General expression for the cross section

\[ d\sigma \sim L^{\mu\nu}W_{\mu\nu} \]

All nuclear physics is on the hadronic tensor

\[
\int d^4p^\mu \underbrace{S_h(p^0, p)S_p(p^0 + q^0, p + q)}_{\text{Nuclear Physics}} \underbrace{A^{\mu\nu}(p, q)}_{\text{Vertex Interaction}}
\]

In Fermi Gas approximation:

\[
\int \frac{d^3p}{2\pi^3} \frac{M}{E_{p+q}} \frac{M}{E_p} \Theta (k_F(r) - |p|) \Theta (|p| - k_F(r)) \delta (q^0 + E_p - E_{p+q})
\]
The Impulse Approximation

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All nuclear physics is on the hadronic tensor

\[ \int d^4 p^\mu S_h(p^0, p)S_p(p^0 + q^0, p + q) \underbrace{A^{\mu\nu}(p, q)}_{\text{Vertexinteraction}} \]

NuclearPhysics

In Fermi Gas approximation:

\[ \int d^3 r \int \frac{d^3 p}{2\pi^3} \frac{M}{E_p} \Theta (k_F(r) - |p|) \frac{M}{E_{p+q}} \Theta (|p| - k_F(r)) \delta (q^0 + E_p - E_{p+q}) A^{\mu\nu}(p, q) \]
$ph$ excitation $\rightarrow$ series of $ph$ and $\Delta h$ excitations.

Thanks to S. Dytman and S. Boyd for the plot.
MiniBooNE observables

- CCQE (like)
  - full GiBUU in-med mod. + FSI
  - $M_A = 1$ GeV
  - no parameter tuning
  - in addition: RPA correlations by Nieves et al. PRC73 (2006)
  - compared to MiniBooNE Monte Carlo output (T. Katori)

Tina Leitner, Universität Giessen

Theory of low energy nuclear effects
FSI dressing up the nucleon propagator in the $ph$ excitation

$$S_{p,h}(\omega, \mathbf{p}) = \mp \frac{1}{\pi} \frac{\text{Im} \Sigma(\omega, \mathbf{p})}{\left[ \omega - \frac{\mathbf{p}^2}{2M} - \text{Re} \Sigma(\omega, \mathbf{p}) \right]^2 + [\text{Im} \Sigma(\omega, \mathbf{p})]^2}$$

- Hole Interacting particles in a Fermi Sea FS
- Particle Interaction of the ejected nucleon with the final nuclear state

In the limit $\Sigma \to 0$ we recover Fermi Gas
Qualitatively agreement with Benhar, Farina, Nakamura, Sakuda and Seki [PRD 72 (2005) 053005]

- RPA corrections are not included, but probably small for $|q| \geq 500$ MeV
- Pion production and 2N channels should be included in the "dip" and $\Delta$ regions.
**DWIA** $\rightarrow$ Complex optical potential distorts outgoing nucleon wave
- Complex potential removes all events not in a given nuclear channel
- DWIA underestimates cross sections in semi-inclusive reactions
- Does NOT conserve probability (Violates Unitarity)

**MC** $\rightarrow$ Transport simulation through a cascade model keeps track:
- Change in energy and angle of the emitted nucleon
- Production of secondary nucleons

**Transport model** $\rightarrow$ Semiclassical transport equation explicitly solved
- Also allows for particle tracking
- E.g. GiBUU
For a given leptonic part kinematics $q^\mu$ we randomly select a point in the nucleus where the boson absorption takes place according to the profile $d^5/d\Omega' dE' d^3r$

Pick a random nucleon from the local Fermi sea with given momentum $p$

Fix the kinematics imposing energy conservation

$$E = q^0 + \sqrt{p^2 + M^2 - k_F^2(r)/2M}$$

Pauli Blocking effects are explicitly included
Nucleon propagation in nuclear medium

Move the nucleon through finite steps in a real potential

\[ V(r) = -k_F(r)/2M \]

Consider a NN collision at every step according to NN elastic cross section and decide if a secondary nucleon is produced

\[ \hat{\sigma}^{N_1N_2} = \int d\Omega_{CM} \frac{d\sigma^{N_1N_2}}{d\Omega_{CM}} C_T(q, \rho) \Theta \left( \kappa - \frac{|\mathbf{p} \cdot \mathbf{p}_{CM}|}{|\mathbf{p}| |\mathbf{p}_{CM}|} \right) \]

Medium renormalization and Pauli blocking effects
$^{40}\text{Ar}(\nu, \mu^- + N)$, $^{40}\text{Ar}(\bar{\nu}, \mu^+ + N)$

\[\nu + ^{40}\text{Ar} \rightarrow \nu + p + X\]

$E_{\nu} = 500$ MeV

\[T_p \text{ [MeV]}\]

\[10^9 \frac{d\sigma}{dT} \text{ [cm}^2/\text{MeV]}\]

\[\nu + ^{40}\text{Ar} \rightarrow \nu + n + X\]

$E_{\nu} = 500$ MeV

\[T_n \text{ [MeV]}\]

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\[\nu + ^{40}\text{Ar} \rightarrow \nu + p + X\]

$E_{\nu} = 150$ MeV

\[T_p \text{ [MeV]}\]

\[10^9 \frac{d\sigma}{dT} \text{ [cm}^2/\text{MeV]}\]

\[\nu + ^{40}\text{Ar} \rightarrow \nu + n + X\]

$E_{\nu} = 150$ MeV

\[T_n \text{ [MeV]}\]

\[10^9 \frac{d\sigma}{dT} \text{ [cm}^2/\text{MeV]}\]
$^{40}\text{Ar}(\nu, \nu + N)$

\[ \nu_\mu^{+40}\text{Ar} \rightarrow \mu^- + p + X \]

\[ E_\nu = 500 \text{ MeV} \]

\[ \nu_\mu^{+40}\text{Ar} \rightarrow \mu^- + n + X \]

\[ E_\nu = 500 \text{ MeV} \]

\[ \bar{\nu}_\mu^{+40}\text{Ar} \rightarrow \mu^+ + p + X \]

\[ E_\nu = 500 \text{ MeV} \]

\[ \bar{\nu}_\mu^{+40}\text{Ar} \rightarrow \mu^+ + n + X \]

\[ E_\nu = 500 \text{ MeV} \]
Effects on the extraction of $g_A^s$

\[ \nu^{16}O \rightarrow \nu + N + X \]
\[ E_\nu = 150 \text{ MeV} \]
\[ g_A^s = -0.19 \]

\[ \nu^{40}Ar \rightarrow \nu + N + X \]
\[ E_\nu = 500 \text{ MeV} \]
\[ g_A^s = -0.19 \]
- GiBUU: Transport Model
- Madrid: Proton in a realistic potential
- Ankowsky: Effective spectral functions
- Nieves: FG + RPA + FSI + Rescattering (No $\pi$ effects)
Proton Kinetic Energy (GeV)

$\frac{d^2 \sigma_{\text{gen}}}{dt_p \cos \theta_p} \times 10^{-38}$ cm$^2$/GeV

For $E_p$ for QE: $\nu_e + C_{12} \rightarrow \mu^- X$ for $E_{\nu} = 0.5$ GeV and $\theta_p = 60$ degrees

For $E_p$ for QE: $\nu_e + C_{16} \rightarrow p^- X$ for $E_{\nu} = 0.5$ GeV and $\theta_p = 60$ degrees

$\theta_p = 0.5$ GeV and $\nu_X$ for $E_{\mu} \rightarrow p + C_{12}$

$\theta_p = 1.0$ GeV and $\nu_X$ for $E_{\mu} \rightarrow p + O_{16}$

Proton Kinetic Energy (GeV)
Conclusions

- General qualitative agreement on which nuclear effects are relevant
  ...and how they affect cross sections
- Quantitative agreement not so good
Thanks to Profs. S. Boyd, S. Ditman and J. Sobczyk for permission to use their plots

and to the audience!!