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

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

Many Body expansion of Absorption by \textbf{one Nucleon}, 2N,\ldots

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

Excitation of \(\Delta\) or higher resonances
$W^+ \ n \rightarrow p$

$W^+ \ N \rightarrow \Delta, N^*$

$W^+NN \rightarrow NN$

$W^+N \rightarrow N\pi, N\rho, ...$

\[ \sum_{N<F} W^+N \rightarrow \Delta \]

\[ \sum_{N<F} \Delta^2 \]

\[ \sum_{N<F} \]
\[ W^+ n \rightarrow p \]

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

\[ W^+ N \rightarrow N \pi, N\rho, ... \]
\[ W^+ n \rightarrow p \]
\[ W^+ N \rightarrow \Delta, N^* \]
\[ W^+ N \rightarrow N \pi, N \rho, ... \]
\[ W^{+NN} \rightarrow NN \]
\[ \sum_{N \not= F} \]
\[ \pi, \rho, ... \]
We work in nuclear matter and get results via LDA
Main features of the model

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)

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

$$\int d^4 p^\mu S_h(p^0, p) S_p(p^0 + q^0, p + q) \underbrace{A^{\mu\nu}(p, q)}_{\text{Vertex interaction}}$$

In Fermi Gas approximation:

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

General expression for the cross section

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

All nuclear physics is on the hadronic tensor

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

In Fermi Gas approximation:

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

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Tina Leitner, Universität Giessen

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

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

- Hole Interacting particles in a Fermi Sea \textbf{FS}
- Particle Interaction of the ejected nucleon with the final \textit{nuclear state}

In the limit $\Sigma \rightarrow 0$ we \textit{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 → 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 → Transport simulation through a cascade model keeps track:
  - Change in energy and angle of the emitted nucleon
  - Production of secondary nucleons

Transport model → Semiclassical transport equation explicitly solved
  - Also allows for particle tracking
  - E.g. GiBUU
The Cascade Model

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
Move the nucleon through finite steps in a real potential

\[ V(r) = -\frac{k_F(r)}{2M} \]

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
$^{40}\text{Ar}(\nu, \mu^- + N)$, $^{40}\text{Ar}(\bar{\nu}, \mu^+ + N)$

\begin{align*}


\nu + ^{40}\text{Ar} &\rightarrow \nu + p + X \\
E_{\nu} &= 500 \text{ MeV} \\

\frac{d\sigma}{dT_p} [\text{cm}^2/\text{MeV}] \\


\nu + ^{40}\text{Ar} &\rightarrow \nu + n + X \\
E_{\nu} &= 500 \text{ MeV} \\

\frac{d\sigma}{dT_n} [\text{cm}^2/\text{MeV}] \\

\nu + ^{40}\text{Ar} &\rightarrow \nu + p + X \\
E_{\nu} &= 150 \text{ MeV} \\

\frac{d\sigma}{dT_p} [\text{cm}^2/\text{MeV}] \\

\nu + ^{40}\text{Ar} &\rightarrow \nu + n + X \\
E_{\nu} &= 150 \text{ MeV} \\

\frac{d\sigma}{dT_n} [\text{cm}^2/\text{MeV}] \\

\end{align*}
$^{40}$Ar($\nu, \nu + N$)

$\nu_\mu + ^{40}$Ar $\rightarrow \mu^- + p + X$
$E_\nu = 500$ MeV

$\bar{\nu}_\mu + ^{40}$Ar $\rightarrow \mu^+ + p + X$
$E_{\bar{\nu}} = 500$ MeV

$\nu_\mu + ^{40}$Ar $\rightarrow \mu^- + n + X$
$E_\nu = 500$ MeV

$\bar{\nu}_\mu + ^{40}$Ar $\rightarrow \mu^+ + n + X$
$E_{\bar{\nu}} = 500$ MeV
Effects on the extraction of $g_A^s$

\[ \nu^{+16}\text{O} \rightarrow \nu + N + X \]
\[ E_\nu = 150 \text{ MeV} \]
\[ g_A^s = -0.19 \]
\[ g_A^s = 0.0 \]

\[ \nu^{+40}\text{Ar} \rightarrow \nu + N + X \]
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\[ g_A^s = -0.19 \]
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\[ \nu^{+40}\text{Ar} \rightarrow \nu + N + X \]
\[ E_\nu = 500 \text{ MeV} \]
\[ g_A^s = -0.19 \]
\[ g_A^s = 0.0 \]
- 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)

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40


\frac{d^2\sigma_{el}^{QE}}{dE_p d\cos\theta_p} \times 10^{-38} \text{ cm}^2\text{GeV}^{-1}

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40

E_p \text{ for } \nu_p + C12 \rightarrow \mu^- X \text{ for } E_{\nu} = 0.5 \text{ GeV and } \theta_p = 60 \text{ degrees}

Genie
Ankowski
Nuwro
Nieves

E_p \text{ for } \nu_p + O16 \rightarrow p^- X \text{ for } E_{\nu} = 0.5 \text{ GeV and } \theta_p = 60 \text{ degrees}

E_p \text{ for } \nu_p + C12 \rightarrow \mu^- X \text{ for } E_{\nu} = 1.0 \text{ GeV and } \theta_p = 60 \text{ degrees}

Genie
Ankowski
Nuwro

E_p \text{ for } \nu_p + O16 \rightarrow p^- X \text{ for } E_{\nu} = 1.0 \text{ GeV and } \theta_p = 60 \text{ degrees}

Neut
Ankowski
Genie
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!!