Neutrino cross sections and nuclear structure

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Aim of the talk

How the uncertainties on the nuclear structure affects the $\nu$-nucleus cross section
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Specific case
Precision $\nu$ astronomy
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How the uncertainties on the nuclear structure affects the $\nu$-nucleus cross section

Specific case
Precision $\nu$ astronomy
SUPERNOVAE
Disentangling

\[ \nu_x, \bar{\nu}_x \rightarrow T = 6.0 \text{ MeV} \quad T = 7.5 \text{ MeV} \]

Excitation energy \( \omega \leq 100 \text{ MeV} \)
Momentum transfer \( q \leq 1.0 \text{ fm}^{-1} \)
Ab initio calculations

Realistic nucleon-nucleon interaction
Ab initio calculations
Realistic nucleon-nucleon interaction

Effective theories
Nucleon-nucleon interactions linked to the theory
Random Phase Approximation (RPA)

\[ |\nu\rangle = Q^\dagger_\nu |0\rangle \quad Q_\nu |0\rangle = 0 \]

\[ Q^\dagger_\nu = \sum_{ph} X_{ph} a_p^\dagger a_h - \sum_{ph} Y_{ph} a_h^\dagger a_p \]

\[(\epsilon_p - \epsilon_h - \omega)X_{ph} + \sum_{p'h'} [v_{ph,p'h'} X_{p'h'} + u_{ph,p'h'} Y_{p'h'}] = 0 \]

\[(\epsilon_p - \epsilon_h + \omega)Y_{ph} + \sum_{p'h'} [u_{ph,p'h'} X_{p'h'} + v_{ph,p'h'} Y_{p'h'}] = 0 \]

\[ v_{ph,p'h'} = \langle ph'|V|h'p'\rangle - \langle ph'|V|p'h\rangle \]

\[ u_{ph,p'h'} = \langle pp'|V|h'h\rangle - \langle pp'|V|h'h\rangle \]
Effective interaction

\[ V_{\text{eff}}(r) = V_1(r, \rho) + V_2(r) \vec{r}_1 \cdot \vec{r}_2 \]
\[ + V_3(r) \vec{\sigma}_1 \cdot \vec{\sigma}_2 + V_4(r) \vec{\sigma}_1 \cdot \vec{\sigma}_2 \vec{r}_1 \cdot \vec{r}_2 \]
\[ + V_5(r) S_{12}(r) + V_6(r) S_{12}(r) \vec{r}_1 \cdot \vec{r}_2 \]

\[ S_{12}(r) = 3 \frac{\vec{\sigma}_1 \cdot \vec{r}_1 \vec{\sigma}_2 \cdot \vec{r}_2}{r^2} - \vec{\sigma}_1 \cdot \vec{\sigma}_2 \]

\[ V_1(r, \rho) = V_c(r) + V_\rho(r) \rho(r)^\alpha \]
\[ \rho(r_{12}) = [\rho(r_1) \rho(r_2)]^{1/2} \]
\[ \alpha = 1 \]
$^{208}\text{Pb}\ (\nu,\nu')\ ^{208}\text{Pb}$

$\sigma(\nu,\nu')$

$f(\varepsilon)/<\varepsilon> \times 1000$

$E_\nu$ [MeV]

$\varepsilon_\nu$ [MeV]
$^{12}\text{C} (\nu,\nu')^{12}\text{C}$

$d\sigma/d\omega \left[ 10^{-42} \text{ cm}^2 \text{ MeV}^{-1} \right]$

$\varepsilon_\nu [\text{MeV}]$

$1^+ \text{ IV}$

$1^+ \text{ IS}$
\[ E \quad [\text{MeV}] \]

\[ ^{12}\text{B} \quad ^{12}\text{C} \quad ^{12}\text{N} \]

\[ 1^+ \quad T=1 \]

\[ (\bar{\nu}, e^+) \quad [p,n] \]

\[ \gamma \]

\[ \beta^- \quad \beta^+ \]

\[ (\nu, e^-) \quad [n,p] \]

exp

LM

LMtt

FR

FRtt

Nuclear structure
$^{12}\text{C} : 1^+ \text{ Isoscalar}$

$1^+ \ ^{12}\text{C}(e,e')^{12}\text{C}$

$\omega = 12.7 \text{ MeV}$

Data: Buti et al. PRC 33 (1986) 755
12C : 1\(^+\) Isovector

\[ I^+ \, \text{^{12}C}(e,e')\text{^{12}C} \]

\[ \omega = 15.1 \, \text{MeV} \]

Data: Hicks et al. PRC 36 (1987) 485
\[
\left( \frac{d^2\sigma}{d\Omega d\epsilon} \right)_{e,e'} = \sigma_M \frac{1}{2J_i + 1} \left[ v_L | < J_f || C^Y_j || J_i > |^2 
+ v_T | < J_f || T^Y_j || J_i > |^2 \right]
\]

\[
\left( \frac{d^2\sigma}{d\Omega d\epsilon} \right)_{\nu,\nu'} = G^2 \frac{\epsilon'_\nu}{\epsilon_\nu} \frac{1}{2J_i + 1} \left[ w^A_C | < J_f || C^A_j || J_i > |^2 + w^A_L | < J_f || L^A_j || J_i > |^2 + w^V_L | < J_f || C^Y_j || J_i > |^2 + w^A_{LC} \text{Re} \left( < J_f || C^A_j || J_i > < J_f || C^A_j || J_i >^* \right) + w^A_T | < J_f || T^A_j || J_i > |^2 + w^V_T | < J_f || T^Y_j || J_i > |^2 + w^AV_T \text{Re} \left( < J_f || T^A_j || J_i > < J_f || T^Y_j || J_i >^* \right) \right]
\]
$^{12}\text{C} : 1^+ \text{ Isovector}$

$1^+ \ ^{12}\text{C}(e,e')^{12}\text{C}$

$\omega = 15.1 \text{ MeV}$

$R_T [\text{MeV}^{-1}]$

$q [\text{fm}^{-1}]$

$LM$

$LMtt$

$FR$

$FRtt$
$^{12}\text{C} : 1^+ \text{ Isovector}$

$1^+ \ ^{12}\text{C}(e,e')^{12}\text{C}$

$\omega = 15.1 \text{ MeV}$
\[ Q(q) = \frac{|< J_f || T_j^{\text{exp}}(q) || J_i > |^2_{\text{e,e'}}}{|< J_f || T_j^{\text{V}}(q) || J_i > |^2_{\text{RPA}}} \]

\[
\left( \frac{d^2\sigma}{d\Omega d\epsilon} \right)_{\nu,\nu'}^{\text{scal}} = Q(q) \left( \frac{d^2\sigma}{d\Omega d\epsilon} \right)_{\nu,\nu'}^{\text{RPA}}
\]
$^{12}\text{C} : 1^+ \text{ Isovector}$

$1^+ \, ^{12}\text{C}(e,e')^{12}\text{C}$

$R_T \, [\text{MeV}^{-1}]$

$q \, [\text{fm}^{-1}]$

$\omega=15.1 \text{ MeV}$

Kubodera

M. Fukugita, Y. Kohyama and K. Kubodera, Phys. Lett. B 212 (1988) 139.
\( N_{NC} = (\nu_e, \nu'_e) \)
\( N_{np} = (\nu_e, e^-) \)
\[ N_{NC} = (\nu_e, \nu'_e) + (\bar{\nu}_e, \bar{\nu}'_e) \]
\[ N_{np} = (\nu_e, e^-) \]
\[ N_{pn} = (\bar{\nu}_e, e^+) \]
\[ \begin{align*}
N_{NC} &= (\nu_e, \nu_e') + (\overline{\nu}_e, \overline{\nu}_e') + (\nu_x, \nu_x') + (\overline{\nu}_x, \overline{\nu}_x') \\
N_{np} &= (\nu_e, e^-) \\
N_{pn} &= (\overline{\nu}_e, e^+) 
\end{align*} \]
\[ N_i = \frac{1}{4\pi} \frac{E_B f_i}{D^2} \frac{n_t \eta}{\langle \epsilon_\nu \rangle} \int_{\epsilon_{th}}^{\infty} f(\epsilon_\nu) \sigma(\epsilon_\nu) d\epsilon_\nu \]

**Supernova parameters**

\( E_B \sim 5.0 \times 10^{52} \text{ erg} = 8.01 \times 10^{60} \text{ MeV} \) (Energy)

\( f_i = 1/6 \) (Fraction of the energy carried by \( \nu_i \))

\( D = 10 \text{ kpc} \) (Distance from the earth)

**LVD parameters** [1]

\( n_t = 4.23 \times 10^{31} \) (Number of \(^{12}\text{C} \) target nuclei)

\( \eta_{NC} = 0.55, \eta_{np}(\nu, e^-) = 0.75, \eta_{pn}(\overline{\nu}, e^+) = 0.90 \) (efficiencies)

| Number of events | \( \nu + e^- \) | \( \overline{\nu} + e^+ \) | NC T=6.0 MeV | NC T=7.5 MeV |
|------------------|----------------|----------------|-------------|-------------|
| Kubodera         | 7              | 9              | 25          | 32          |
| \( N_{min} \)    | 8              | 43             | 64          | 84          |
| \( N_{max} \)    | 14             | 63             | 112         | 151         |

[1] N. Yu. Agafonova et al., Astrop. Phys. 27 (2007) 254
\[ N_{NC} = N_{NC}^T + N(\nu_e, \nu'_e)_4 + N(\bar{\nu}_e, \bar{\nu}'_e)_5 \]

\[ N_{NC}^T = N(\nu_x, \nu'_x)_T + N(\bar{\nu}_x, \bar{\nu}'_x)_T \]

\[ R = \frac{N_{NC}^T}{N_{NC}} = \frac{N_{NC} - \left[ N(\nu_e, \nu'_e)_4 + N(\bar{\nu}_e, \bar{\nu}'_e)_5 \right]}{N_{NC}} \]
\( R \) vs. \( T \) [MeV]

- Data points labeled as "Kubodera"
\[ N_{np} = N(\nu_e, e^-)_4 \]
\[ N_{pn} = N(\bar{\nu}_e, e^+)_5 \]

\[ R_{emp} = \frac{1}{N_{emp}^{NC}} \left[ N_{emp}^{NC} - N_{np}^{emp} \left( \int_{\epsilon_{th}}^{\infty} f(\epsilon) \sigma_{\nu_e, \nu_e'}(\epsilon) \, d\epsilon \right) \right. \\
\left. - \eta_{np} \int_{\epsilon_{th}}^{\infty} f(\epsilon) \sigma_{\nu_e, e^-}(\epsilon) \, d\epsilon \right] \\
\left. - N_{pn}^{emp} \left( \int_{\epsilon_{th}}^{\infty} f(\epsilon) \sigma_{\bar{\nu}_e, \bar{\nu}_e'}(\epsilon) \, d\epsilon \right) \right] \\
\left. - \eta_{pn} \int_{\epsilon_{th}}^{\infty} f(\epsilon) \sigma_{\bar{\nu}_e, e^+}(\epsilon) \, d\epsilon \right] \]

In our simulation \( N_{emp} = N(\text{Kubodera}) \)
$R_{\text{emp}}$ vs $T$ [MeV]

- Kubodera
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Large uncertainties above the nucleon emission threshold (Giant resonances)
Conclusions

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Discrete excitations are better described.
Uncertainties on the magnitude of the cross sections.
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Nuclear structure uncertainties are relevant for precision $\nu$ astromomy

Large uncertainties above the nucleon emission threshold (Giant resonances)

Discrete excitations are better described
Uncertainties on the magnitude of the cross sections

Ratios of observables are stable against cross section uncertainties
\begin{center}
\textbf{\( \mu \) capture rate}

\begin{tabular}{|c|c|c|c|c|c|}
\hline
10\(^3\) s\(^{-1}\) & LM & LMtt & FR & FRtt & exp [1] \\
\hline
no scal & 34.98 & 33.38 & 35.14 & 34.30 & \\
scal & 14.10 & 13.35 & 14.14 & 13.76 & 6.2\(\pm\)0.3 \\
\hline
\end{tabular}

\textbf{\(< \sigma_e >\) from \( \mu \) decay at rest}

\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
10\(^{-42}\) cm\(^2\) & LM & LMtt & FR & FRtt & Kub. & exp [2] \\
\hline
no scal & 26.55 & 25.22 & 26.85 & 26.64 & \\
scal & 14.24 & 13.55 & 14.40 & 14.30 & 9.19 & 8.9\(\pm\)0.12 \\
\hline
\end{tabular}

[1] D.F. Measday, Phys. Rep. 354 (1001) 243
[2] L.B. Auerbach et al. (LSND), Phys. Rev. C 64 (2001) 065501
Total photoabsorption

\[ \sigma_\gamma [\text{mb}] \]

\[ \omega [\text{MeV}] \]

\[ ^{208}\text{Pb} \]