Neutrino-nucleus scattering : from very low energies to the quasi-elastic peak

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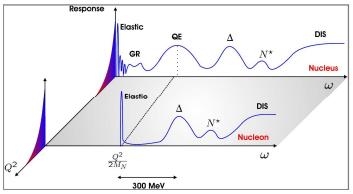
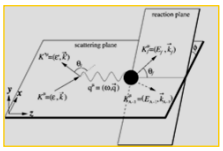
Neutrino-hadron scattering



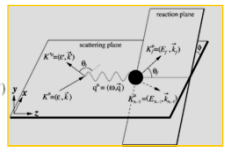


Neutrino-nucleus scattering : the ingredients

Cross section :

$$d\sigma = \frac{1}{\vec{\beta}}\overline{\sum_{if}}|M_{fi}|^2 \frac{M_i}{e'}\frac{M_{A-1}}{E_{A-1}}\frac{M_N}{E_f}d^3\vec{k}_{A-1}d^3\vec{k}'d^3\vec{k}_f$$

$$(2\pi)^{-5}\delta^4(K^\mu + K_A^\mu - K'^\mu - K_{A-1}^\mu - K_f^\mu)$$



$$\frac{d^5\sigma}{d\varepsilon' d^2\Omega_{k'} d^2\Omega_f} = \frac{M_i M_N M_{A-1}}{(2\pi)^5 M_{A'}} k'^2 k_f f_{rec}^{-1} \overline{\sum_{if}}|M_{fi}|^2$$

with $$\overline{\sum_{if}}|M_{fi}|^2 = \frac{G_F^2}{2}\left[\frac{M_{\tilde{B}}^2}{Q^2 + M_{\tilde{B}}^2}\right]^2 L_{\alpha\beta} W^{\alpha\beta}$$

hadron tensor

lepton tensor

Cross section

Lepton tensor

$$\frac{d^2\sigma}{d\Omega\, d\omega} = (2\pi)^4\, k_f \varepsilon_f \sum_{s_f, s_i} \frac{1}{2J_i + 1} \sum_{M_f, M_i} \left|\left\langle f \left| \hat{H}_W \right| i \right\rangle\right|^2$$

$$\hat{H}_W = \frac{G}{\sqrt{2}} \int d\vec{x}\, \hat{j}^{\mu,leptonic}(\vec{x})\, \hat{J}^{\mu,hadronic}(\vec{x})$$

Hadron current

$$J^\mu = F_1(Q^2)\gamma^\mu + i\frac{\kappa}{2M_N}F_2(Q^2)\sigma^{\mu\nu}q_\nu + G_A(Q^2)\gamma^\mu\gamma_5 + \frac{1}{2M_N}G_P(Q^2)q^\mu\gamma_5$$

$$l_{\alpha\beta} \equiv \overline{\sum_{s,s'}}[\overline{u}_l\gamma_\alpha(1-\gamma_5)u_l]^\dagger[\overline{u}_\nu\gamma_\beta(1-\gamma_5)u_\nu]$$

with

$$\vec{J}_c^{\,\alpha}(\vec{x}) = \frac{1}{2M_i}\sum_{i=1}^{A} G_E^{i,\alpha}\left[\delta(\vec{x}-\vec{x}_i)\,\overrightarrow{\nabla}_i - \overleftarrow{\nabla}_i\,\delta(\vec{x}-\vec{x}_i)\right],$$

$$\vec{J}_m^{\,\alpha}(\vec{x}) = \frac{1}{2M}\sum_{i=1}^{A} G_M^{i,\alpha}\,\vec{\nabla}\times\vec{\sigma}_i\,\delta(\vec{x}-\vec{x}_i),$$

$$\vec{J}_A^{\,\alpha}(\vec{x}) = \sum_{i=1}^{A} G_A^{i,\alpha}\,\vec{\sigma}_i\,\delta(\vec{x}-\vec{x}_i),$$

$$J_V^{0,\alpha}(\vec{x}) = \rho_V^{\alpha}(\vec{x}) = \sum_{i=1}^{A} G_E^{i,\alpha}\,\delta(\vec{x}-\vec{x}_i),$$

$$J_A^{0,\alpha}(\vec{x}) = \rho_A^{\alpha}(\vec{x}) = \frac{1}{2M_i}\sum_{i=1}^{A} G_A^{i,\alpha}\,\vec{\sigma}_i\cdot\left[\delta(\vec{x}-\vec{x}_i)\,\overrightarrow{\nabla}_i - \overleftarrow{\nabla}_i\,\delta(\vec{x}-\vec{x}_i)\right]$$

$$F_i = \begin{cases} \left(\frac{1}{2}-2\sin^2\theta_W\right)F_{i,p}^{EM} - \frac{1}{2}F_{i,n}^{EM} & \text{for } \lambda \\ \left(F_{i,p}^{EM} - F_{i,n}^{EM}\right) & \text{for CC reactions} \end{cases}$$

$$J_P^{0,\alpha}(\vec{x}) = \rho_P^{\alpha}(\vec{x}) = \frac{m_\mu}{2M}\sum_{i=1}^{A} G_P^{i,\alpha}\,\vec{\nabla}\cdot\vec{\sigma}_i\,\delta(\vec{x}-\vec{x}_i)$$

$$G_A = \begin{cases} -\frac{g_A}{2}G & \text{for NC reactions} \\ g_A G & \text{for CC reactions} \end{cases}$$

Q^2 dependence : dipole parametrization

$$G = (1+Q^2/M^2)^{-2}$$

$$G_P(Q^2) = \frac{2M_N}{Q^2+m_\pi^2}G_A(Q^2)$$

Cross section

Lepton tensor

$$l_{\alpha\beta} \equiv \sum_{s,s'}[\overline{u}_l\gamma_\alpha(1-\gamma_5)u_l]^\dagger[\overline{u}_\nu\gamma_\beta(1-\gamma_5)u_\nu]$$

Hadron current

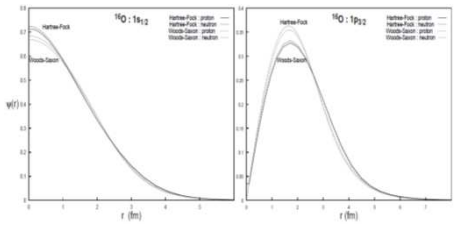
$$\left(\frac{d^2\sigma_{i\to f}}{d\Omega d\omega}\right)_{\frac{\nu}{e}} = \frac{G^2\varepsilon_f^2}{\pi}\frac{2\cos^2\left(\frac{\theta}{2}\right)}{2J_i+1}\left[\sum_{l=0}^{\infty}\sigma_{CL}^l + \sum_{t=1}^{\infty}\sigma_T^l\right]$$

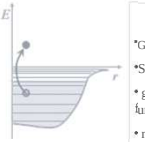
$$\sigma_{CL}^l = \left|\left\langle J_f\left\|\widehat{\mathcal{M}}^l(\kappa)+\frac{\omega}{|\vec{q}|}\widehat{\mathcal{L}}^l(\kappa)\right\|J_i\right\rangle\right|^2$$

$$\sigma_T^l = \left(-\frac{q_\mu^2}{2|\vec{q}|^2}+\tan^2\left(\frac{\theta}{2}\right)\right)\left[\left|\left\langle J_f\left\|\widehat{\mathcal{J}}^{mag}(\kappa)\right\|J_i\right\rangle\right|^2+\left|\left\langle J_f\left\|\widehat{\mathcal{J}}^{el}(\kappa)\right\|J_i\right\rangle\right|^2\right]$$

$$\mp\tan\left(\frac{\theta}{2}\right)\sqrt{-\frac{q_\mu^2}{|\vec{q}|^2}+\tan^2\left(\frac{\theta}{2}\right)}\left[2\Re\left(\left\langle J_f\left\|\widehat{\mathcal{J}}^{mag}(\kappa)\right\|J_i\right\rangle\left\langle J_f\left\|\widehat{\mathcal{J}}^{el}(\kappa)\right\|J_i\right\rangle^*\right)\right]$$

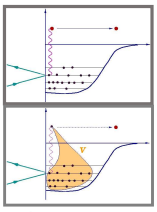
Bound state wave functions

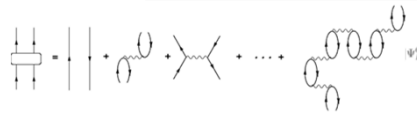




Continuum RPA

- Green's function approach
- Skyrme II residual interaction
- ground state : Hartree-Fock single-particle wave functions (Skyrme)
- non-relativistic





$$\Psi_{RPA}^{C} = \sum_{C'}\left[X_{C,C'}\,|p'h'^{-1}\rangle - Y_{C,C'}\,|h'p'^{-1}\rangle\right.$$

$$\Pi^{(RPA)}(x_1,x_2;E_x) = \Pi^{(0)}(x_1,x_2;E_x) + \frac{1}{\hbar}\int dx dx' \Pi^0(x_1,x;E_x)\tilde{V}(x,x')\Pi^{(RPA)}(x',x_2;E_x)$$

•Coulomb correction in charged current interactions :

- ✓ Low energies : Fermi function

$$F(Z',E) = \frac{2\pi\eta}{1-e^{-2\pi\eta}} \qquad \eta \sim \mp Z'\alpha$$

- ✓ High energies : modified effective momentum approximation (J. Engel, PRC57,2004 (1998))

$$q_{eff} = q + 1.5\left(\frac{Z'\alpha\hbar c}{R}\right)$$

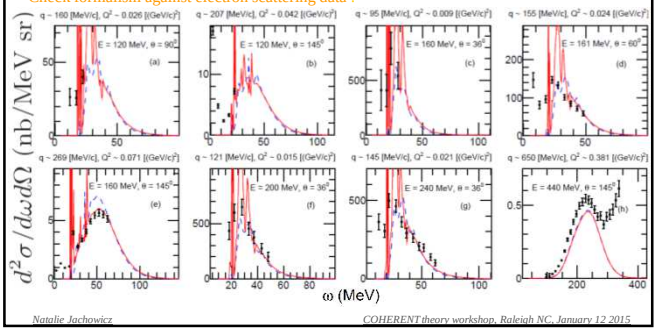
$$\Psi_l^{eff} = \zeta(Z',E,q)\,\Psi_l \qquad \zeta(Z',E,q) = \sqrt{\frac{q_{eff}E_{eff}}{qE}}$$

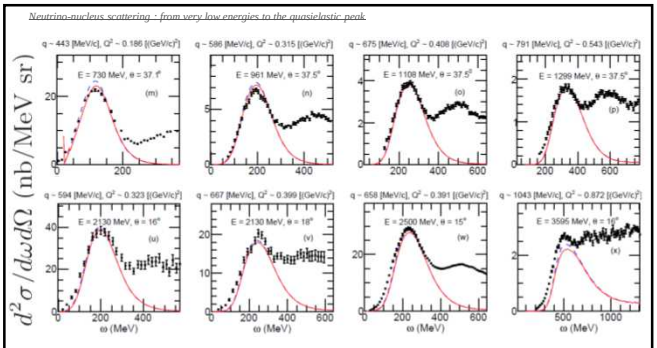
•Relativistic corrections at higher energies (J. Jeschonnek and T. Donnelly, PRC 57, 2438 (1998)):

$$\lambda \rightarrow \lambda(1+\lambda) \qquad \lambda = \omega/2M_N$$

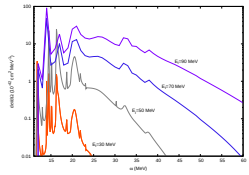
•Final state interactions : taken into account through the calculations of the wave function of the outgoing nucleon in the (real) nuclear potential generated using the Skyrme force

Check formalism against electron scattering data :

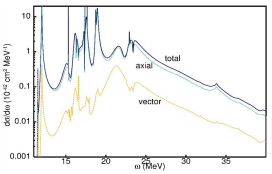




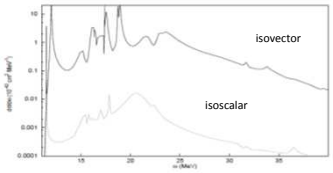
Neutrino scattering results :

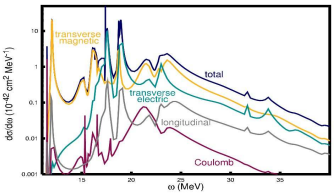


$^{16}O(\nu_{50\,MeV}, \nu')\,^{16}O^*$

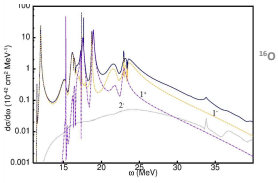


Continuum Random Phase Approximation (CRPA)

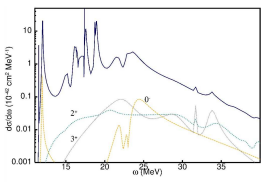




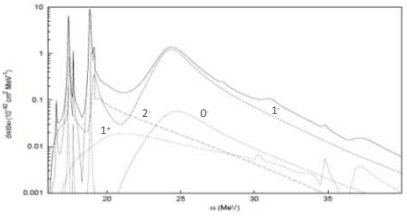
Multipole contributions :



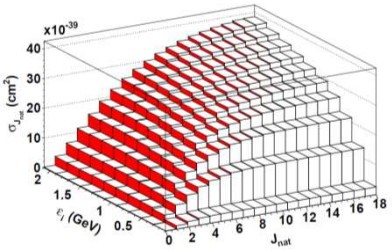
^{16}O



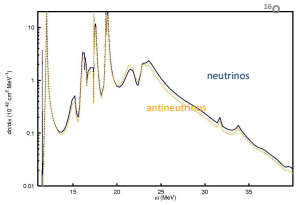
$^{12}C(\nu_{50\,MeV}, \nu')\,^{12}C^*$

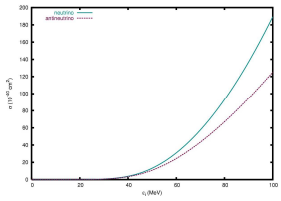


Multipole distribution for higher incoming energies :

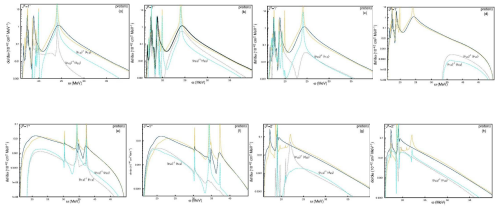


Neutrinos versus antineutrinos

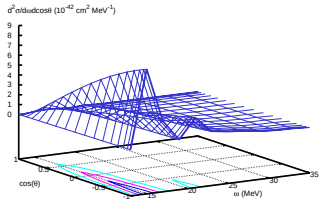




Contribution of different single-particle channels in ^{12}C



Double-differential cross sections :



Strangeness in the nucleon

Axial form factor :

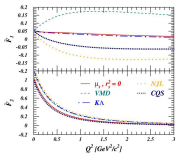
$$G_A(Q^2) = -\frac{(\tau_3 g_A - g_A^s)}{2} G(Q^2), \quad g_A = 1.262$$

$$G(Q^2) = (1 + Q^2/M^2)^{-2}, \quad M = 1.032$$

Weak vector form factors :

$$F_1^s = \frac{1}{6} \frac{-r_s^2 Q^2}{(1 + Q^2/M_1^2)^2}, \quad M_1 = 1.3$$

$$F_2^s = \frac{\mu_s}{(1 + Q^2/M_2^2)^2}, \quad M_2 = 1.26$$



Model	$\mu_s(\mu_N)$	r_s^2(fm²)
VMD	-0.31	0.16
KA	-0.35	-0.007
NJL	-0.45	-0.17
CQS (K)	0.115	-0.095

Traditionally :

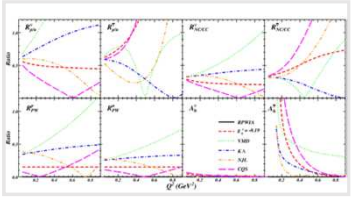
•strangeness contribution to the ***weak vector formfactors*** : Parity Violating Electron Scattering (Sample, Happex, G0, …)

Correlated !

•strangeness contribution to the ***axial current*** : neutrino scattering

vector current contributions are suppressed

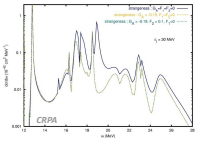
-no radiative corrections

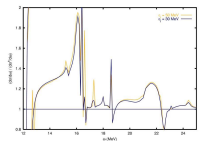


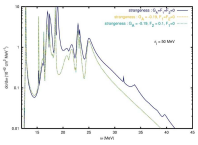
N.J., P. Vancraeyveld, P. Lava, J. Ryckebusch, PRC76, 055501 (2007).

Neutrino cross sections including strangeness

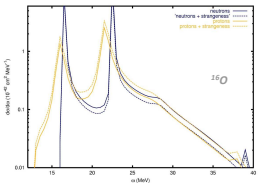
- Generally : net strangeness effect vanishes for isoscalar targets
- close to particle knockout threshold the influence becomes larger due to binding energy differences between protons and neutrons
- differential cross sections differ, energy of reaction products can be very different







proton/neutron cross sections

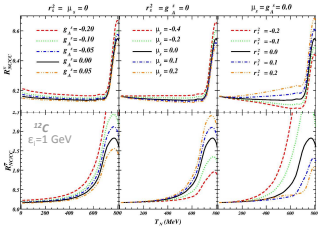


- differences up to 20%
- opposite effect for protons and neutrons

Ratio of neutral-to-charged current neutrino scattering

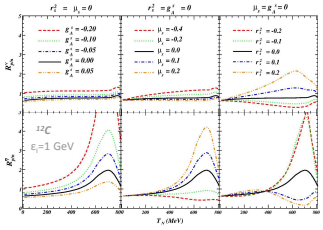
$$R_\nu = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,p)} \Big/ \left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\nu,p)}$$

$$R_{\bar\nu} = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\bar\nu,p)} \Big/ \left(\frac{d\sigma}{dT_N}\right)^{CC}_{(\bar\nu,n)}$$



Ratio of neutral current neutrino scattering off a proton/neutron

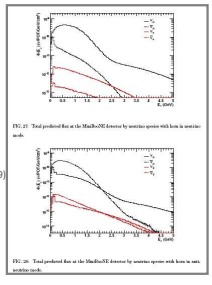
$$R_{p/n} = \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,p)} \Big/ \left(\frac{d\sigma}{dT_N}\right)^{NC}_{(\nu,n)}$$

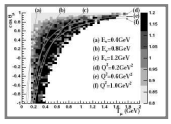


Interactions at intermediate energies

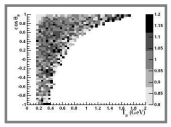
MiniBooNe Flux

Phys. Rev. D. 79, 072002 (2009)





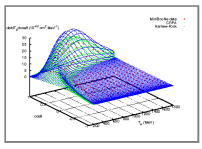
Modified Pauli-blocking



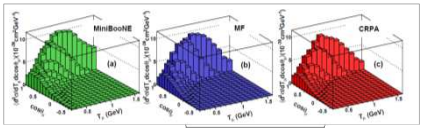
Phys. Rev. Lett. 100, 032301 (2008)

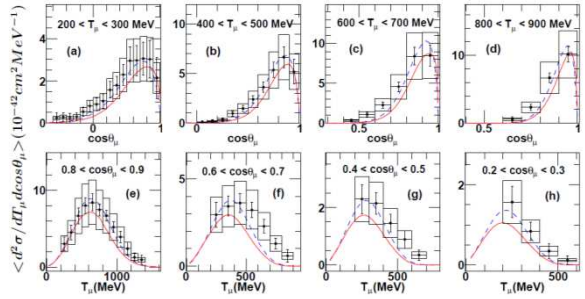
Comparison with MiniBooNe data

neutrinos

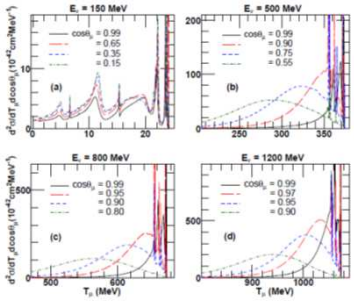


antineutrinos





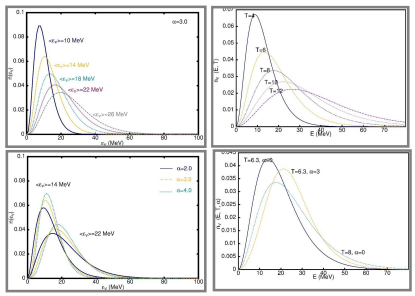
Forward scattering



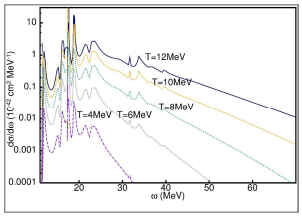
Supernova neutrinos

$$n_{SN[\langle\varepsilon\rangle,\alpha]}(\varepsilon) = \left(\frac{\varepsilon}{\langle\varepsilon\rangle}\right)^{\alpha} e^{-(\alpha+1)\frac{\varepsilon}{\langle\varepsilon\rangle}}$$

Spectra



Folded cross sections supernova neutrino spectra :



Cumulative folded cross sections: