Nuclear physics with SNS neutrinos: overview

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Motivation

Why use neutrinos from the SNS to understand nuclear structure?

- understanding of structure of nucleus, e.g. resonances, nuclear density distributions

- tests of nuclear models

- applications to other nuclei and or other energies, e.g. astrophysics, oscillations, neutrino detection

- tests of couplings (beyond standard model physics)
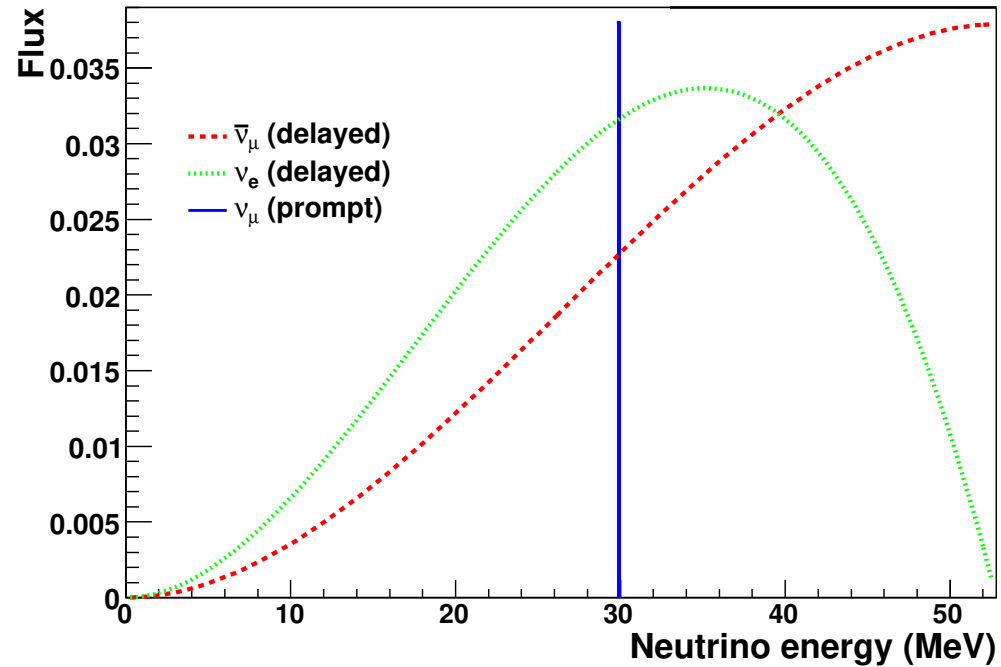
Electron neutrino spectrum from muon decay at rest

Fig. from Scholberg 2006

Energy peaks at 30 - 40 MeV or so.

Nuclear processes for which decay at rest at rest neutrinos are well suited
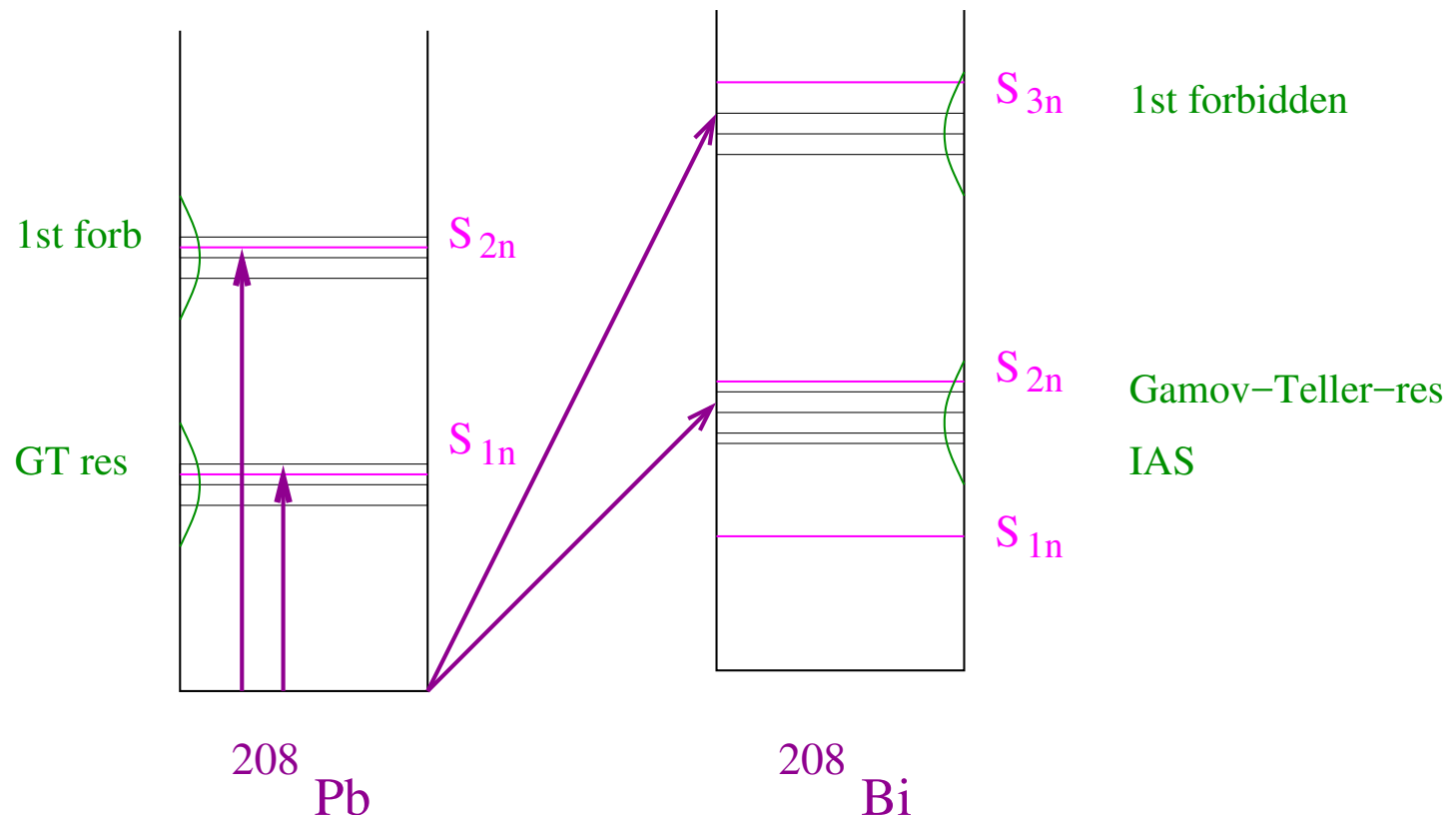
- low energy neutrino inelastic cross sections

- CEvNS

At these energies it makes sense to use low energy nuclear structure methods to describe nuclei.

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Inelastic cross sections

1st forb S_{2n} S_{3n} 1st forbidden

GT res S_{1n} S_{2n} Gamov−Teller−res

IAS

S_{1n}

^{208}Pb

^{208}Bi

Schematic of resonances in lead for ~ 40 MeV neutrinos

Neutrons come out if you are above certain thresholds.

6

Allowed transitions

Allowed weak interaction in nuclei proceeds by the isospin operator, τ , or the Gamow-Teller $\sigma \cdot \tau$ operator.
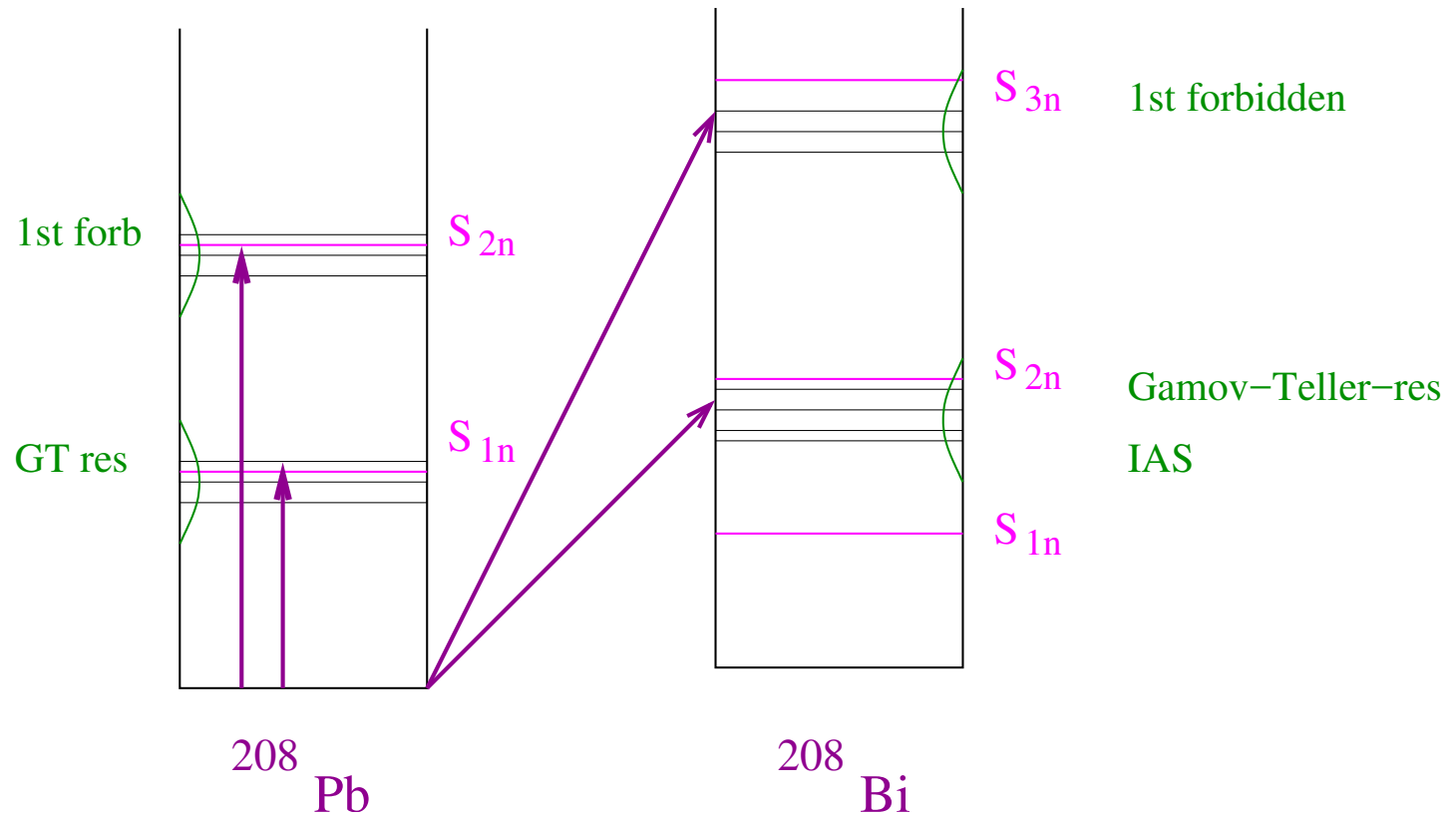
e.g. $\langle \psi_{f,nuclear} | \sigma \cdot \tau | \psi_{i,nuclear} \rangle$

looks similar to the strong force at forward angles. (p,n) reaction data tells you something about position of allowed resonances.

(p, n) doesn't tell you about g_A.

Open question: what is g_A quenching for this momentum transfer? The same as in beta decay for similar mass nuclei?

Inelastic cross sections

Schematic of resonances in lead for ~ 40 MeV neutrinos

Forbidden transitions

Relevant for neutrino nucleus inelastic scattering are the transitions that come from taking into account the ingoing and outgoing lepton wavefunctions. i.e. $\exp(q \cdot r) \approx 1 + q \cdot r + ...$, 1st forbidden includes operators that have the momentum and position dependence combined with the spin and isospin operators.
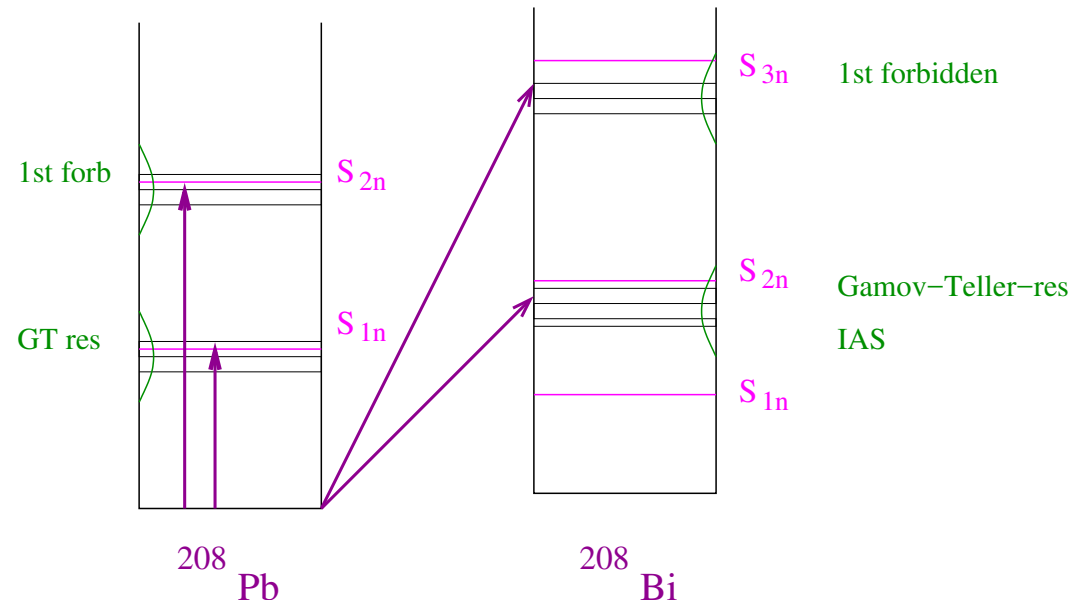
What are the positions of and transitions strengths for these nuclear states? This is needed to predict the electron spectrum, # of neutrons
What is g_A quenching for forbidden transitions? Is it the same as for allowed transitions?

Understanding the neutrino-nucleus cross sections
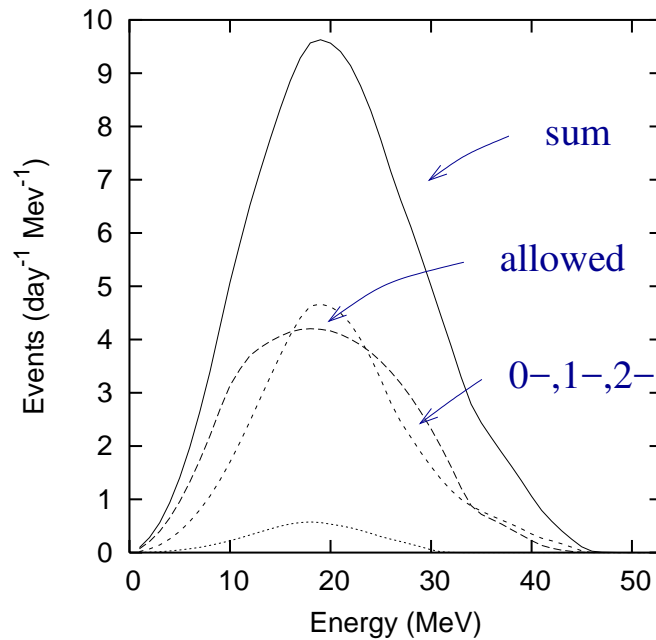
Multipole contributions to ν_e-lead scattering GM 2004

Theory would like as much information as possible from experiment, to try and reconstruct this picture. Electron energies, # of neutrons per electron
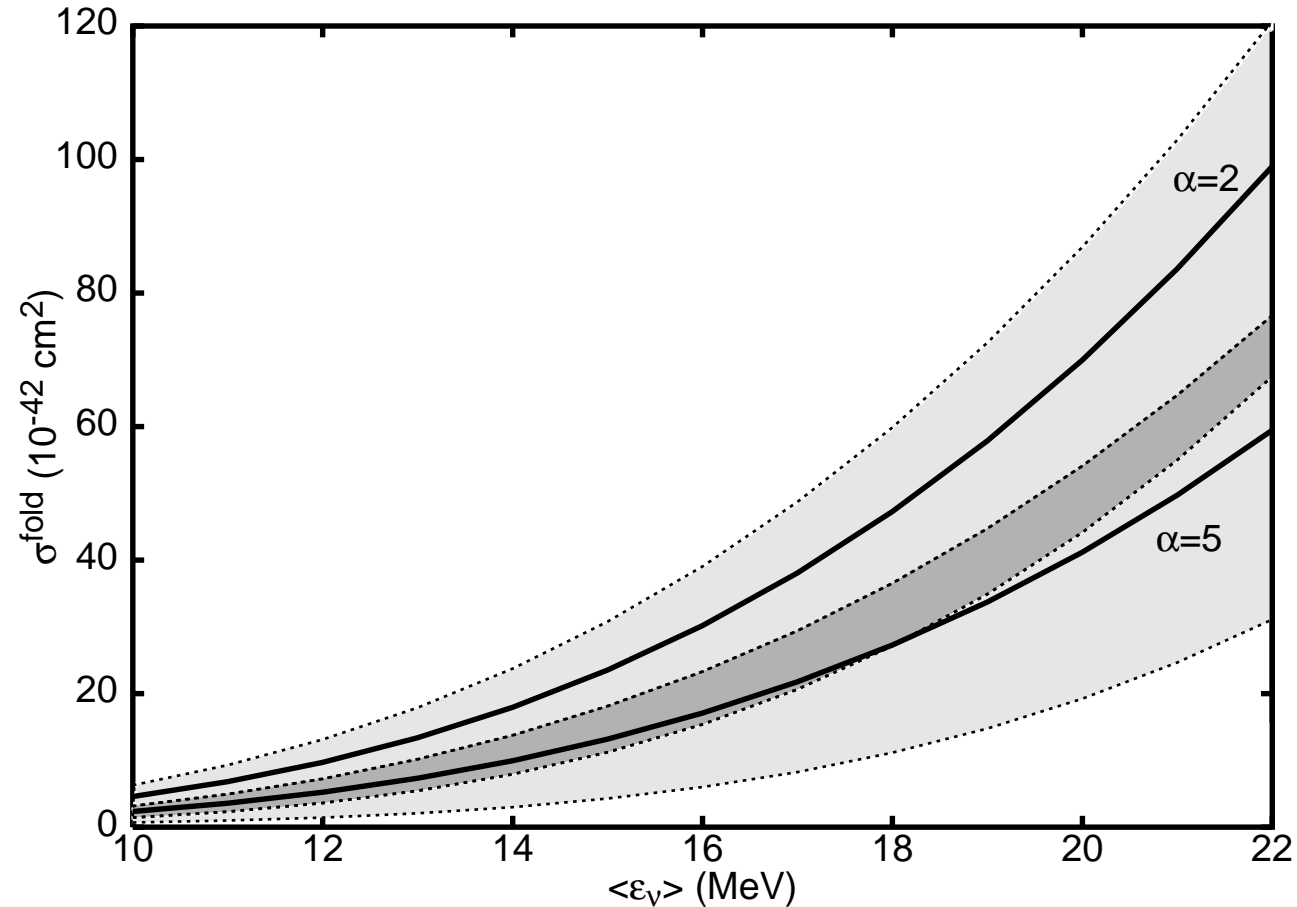
Uncertainty in SN neutrino reconstruction

Fig. from Jachowicz et al 2006

Uncertainties in lead neutral current cross section folded for various types of spectra for SN neutrinos. Measurements could reduce these uncertainties.

Measurements of inelastic cross sections help:

- determine strength distribution, e.g. where resonances lie

- normalize theory, what is g_A quenching at $\sim 100\,\mathrm{MeV}$ momentum transfer

- benchmark models for other nuclei

- applications, e.g. interpreting a future neutrino-lead SN measurement

Nuclear processes for which decay at rest at rest neutrinos are well suited

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Basic cross section

Coherent elastic neutrino nucleus scattering cross section

$$\frac{d\sigma}{dT}(E, T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E} \right)^2 - \frac{MT}{E^2} \right] \frac{Q_W^2}{4} F^2(Q^2)$$

- E : neutrino energy, T : nuclear recoil

- $Q^2 = \frac{2E^2 TM}{(E^2 - ET)}$: squared momentum transfer

- $Q_W = N - Z(1 - 4\sin^2\theta_W)$: weak charge

- F(Q^2): form factor - largest uncertainty in cross section

Assumes a spin zero nucleus, no non-standard model interactions

Comparing the recoil spectrum with theory

Fold cross section (previous slide) with incoming neutrino
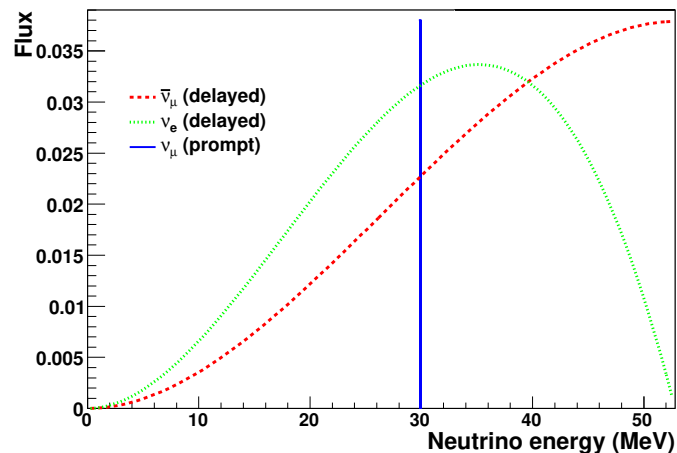spectrum (left) to find nuclear recoil spectrum (right)
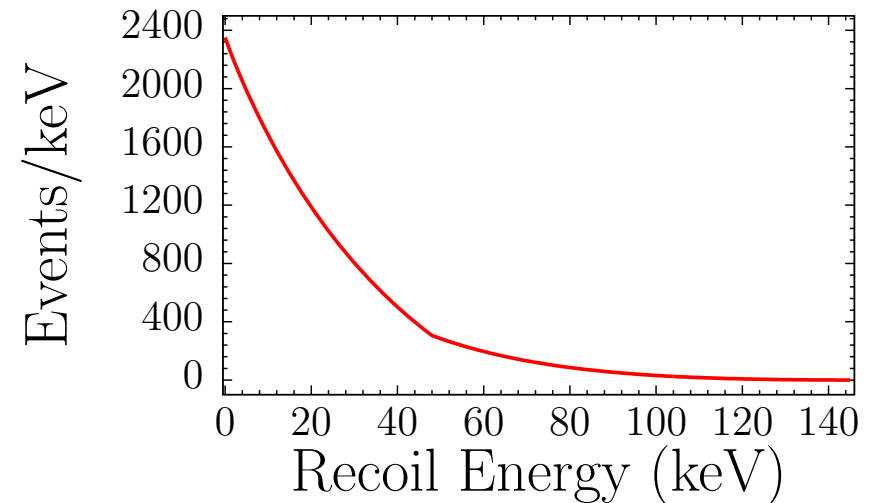

Fig. from Scholberg 2006

Fig. from Patton et al 2012

Form factor

Form factor, $F(Q^2)$ is the Fourier transform of the density distributions of protons and neutrons in the nucleus.

$$F(Q^2) = \frac{1}{Q_W} \int \left[\rho_n(r) - (1 - 4\sin^2\theta_W)\rho_p(r) \right] \frac{\sin(Qr)}{Qr} r^2 dr$$

- Proton form factor term is suppressed by $1 - 4\sin^2(\theta_W)$

- Neutron form factor is not suppressed

A form factor measurement would be complementary to PREX, CREX next talk!

Nuclear-neutron form factor from CEvNS

Taylor expand the $\sin(Qr)$ form factor:

$$
\begin{aligned}
F_n(Q^2) &= \frac{1}{Q_W} \int \rho_n(r) \frac{\sin(Qr)}{Qr} r^2 dr \\
&\approx \frac{N}{Q_W}\left(1 - \frac{Q^2}{3!}\langle R_n^2\rangle + \frac{Q^4}{5!}\langle R_n^4\rangle - ...\right)
\end{aligned}
$$

Moments of the density distribution, $\langle R_n^2\rangle$, $\langle R_n^4\rangle$ characterize the form factor. The recoil curve can then be fit to these two parameters. Directly determine the moments from experiment.

Kelly Patton's talk

17

Nuclear-neutron form factor from CνNS
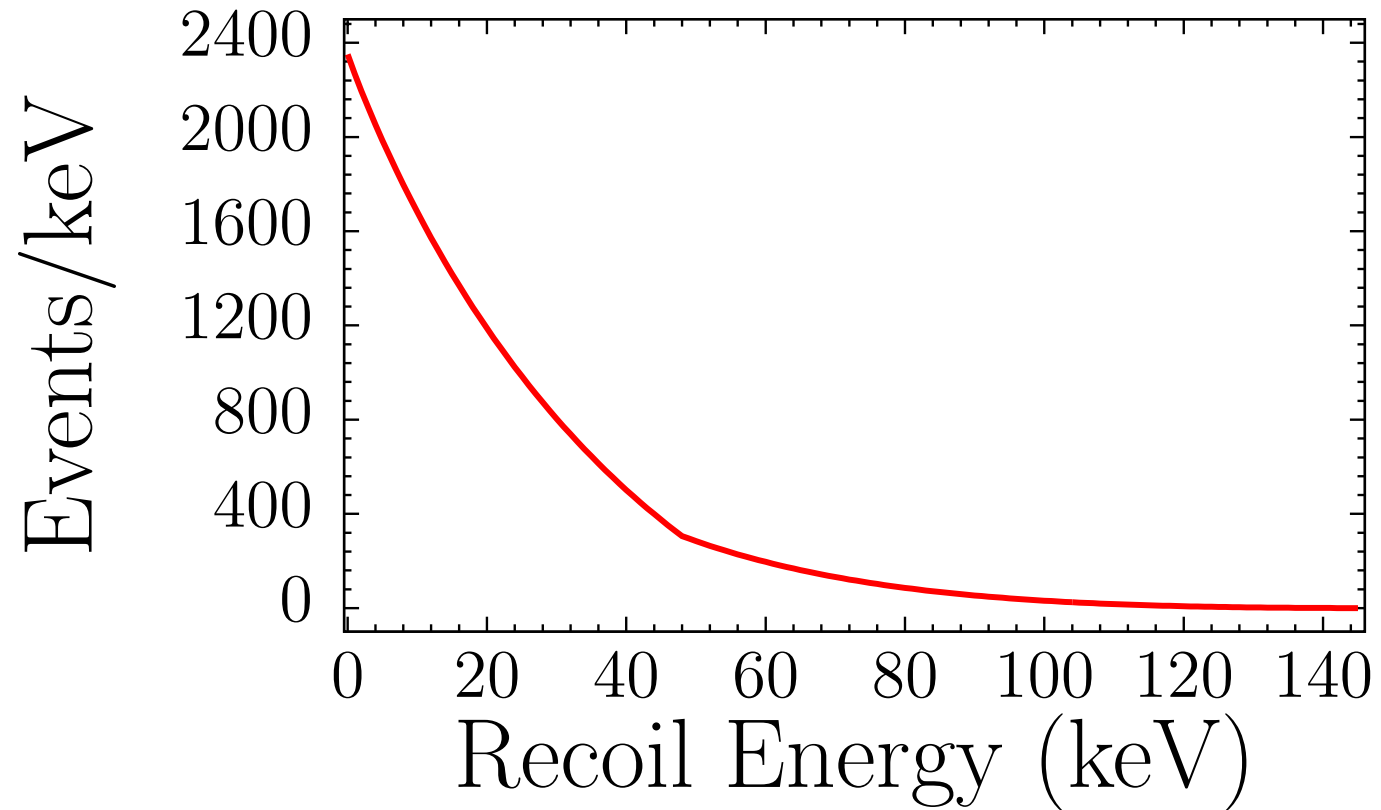
Increasing $\langle R_n^2 \rangle$ pulls the curve up at 30 keV and increasing $\langle R_n^4 \rangle$ pulls the curve down around 60 keV. Looking for a change in the shape of the curve. Kelly Patton's talk

Probing the axial vector contribution

If the nucleus has spin, axial terms in cross section

Coherent elastic neutrino nucleus scattering cross section

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi}M[(G_V + G_A)^2 + (G_V - G_A)^2(1 - \frac{2T}{E})^2$$
$$-(G_V^2 - G_A^2)\frac{MT}{E^2}]$$

$G_V \approx \frac{1}{2}NF(Q^2)$, $G_A \sim (\text{net spin})F^A(Q^2)$

Axial contribution ($\propto 1/N$) is larger for lighter nuclei. This cross section has a different shape. for more discussion see Moreno and Donnelly

Fundamental symmetries: non standard interactions

Some nonstandard interactions are currently poorly constrained. Examples are vector couplings for electron neutrinos with up and down quarks, ϵ_{ee}^{uV} and ϵ_{ee}^{dV}, although there are other couplings that contribute as well, e.g.

$$\mathcal{L}_{\nu Hadron}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} \left[\bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5)\nu_\beta\right] *$$

$$\left(\varepsilon_{\alpha\beta}^{qL}\left[\bar{q}\gamma_\mu(1-\gamma^5)q\right] + \varepsilon_{\alpha\beta}^{qR}\left[\bar{q}\gamma_\mu(1+\gamma^5)q\right]\right)$$

The vector couplings are the ones relevant for spin zero nuclei $\varepsilon_{\alpha\beta}^{qV} = \varepsilon_{\alpha\beta}^{qL} + \varepsilon_{\alpha\beta}^{qR}$.

Shifts overall recoil curve. However, other NSI will change the shape of the curve (yesterday's talks).

Conclusions

significant potential for interesting nuclear physics:

- tests of nuclear models, forces, couplings

- inelastic: g_A at ~ 100 MeV momentum transfer

- inelastic: benchmark for SN neutrino detection nuclei

- CEVNS: nuclear neutron form factor

- CEVNS: farther in future: axial form factor

- CEVNS: beyond the standard model couplings