CEνNS as a Probe of Nuclear Neutron Density Distributions

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K. M. Patton, J. Engel, G. C. McLaughlin and N. Schunck, *Phys. Rev. C* **86**, 024612 (2012).
K. M. Patton, G. C. McLaughlin and K. Scholberg, *Int. J. Mod. Phys. E* **22** 1330013 (2013).

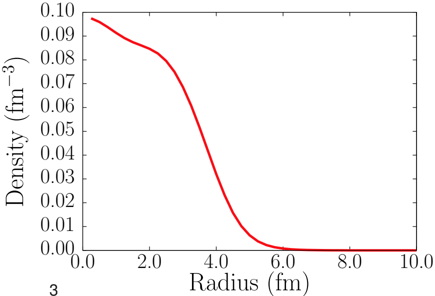
CEνNS Review

- Astrophysics applications: SN dynamics and detection
- Beyond the Standard Model physics: sterile neutrinos, neutrino magnetic moment
- Background in dark matter searches
- Many ongoing experiments working with various materials
- First measurement by COHERENT!

Understanding the Nucleus

- CEνNS can also be used to understand the nucleus
  - Largest uncertainty in cross section comes from the nuclear form factor
  - Specifically the neutrons
  - CEνNS is an alternative to other methods to measure nuclear properties
- Look for moments of density distribution

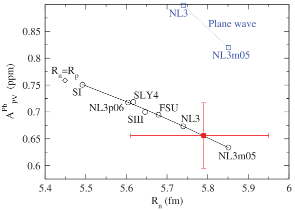
$$\langle R_n^k \rangle = \frac{\int \rho_n r^k d^3 r}{\int \rho_n d^3 r}$$



Neutron Density in the Nucleus

- Previous work used hadronic scattering to deduce the neutron RMS radius
- PREX at JLAB has measured the neutron radius in ^{208}Pb [1]

- Parity violating electron scattering
- Measure parity violating asymmetry, which is a measure of nuclear neutron form factor
- Current measurement of RMS radius has 2.5% error



- Is it possible to understand the structure of the nuclear neutron distribution using neutrino scattering?

[1] S. Abrahamyan *et al.* (PREX Collaboration), Phys. Rev. Lett. **108**, 112502 (2012)

CEνNS: Coherent Elastic Neutrino-Nucleus Scattering

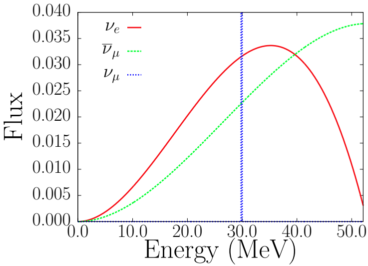
$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

- Neutrino scatters from nucleus as a whole, not individual nucleons
- $F(Q^2)$ is the form factor
  - Finite size correction, neutrino sees nucleus as more than a point particle

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

Neutrino Scattering

- Consider neutrinos from a stopped pion source
- Since scattering is low energy, use a Taylor expansion for $F(Q^2)$ around $Q = 0$



- After expansion:

$$F(Q^2) = N\left(1 - \frac{Q^2}{3!}\langle R_n^2\rangle + \frac{Q^4}{5!}\langle R_n^4\rangle - \frac{Q^6}{7!}\langle R_n^6\rangle + \cdots\right)$$

- Moments calculated or measured

Effective Moments

- Argon is almost completely ^{40}Ar
- Germanium and xenon both have several naturally occurring isotopes
- Define effective second and fourth moments using weighted sums

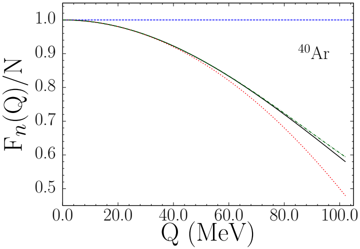
$$\langle R_n^2 \rangle_{eff}^{1/2} = \left(\frac{\sum_i N_i^2 X_i M_i \langle R^2 \rangle_{n,i}}{\sum_i N_i^2 X_i M_i} \right)^{1/2}$$

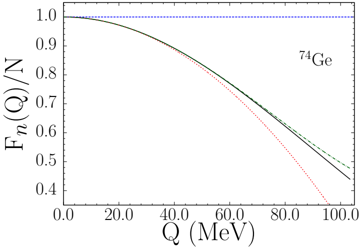
$$\langle R_n^4 \rangle_{eff}^{1/4} = \left(\frac{\sum_i N_i^2 X_i M_i^2 \langle R^4 \rangle_{n,i}}{\sum_i N_i^2 X_i M_i^2} \right)^{1/4}$$

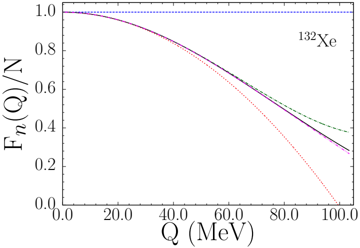
- X_i is the mass fraction of the isotope with neutron number N_i and mass M_i

Form Factors from Moments

- Black - exact form factor
- Colors show expansion with different cutoff points
- Cutoff after $\langle R_n^4 \rangle$ for ^{40}Ar and Ge, after $\langle R_n^6 \rangle$ for Xe

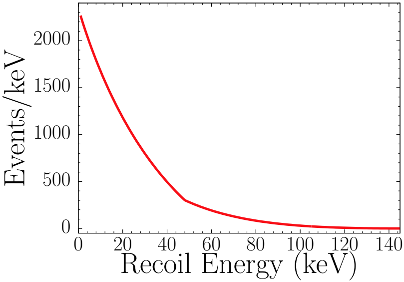






Typical Scattering Curve

$$\frac{dN}{dT}(T) = N_t C \int_{E_{min}(T)}^{m_\mu/2} f(E) \frac{d\sigma}{dT}(E,T) dE$$



- 1 tonne ^{40}Ar detector with flux 3×10^7 $\nu/(\text{cm}^2\ \text{s})$ of each flavor

Monte Carlo Basics

- Assume $L_\nu = 3 \times 10^7 \nu/(\text{cm}^2\ \text{s})$ ($\sim$ 20 m from SNS)
- Create database of scattering curves
  - Use range of $\langle R_n^2 \rangle^{(1/2)}$ and $\langle R_n^4 \rangle^{(1/4)}$ values
  - Allow luminosity (L_ν) to float
- Remove highest and lowest energy bins due to expected backgrounds
- Add random statistical error to a nuclear model scattering curve and compare to database
- Choose the values of $\langle R_n^2 \rangle^{(1/2)}$, $\langle R_n^4 \rangle^{(1/4)}$, and L_ν that give the lowest χ^2 value

Results - 3.5 tonne ^{40}Ar

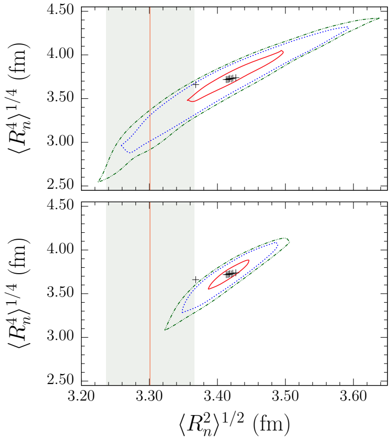


Figure from Patton *et al.*, Phys. Rev. C **86** 024612 (2012)

- Results using a 3.5 tonne detector over 1 year
- 97%, 91%, and 40% confidence levels
- Black points show Skyrme model predictions
- Colored band shows experimental result from Ozawa *et al.* [1]

[1] A. Ozawa *et al.*, Nucl. Phys. A **709**, 60 (2002)

Results

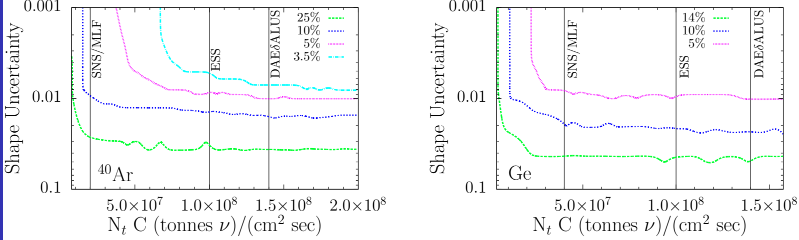
- 3.5 tonne ^{40}Ar detector
  - RMS radius to 5%
  - Fourth moment to 20%
- 1.5 tonne Ge detector
  - Effective RMS radius to 5%
  - Effective Fourth moment to 15%
- 300 kg Xe detector
  - Effective RMS radius to 4%
  - Effective Fourth moment to 7%
- With independent measures of L_ν, uncertainties reduced

How well do we need to understand the detector?

- Need to include uncertainties from detector response
- Assume energy shape uncertainty is the largest effect
  - Results from differences in understanding signal detection efficiency between energy bins
  - Caused by uncertainties on energy-dependent detector response, signal selection effects, and backgrounds as a function of energy
- Percent-level or better is challenging but not inconceivable
- Added as uncorrelated Gaussian fluctuations in each energy bin

Argon and Germanium

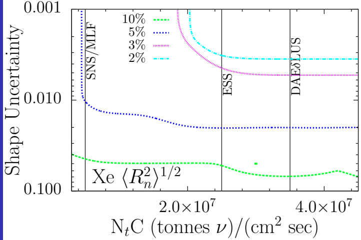
- Solid lines indicate a 2 tonne detector 20 m from the source at indicated sites for 1 year
- $\langle R_n^2 \rangle^{1/2}$ could be measured to 5% if shape uncertainty is understood to 1% level

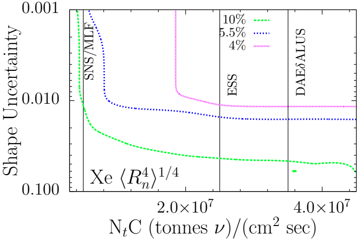


Figures from Patton, Scholberg, and McLaughlin *IJMPE* (2013)

Xenon

- Solid lines indicate a 500 kg detector 20 m from the source at indicated sites for 1 year
- Both $\langle R_n^2 \rangle^{1/2}$ (left) and $\langle R_n^4 \rangle^{1/4}$ (right) could be measured to 5% if shape uncertainty is understood to 1% level





Figures from Patton, Scholberg, and McLaughlin *IJMPE* (2013)

Conclusions

- Suggest CENNS can be used to probe the nuclear neutron form factor and the neutron density
- Characterize the form factor with effective moments ($\langle R_n^2 \rangle^{1/2}$ and $\langle R_n^4 \rangle^{1/4}$)
- Neutron RMS radius measured to a few percent with energy shape uncertainty of 1% or better
- Provides a theoretically clean way to measure the neutron density in the nucleus