Neutrino Charge Radii from Coherent Elastic $\nu$-Nucleus Scattering

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Coherent Elastic Neutrino-Nucleus Scattering

- Predicted in 1974 for $qR \lesssim 1$

\[ \frac{d\sigma}{dT}(E, T) \sim \frac{G_F^2 M}{4\pi} \left( 1 - \frac{MT}{2E^2} \right) N^2 F_N^2(q^2) \]

- Observed in 2017 in the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($N_{Cs} = 78$, $N_I = 74$) [G. Rich talk]

Several oncoming new experiments: CONUS [M. Lindner talk], CONNIE, NU-CLEUS [J. Rothe talk], MINER, Ricochet, TEXONO, $\nu$GEN
Taking into account interactions with both neutrons and protons

\[
\frac{d\sigma}{dT}(E, T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E^2}\right) \left[g_V^n N F_N(q^2) + g_V^p Z F_Z(q^2)\right]^2
\]

\[
g_V^n = -\frac{1}{2} \quad g_V^p = \frac{1}{2} - 2 \sin^2 \vartheta_W = 0.0227 \pm 0.0002
\]

The neutron contribution is dominant! \(\Rightarrow\) \[
\frac{d\sigma}{dT} \sim N^2 F_N^2(q^2)
\]

The form factors \(F_N(q^2)\) and \(F_Z(q^2)\) describe the loss of coherence for \(qR \gtrsim 1\). [see: Bednyakov, Naumov, arXiv:1806.08768]

Coherence requires very small values of the nuclear kinetic recoil energy \(T \simeq q^2/2M\):

\[
qR \lesssim 1 \quad \leftrightarrow \quad T \lesssim \frac{1}{2MR^2}
\]

\[
M \approx 100 \text{ GeV}, \quad R \approx 5 \text{ fm} \quad \Rightarrow \quad T \lesssim 10 \text{ keV}
\]
In the COHERENT experiment neutrino-nucleus scattering is not completely coherent:

Partial coherency gives information on the nuclear neutron form factor $F_N(q^2)$, which is the Fourier transform of the neutron distribution in the nucleus.

Helm form factor: \[ F_{N}^{\text{Helm}}(q^2) = 3 \frac{j_1(qR_0)}{qR_0} e^{-q^2s^2/2} \]

Spherical Bessel function of order one: \[ j_1(x) = \frac{\sin(x)}{x^2} - \frac{\cos(x)}{x} \]

Obtained from the convolution of a sphere with constant density and radius \( R_0 \) (bulk radius) and a gaussian density with standard deviation \( s \)

Rms radius: \[ R^2 = \frac{3}{5} R_0^2 + 3s^2 \]

Surface thickness: \( s \simeq 0.9 \text{ fm} \)
Helm form factor: \[ F_N^{\text{Helm}}(q^2) = 3 \frac{j_1(qR_0)}{qR_0} e^{-q^2s^2/2} \]

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The nuclear proton and neutron distributions

- The nuclear proton distribution (charge density) is probed with electromagnetic interactions.
- Most sensitive are electron-nucleus elastic scattering and muonic atom spectroscopy.
- Hadron scattering experiments give information on the nuclear neutron distribution, but their interpretation depends on the model used to describe non-perturbative strong interactions.
- More reliable are neutral current weak interaction measurements. But they are more difficult.
- Before 2017 there was only one measurement of $R_n$ with neutral-current weak interactions through parity-violating electron scattering:

$$R_n(^{208}\text{Pb}) = 5.78^{+0.16}_{-0.18}\text{ fm}$$

[PREX, PRL 108 (2012) 112502]
The rms radii of the proton distributions of $^{133}$Cs and $^{127}$I have been determined with muonic atom spectroscopy:

$$R_p^{(\mu)}(^{133}\text{Cs}) = 4.804 \text{ fm} \quad R_p^{(\mu)}(^{127}\text{I}) = 4.749 \text{ fm}$$

Fit of the COHERENT data:

$$R_n(^{133}\text{Cs}) \simeq R_n(^{127}\text{I}) = 5.5^{+0.9}_{-1.1} \text{ fm}$$

This is the first determination of $R_n$ with neutrino-nucleus scattering.

The uncertainty is large, but it can be improved in future experiments.

Relativistic mean field nuclear model:

$$R_p(^{133}\text{Cs}) = 4.79 \text{ fm} \quad R_p(^{127}\text{I}) = 4.73 \text{ fm}$$

$$R_n(^{133}\text{Cs}) = 5.01 \text{ fm} \quad R_n(^{127}\text{I}) = 4.94 \text{ fm}$$
In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

Radiative corrections generate an effective electromagnetic interaction vertex

\[ \Lambda_\mu(q) = (\gamma_\mu - q_\mu \gamma / q^2) F(q^2) \]

\[ F(q^2) = F(0) + q^2 \left. \frac{dF(q^2)}{dq^2} \right|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots \]

In the Standard Model:

\[ \langle r_{\nu_\ell}^2 \rangle_{SM} = \frac{G_F}{4\sqrt{2}\pi^2} \left[ 3 - 2 \log \left( \frac{m_\ell^2}{m_W^2} \right) \right] \]

[see the review CG, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]
Neutrino Charge Radii

► In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

► Radiative corrections generate an effective electromagnetic interaction vertex

\[ \Lambda_\mu(q) = (\gamma_\mu - q_\mu \hat{q}/q^2) F(q^2) \]

► \( F(q^2) = F(0) + q^2 \frac{dF(q^2)}{dq^2} \bigg|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots \)

► In the Standard Model:


\[ \langle r_{\nu_e}^2 \rangle_{SM} = 4.1 \times 10^{-33} \text{ cm}^2 \quad \langle r_{\nu_\mu}^2 \rangle_{SM} = 2.4 \times 10^{-33} \text{ cm}^2 \quad \langle r_{\nu_\tau}^2 \rangle_{SM} = 1.5 \times 10^{-33} \text{ cm}^2 \]

[see the review CG, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]
Experimental Bounds

<table>
<thead>
<tr>
<th>Method</th>
<th>Experiment</th>
<th>Limit $[\text{cm}^2]$</th>
<th>CL</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor $\bar{\nu}_e-e^-$</td>
<td>Krasnoyarsk</td>
<td>$</td>
<td>\langle r^2_{\nu_e} \rangle</td>
<td>&lt; 7.3 \times 10^{-32}$</td>
</tr>
<tr>
<td></td>
<td>TEXONO</td>
<td>$-4.2 \times 10^{-32} &lt; \langle r^2_{\nu_e} \rangle &lt; 6.6 \times 10^{-32}$</td>
<td>90%</td>
<td>2009</td>
</tr>
<tr>
<td>Accelerator $\nu_e-e^-$</td>
<td>LAMPF</td>
<td>$-7.12 \times 10^{-32} &lt; \langle r^2_{\nu_e} \rangle &lt; 10.88 \times 10^{-32}$</td>
<td>90%</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td>LSND</td>
<td>$-5.94 \times 10^{-32} &lt; \langle r^2_{\nu_e} \rangle &lt; 8.28 \times 10^{-32}$</td>
<td>90%</td>
<td>2001</td>
</tr>
<tr>
<td>Accelerator $\nu_\mu-e^-$</td>
<td>BNL-E734</td>
<td>$-4.22 \times 10^{-32} &lt; \langle r^2_{\nu_\mu} \rangle &lt; 0.48 \times 10^{-32}$</td>
<td>90%</td>
<td>1990</td>
</tr>
<tr>
<td></td>
<td>CHARM-II</td>
<td>$</td>
<td>\langle r^2_{\nu_\mu} \rangle</td>
<td>&lt; 1.2 \times 10^{-32}$</td>
</tr>
</tbody>
</table>

Phenomenological Bounds

- From a combined fit of $\nu_e e^-$ and $\bar{\nu}_e e^-$ data:  
  $[\text{Barranco, Miranda, Rashba, PLB 662 (2008) 431}]$
  $-0.26 \times 10^{-32} < \langle r^2_{\nu_e} \rangle < 6.64 \times 10^{-32} \text{ cm}^2$  (90% CL)

- From CHARM-II and CCFR data:  
  $[\text{Hirsch, Nardi, Restrepo, PRD 67 (2003) 033005}]$
  $-0.52 \times 10^{-32} < \langle r^2_{\nu_\mu} \rangle < 0.68 \times 10^{-32} \text{ cm}^2$  (90% CL)

[see the review CG, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]
Neutrino charge radii contributions to CEνNS $\nu_\ell + N \rightarrow \nu_\ell + N$:

$$
\frac{d\sigma_{\nu_\ell-N}}{dT}(E, T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E^2}\right) \left\{ g_V^n N F_N(q^2) \right. \\
+ \left( g_V^p - \frac{2}{3} m_W^2 \sin^2 \vartheta_W \langle r_{\nu_\ell}^2 \rangle_{ee} \right) Z F_Z(q^2) \bigg] \right. \\
+ \frac{4}{9} m_W^4 \sin^4 \vartheta_W Z^2 F_Z^2(q^2) \sum_{\ell' \neq \ell} |\langle r_{\nu_\ell}^2 \rangle_{\ell'\ell}|^2 \bigg\} 
$$

In the Standard Model there are only diagonal charge radii $\langle r_{\nu_\ell}^2 \rangle \equiv \langle r_{\nu_\ell}^2 \rangle_{ee}$ because lepton numbers are conserved.

Since $g_V^p = \frac{1}{2} - 2 \sin^2 \vartheta_W$, diagonal charge radii generate the coherent shifts

$$
\sin^2 \vartheta_W \rightarrow \sin^2 \vartheta_W \left(1 + \frac{1}{3} m_W^2 \langle r_{\nu_\ell}^2 \rangle\right)
$$

In general, the neutrino charge radius matrix $\langle r_{\nu_\ell}^2 \rangle$ can be non-diagonal and the transition charge radii generate the incoherent contribution

$$
\frac{4}{9} m_W^4 \sin^4 \vartheta_W Z^2 F_Z^2(q^2) \sum_{\ell' \neq \ell} |\langle r_{\nu_\ell}^2 \rangle_{\ell'\ell}|^2 \iff \nu_\ell + N \rightarrow \nu_{\ell'} \neq \ell + N
$$

Neutrinos at the Oak Ridge Spallation Neutron Source are produced by a pulsed proton beam striking a mercury target.

- Prompt monochromatic $\nu_\mu$ from stopped pion decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\frac{dN_{\nu_\mu}}{dE} = \eta \delta \left( E - \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \right)$$

- Delayed $\bar{\nu}_\mu$ and $\nu_e$ from the subsequent muon decays:

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\frac{dN_{\bar{\nu}_\mu}}{dE} = \eta \frac{64E^2}{m_\mu^3} \left( \frac{3}{4} - \frac{E}{m_\mu} \right)$$

$$\frac{dN_{\nu_e}}{dE} = \eta \frac{192E^2}{m_\mu^3} \left( \frac{1}{2} - \frac{E}{m_\mu} \right)$$

- The spectrum is especially sensitive to the difference of the properties of $\nu_\mu$ and those of $\bar{\nu}_\mu$ and $\nu_e$.

- Note that $\langle r_{\nu}^2 \rangle_{\ell \ell'} = -\langle r_{\bar{\nu}}^2 \rangle_{\ell \ell'}$. 
Fit without transition charge radii

[Cadeddu, CG, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, in preparation]

Time-integrated COHERENT data

▶ Fixed neutron distribution radii:

\[ R_n(^{133}\text{Cs}) = 5.01 \text{ fm} \quad R_n(^{127}\text{I}) = 4.94 \text{ fm} \]

\[ \chi^2_{\text{min}} = 2.7 \quad \text{NDF} = 10 \quad \text{GoF} = 99\% \]

Marginal 90\% CL bounds \([10^{-32} \text{ cm}^2]\):

\[ -69 < \langle r^2_{\nu_e} \rangle < 19 \quad -15 < \langle r^2_{\nu_\mu} \rangle < 21 \]

▶ Free neutron distribution radii:

\[ \chi^2_{\text{min}} = 2.5 \quad \text{NDF} = 8 \quad \text{GoF} = 96\% \]

Marginal 90\% CL bounds \([10^{-32} \text{ cm}^2]\):

\[ -69 < \langle r^2_{\nu_e} \rangle < 40 \quad -33 < \langle r^2_{\nu_\mu} \rangle < 38 \]
Fit with transition charge radii

[Caiceddu, CG, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, in preparation]

Time-integrated COHERENT data

- Fixed neutron distribution radii:
  \[ R_{n}(^{133}\text{Cs}) = 5.01 \text{ fm} \quad R_{n}(^{127}\text{I}) = 4.94 \text{ fm} \]
  \[ \chi^2_{\text{min}} = 2.6 \quad \text{NDF} = 7 \quad \text{GoF} = 92\% \]
  Marginal 90\% CL bounds [10^{-32} \text{ cm}^2]:
  \[ -69 < \langle r_{\nu_e}^2 \rangle < 19 \quad -15 < \langle r_{\nu_\mu}^2 \rangle < 22 \]
  \[ |\langle r_{\nu_e}^2 \rangle_{e\mu}| < 25 \quad |\langle r_{\nu_e}^2 \rangle_{e\tau}| < 44 \quad |\langle r_{\nu_\mu}^2 \rangle_{\mu\tau}| < 31 \]

- Free neutron distribution radii:
  \[ \chi^2_{\text{min}} = 2.5 \quad \text{NDF} = 5 \quad \text{GoF} = 77\% \]
  Marginal 90\% CL bounds [10^{-32} \text{ cm}^2]:
  \[ -69 < \langle r_{\nu_e}^2 \rangle < 40 \quad -33 < \langle r_{\nu_\mu}^2 \rangle < 38 \]
  \[ |\langle r_{\nu_e}^2 \rangle_{e\mu}| < 29 \quad |\langle r_{\nu_e}^2 \rangle_{e\tau}| < 49 \quad |\langle r_{\nu_\mu}^2 \rangle_{\mu\tau}| < 35 \]
**COHERENT Time Distribution**

- Prompt monochromatic $\nu_\mu$ from stopped pion decays:
  $$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- Delayed $\bar{\nu}_\mu$ and $\nu_e$ from the subsequent muon decays:
  $$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

The time distribution of the data increases the information on the difference between the properties of $\nu_\mu$ and those of $\bar{\nu}_\mu$ and $\nu_e$. 
Fit of Time-dependent COHERENT data

[Cadeddu, CG, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, in preparation]

Fixed neutron distribution radii:

\[ R_n^{(^{133}\text{Cs})} = 5.01 \text{ fm} \quad R_n^{(^{127}\text{I})} = 4.94 \text{ fm} \]

\[ \chi^2_{\text{min}} = 154.2 \quad \text{NDF} = 139 \quad \text{GoF} = 18\% \]

Marginal 90\% CL bounds [\(10^{-32} \text{ cm}^2\)]:

\[ -63 < \langle r_{\nu_e}^2 \rangle < 12 \quad -7 < \langle r_{\nu_{\mu}}^2 \rangle < 9 \]

\[ |\langle r_{\nu_e}^2 \rangle_{e\mu}| < 22 \quad |\langle r_{\nu_e}^2 \rangle_{e\tau}| < 37 \quad |\langle r_{\nu_{\mu}}^2 \rangle_{\mu\tau}| < 26 \]

Free neutron distribution radii:

\[ \chi^2_{\text{min}} = 153.7 \quad \text{NDF} = 137 \quad \text{GoF} = 16\% \]

Marginal 90\% CL bounds [\(10^{-32} \text{ cm}^2\)]:

\[ -61 < \langle r_{\nu_e}^2 \rangle < 16 \quad -11 < \langle r_{\nu_{\mu}}^2 \rangle < 23 \]

\[ |\langle r_{\nu_e}^2 \rangle_{e\mu}| < 26 \quad |\langle r_{\nu_e}^2 \rangle_{e\tau}| < 40 \quad |\langle r_{\nu_{\mu}}^2 \rangle_{\mu\tau}| < 30 \]
Conclusions

▶ The observation of CEνNS in the COHERENT experiment opened the way for new powerful measurements of the properties of nuclei and neutrinos.

▶ First determination of $R_n$ with $\nu$-nucleus scattering:

$$R_n^{(^{133}\text{Cs})} \simeq R_n^{(^{127}\text{I})} = 5.5^{+0.9}_{-1.1} \text{ fm}$$

▶ The time-dependent spectral data of the COHERENT experiment constrain (at 90% CL with a free average neutron distribution radius)

$$-61 < \langle r^2_{\nu e} \rangle < 16 \quad -11 < \langle r^2_{\nu \mu} \rangle < 23 \quad (90\% \text{ CL})$$

▶ First constraints on transition charge radii:

$$|\langle r^2_{\nu} \rangle_{e\mu}| < 26 \quad |\langle r^2_{\nu} \rangle_{e\tau}| < 40 \quad |\langle r^2_{\nu} \rangle_{\mu\tau}| < 30 \quad (90\% \text{ CL})$$

▶ An improvement of about 1 order of magnitude is necessary to be competitive with the current limits of the order of few $\times$ $10^{-32}$ cm$^2$.

▶ An improvement of about 2 orders of magnitude is necessary to reach the Standard Model values

$$\langle r^2_{\nu e} \rangle_{\text{SM}} = 4.1 \times 10^{-33} \text{ cm}^2 \quad \langle r^2_{\nu \mu} \rangle_{\text{SM}} = 2.4 \times 10^{-33} \text{ cm}^2$$

▶ The new CEνNS experiments may allow to approach these values.