Harvesting the Data of the COHERENT Experiment

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WIN 2019
XXVII International Workshop on Weak Interactions and Neutrinos
3-8 June 2019, Bari, Italy
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Based on:

- Cadeddu, Dordei, Reinterpreting the weak mixing angle from atomic parity violation in view of the Cs neutron rms radius measurement from COHERENT, PRD 99 (2019) 033010, arXiv:1808.10202
Coherent Elastic Neutrino-Nucleus Scattering

- Predicted in 1974 for $|\vec{q}| R \lesssim 1$ [Freedman, PRD 9 (1974) 1389]

$$\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2 M}{4\pi} \left( 1 - \frac{MT}{2E^2_\nu} \right) N^2 F_N^2(|\vec{q}|^2)$$ [Drukier, Stodolski, PRD (1984) 2295]

- Observed in 2017 in the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($N_{Cs} = 78$, $N_I = 74$) [Science 357 (2017) 1123, arXiv:1708.01294]

- Several oncoming new experiments: CONUS, CONNIE, NU-CLEUS, MINER, Ricochet, TEXONO, $\nu$GEN

C. Giunti — Neutrino and Nuclear Properties from CE$\nu$NS — Bari — 4 June 2019 — 3/18
Taking into account interactions with both neutrons and protons

\[
\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left( 1 - \frac{MT}{2E_\nu^2} \right) \left[ g^p_N NF_N(|\vec{q}|^2) + g'^p_Z F_Z(|\vec{q}|^2) \right]^2
\]

\[
g^p_N = -\frac{1}{2} \quad \quad g'^p_Z = \frac{1}{2} - 2\sin^2\theta_W = 0.0227 \pm 0.0002
\]

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

The form factors \(F_N(|\vec{q}|^2)\) and \(F_Z(|\vec{q}|^2)\) describe the loss of coherence for \(|\vec{q}| R \gtrsim 1\).

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

\[
|\vec{q}| R \lesssim 1 \quad \iff \quad T \lesssim \frac{1}{2MR^2}
\]

\(M \approx 100\ \text{GeV}, \quad R \approx 5\ \text{fm} \quad \Rightarrow \quad T \lesssim 10\ \text{keV}\)
The COHERENT Experiment

Oak Ridge Spallation Neutron Source

PROTON BEAM
CsI
d = 28.4m
d = 21.1m
d = 19.3m
Hg TARGET
NaI
NIN Cubes
SHIELDING MONOLITH
CENNS-10
(LAr)
CONCRETE AND GRAVEL
MARSGe ARRAY

14.6 kg CsI
scintillating crystal

[COHERENT, arXiv:1803.09183]
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:

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

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

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

The COHERENT energy and time information allow us to distinguish the interactions of $\nu_e$, $\nu_\mu$, and $\bar{\nu}_\mu$. 

![Neutrino Spectra](image_url)

![Neutrino Decays](image_url)

![Neutrino Interaction](image_url)
In the COHERENT experiment neutrino-nucleus scattering is not completely coherent:

\[ T \text{[keV]} \]
\[ \text{counts / 1.71 keV} \]

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

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 $^{133}\text{Cs}$ and $^{127}\text{I}$ have been determined with muonic atom spectroscopy: [Fricke et al, ADNDT 60 (1995) 177]

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

Fit of the COHERENT data to get $R_n(^{133}\text{Cs}) \simeq R_n(^{127}\text{I})$:

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


- This is the first determination of \( R_n \) with neutrino-nucleus scattering.
- The uncertainty is large, but it can be improved in future experiments.
- Predictions of nonrelativistic Skyrme-Hartree-Fock (SHF) and relativistic mean field (RMF) nuclear models:

<table>
<thead>
<tr>
<th></th>
<th>( ^{133}\text{Cs} )</th>
<th></th>
<th>( ^{127}\text{I} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R_p )</td>
<td>( R_n )</td>
<td>( R_p )</td>
</tr>
<tr>
<td>SHF SkM*</td>
<td>4.76</td>
<td>4.90</td>
<td>4.71</td>
</tr>
<tr>
<td>SHF SkP</td>
<td>4.79</td>
<td>4.91</td>
<td>4.72</td>
</tr>
<tr>
<td>SHF SkI4</td>
<td>4.73</td>
<td>4.88</td>
<td>4.67</td>
</tr>
<tr>
<td>SHF Sly4</td>
<td>4.78</td>
<td>4.90</td>
<td>4.71</td>
</tr>
<tr>
<td>SHF UNEDF1</td>
<td>4.76</td>
<td>4.90</td>
<td>4.68</td>
</tr>
<tr>
<td>RMF NL-SH</td>
<td>4.74</td>
<td>4.93</td>
<td>4.68</td>
</tr>
<tr>
<td>RMF NL3</td>
<td>4.75</td>
<td>4.95</td>
<td>4.69</td>
</tr>
<tr>
<td>RMF NL-Z2</td>
<td>4.79</td>
<td>5.01</td>
<td>4.73</td>
</tr>
<tr>
<td>Exp. (( \mu )-atom spect.)</td>
<td>4.804</td>
<td></td>
<td>4.749</td>
</tr>
</tbody>
</table>
Weak Mixing Angle from Atomic Parity Violation

\[ Q_W \simeq q_p Z \left( 1 - 4 \sin^2 \vartheta_W \right) - q_n N \]

COHERENT + APV \[ \Rightarrow \left\{ \begin{array}{l}
R_n = 5.42 \pm 0.31 \text{ fm} \\
\Delta R_{np} = 0.62 \pm 0.31 \text{ fm} \quad \text{neutron skin}
\end{array} \right. \]

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Electromagnetic Interactions

- Effective Hamiltonian: \[ \mathcal{H}_{\text{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x)A^\mu(x) = \sum_{k,j=1}^{\nu_j} \nu_k(x)\Lambda_{kj}^{\nu_j} \nu_j(x)A^\mu(x) \]

- Effective electromagnetic vertex:
  \[ \langle \nu_f(p_f) | j_\mu^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u}_f(p_f)\Lambda_i^f(q)u_i(p_i) \]
  \[ q = p_i - p_f \]

- Vertex function:
  \[ \Lambda_\mu(q) = \left( \gamma_\mu - q_\mu q/q^2 \right) \left[ F_Q(q^2) + F_A(q^2)q^2\gamma_5 \right] - i\sigma_{\mu\nu}q^\nu \left[ F_M(q^2) + iF_E(q^2)\gamma_5 \right] \]

Lorentz-invariant form factors:
- Charge
- Anapole
- Magnetic
- Electric

\[ q^2 = 0 \implies Q_1, a, \mu, \varepsilon \]
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

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

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

In the Standard Model:

\[
\langle r^2 \rangle_{\nu e}^{SM} = -8.2 \times 10^{-33} \text{ cm}^2
\]
\[
\langle r^2 \rangle_{\nu \mu}^{SM} = -4.8 \times 10^{-33} \text{ cm}^2
\]
\[
\langle r^2 \rangle_{\nu \tau}^{SM} = -3.0 \times 10^{-33} \text{ cm}^2
\]
## Experimental Bounds

<table>
<thead>
<tr>
<th>Method</th>
<th>Experiment</th>
<th>Limit $[cm^2]$</th>
<th>CL</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor $\bar{\nu}_e e^-$</td>
<td>Krasnoyarsk</td>
<td>$</td>
<td>\langle r_{\bar{\nu}_e}^2 \rangle</td>
<td>&lt; 7.3 \times 10^{-32}$</td>
</tr>
<tr>
<td></td>
<td>TEXONO</td>
<td>$-4.2 \times 10^{-32} &lt; \langle r_{\bar{\nu}_e}^2 \rangle &lt; 6.6 \times 10^{-32}$</td>
<td>90%</td>
<td>2009</td>
</tr>
<tr>
<td>Accelerator $\nu_e e^-$</td>
<td>LAMPF</td>
<td>$-7.12 \times 10^{-32} &lt; \langle r_{\nu_e}^2 \rangle &lt; 10.88 \times 10^{-32}$</td>
<td>90%</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td>LSND</td>
<td>$-5.94 \times 10^{-32} &lt; \langle r_{\nu_e}^2 \rangle &lt; 8.28 \times 10^{-32}$</td>
<td>90%</td>
<td>2001</td>
</tr>
<tr>
<td>Accelerator $\nu_\mu e^-$</td>
<td>BNL-E734</td>
<td>$-5.7 \times 10^{-32} &lt; \langle r_{\nu_\mu}^2 \rangle &lt; 1.1 \times 10^{-32}$</td>
<td>90%</td>
<td>1990</td>
</tr>
<tr>
<td></td>
<td>CHARM-II</td>
<td>$</td>
<td>\langle r_{\nu_\mu}^2 \rangle</td>
<td>&lt; 1.2 \times 10^{-32}$</td>
</tr>
</tbody>
</table>

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344
Neutrino charge radii contributions to $\nu_\ell - N$ CE$\nu$NS:

$$
\frac{d\sigma_{\nu_\ell - N}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left( 1 - \frac{MT}{2E^2_\nu} \right) \left\{ g^n_V N\bar{F}_N(|\vec{q}|^2) 
+ \left( \frac{1}{2} - 2 \sin^2 \vartheta_W - \frac{2}{3} m_W^2 \sin^2 \vartheta_W \langle r^2_{\nu_\ell \ell} \rangle \right) ZF_Z(|\vec{q}|^2) \right\}^2 
+ \frac{4}{9} m_W^4 \sin^4 \vartheta_W Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} |\langle r^2_{\nu_{\ell' \ell}} \rangle|^2
$$

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

Diagonal charge radii generate the coherent shifts

$$
\sin^2 \vartheta_W \rightarrow \sin^2 \vartheta_W \left( 1 + \frac{1}{3} m_W^2 \langle r^2_{\nu_\ell} \rangle \right) \quad \iff \quad \nu_\ell + N \rightarrow \nu_\ell + N
$$

Transition charge radii generate the incoherent contribution

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

Fit of COHERENT data


Fixed neutron distribution radii (RMF NL-Z2):
\[ R_n^{(133\text{Cs})} = 5.01 \text{ fm} \quad R_n^{(127\text{I})} = 4.94 \text{ fm} \]
\[ \chi^2_{\text{min}} = 154.2 \quad \text{NDF} = 139 \quad \text{GoF} = 18\% \]
Marginal 90\% CL bounds \([10^{-32} \text{ cm}^2]\):
\[ -63 < \langle r^2_{\nu_e} \rangle < 12 \quad -7 < \langle r^2_{\nu_\mu} \rangle < 9 \]
\[ |\langle r^2_{\nu_{e\mu}} \rangle| < 22 \quad |\langle r^2_{\nu_{e\tau}} \rangle| < 37 \quad |\langle r^2_{\nu_{\mu\tau}} \rangle| < 26 \]

Free neutron distribution radii:
\[ \chi^2_{\text{min}} = 154.2 \quad \text{NDF} = 137 \quad \text{GoF} = 15\% \]
Marginal 90\% CL bounds \([10^{-32} \text{ cm}^2]\):
\[ -63 < \langle r^2_{\nu_e} \rangle < 12 \quad -8 < \langle r^2_{\nu_\mu} \rangle < 11 \]
\[ |\langle r^2_{\nu_{e\mu}} \rangle| < 22 \quad |\langle r^2_{\nu_{e\tau}} \rangle| < 38 \quad |\langle r^2_{\nu_{\mu\tau}} \rangle| < 27 \]

The COHERENT energy and time information allow us to distinguish the charge radii of \(\nu_e\) and \(\nu_\mu\).
Conclusions

- The observation of CE$\nu$NS in the COHERENT experiment opened the way for new powerful measurements of the properties of nuclei and neutrinos.

- We obtained the first determination of $R_n$ with $\nu$-nucleus scattering.

- We constrained the neutrino charge radii and obtained the first constraints on the transition charge radii.

- An improvement of about 1 order of magnitude is necessary to be competitive with the current limits on $\langle r^2_{\nu_e} \rangle$ and $\langle r^2_{\nu_\mu} \rangle$.

- An improvement of about 2 orders of magnitude is necessary to reach the Standard Model values of $\langle r^2_{\nu_e} \rangle$ and $\langle r^2_{\nu_\mu} \rangle$.

- The new CE$\nu$NS experiments may allow to approach this goal.
Backup Slides
Cross Section

\[ \sigma(E) \text{ [cm}^2] \]

\[ E \text{ [MeV]} \]

\[ \begin{align*}
\text{CEvNS} \\
^{133}\text{Cs}: & \; F_N(q^2) = F_Z(q^2) = 1 \\
^{133}\text{Cs}: & \; F_N(q^2), \; F_Z(q^2) \\
^{127}\text{I}: & \; F_N(q^2) = F_Z(q^2) = 1 \\
^{127}\text{I}: & \; F_N(q^2), \; F_Z(q^2)
\end{align*} \]

[COHERENT, arXiv:1803.09183]
Helm form factor: \[ F_N^{\text{Helm}}(|\vec{q}|^2) = 3 \frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0} e^{-|\vec{q}|^2s^2/2} \]

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 with radius \( R_0 \) and a gaussian density with standard deviation \( s \)

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

Surface thickness: \[ s \approx 0.9 \text{ fm} \]
Helm form factor: 

$$F_N^{\text{Helm}}(|\vec{q}|^2) = 3 \frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0} e^{-|\vec{q}|^2 s^2/2}$$

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 with radius $R_0$ and a gaussian density with standard deviation $s$

Rms radius: 

$$R^2 = \langle r^2 \rangle = \frac{3}{5} R_0^2 + 3s^2$$

Surface thickness: 

$$s \approx 0.9 \text{ fm}$$
The Electromagnetic Vertex Function is given by:

\[ \Lambda_{\mu}(q) = \left( \gamma_{\mu} - q_{\mu} \frac{q}{q^2} \right) \left[ F_Q(q^2) + F_A(q^2)q^2 \gamma_5 \right] - i\sigma_{\mu\nu}q^\nu \left[ F_M(q^2) + iF_E(q^2)\gamma_5 \right] \]

**Lorentz-invariant form factors:**
- Charge: \( F_Q \)
- Anapole: \( F_A \)
- Magnetic: \( F_M \)
- Electric: \( F_E \)

\[ q^2 = 0 \implies \quad \Phi \quad a \quad \mu \quad \varepsilon \]

**Hermitian form factors:**
- Charge: \( F_Q = F_Q^\dagger \)
- Anapole: \( F_A = F_A^\dagger \)
- Magnetic: \( F_M = F_M^\dagger \)
- Electric: \( F_E = F_E^\dagger \)

**Majorana neutrinos:**
- Charge: \( F_Q = -F_Q^T \)
- Anapole: \( F_A = F_A^T \)
- Magnetic: \( F_M = -F_M^T \)
- Electric: \( F_E = -F_E^T \)

These factors conserve no diagonal charges and electric and magnetic moments.

**For ultrarelativistic neutrinos:**
- \( \gamma_5 \to -1 \implies The phenomenology of the charge and anapole moments are similar and the phenomenology of the magnetic and electric moments are similar.

**For ultrarelativistic neutrinos:**
- The charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.