Coherent neutrino scattering and quenching factor measurement

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Outline

• Introduction to CEvNS

• Measurement of Ge quenching factor

• CEvNS from reactor antineutrinos

• Summary
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• Dark matter direct detection
• Coherent Elastic $\nu$-Nucleus Scattering (CE$\nu$NS )

Moment transfer $q = \sqrt{2ME_R} \lesssim 1/R$  
Nuclear radius

Nuclear recoil energy $E_R \leq \frac{2E_\nu^2}{M+2E_\nu} \sim O(1)$ keV  
for $E_\nu < 50$ MeV

DM direct detection experiments  
detection thresholds of $O(1)$ keV
CEνNS experiments

• πDAR source @ SNS

COHERENT first observed CEνNS in 2017 at the 6.7σ CL with a CsI detector

COHERENT, Science 357,1123 (2017)

Later confirmed in 2020 at more than 3σ CL with Ar detector

COHERENT, PRL 126, 012002 (2021)

• Reactor antineutrino source

CONNIE uses a Si detector with 0.1 keV$_{ee}$ threshold

CONNIE, PRD 100, 092005 (2019)

CONUS uses a Ge detector with 0.3 keV$_{ee}$ threshold

CONNIE, PRL 126, 041804 (2021)

NCC-1701 uses a Ge detector with 0.2 keV$_{ee}$ threshold

Colaresi at al., PRD 104, 072003 (2021) [2108.02880]
Colaresi at al., arXiv: 2202.09672
Jiajun Liao

CEvNS spectrum

• Differential cross section

\[
\frac{d\sigma_{SM}}{dE_R} = \frac{G_F^2 M}{4\pi} q_W^2 \left( 1 - \frac{M E_R}{2 E_\nu^2} \right) F^2(q)
\]

• Event spectrum

\[
\frac{dR}{dE_R} = N_T \int \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu
\]

Only a small portion of nuclear recoiling energy \( E_R \) will go into electronic ionization energy \( E_I \), which is measured.

Quenching factor (QF):

\[ Q \equiv \frac{E_I}{E_R} \]

Measured number of events:

\[
N_i = t \int_{E_I^i}^{E_I^{i+1}} \eta \frac{dR}{dE_R} \left( \frac{1}{Q} - \frac{E_I}{Q} \frac{dQ}{dE_I} \right) dE_I
\]
Lindhard Model


\[ Q(E_R) = \frac{k \, g(\epsilon)}{1 + k \, g(\epsilon)} , \]

where \( g(\epsilon) = 3 \, \epsilon^{0.15} + 0.7 \, \epsilon^{0.6} + \epsilon \)

Dimensionless reduced energy

\[ \epsilon = 11.5Z^{-\frac{7}{3}} \left( \frac{E_R}{\text{keV}_{nr}} \right) \]

The slope of electronic stopping power

\[ k = 0.1333Z^{\frac{2}{3}} \, A^{-\frac{1}{2}} \]

a larger \( k \) value leads to larger fraction of total energy going into electron.

Key approximations:

- The atomic binding energy of electrons is negligible.
- Energy transfers to electrons are small relative to energy transfers to atoms.

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The new dataset may be explained by the Lindhard model supplemented with the Migdal effect. 

Modified Lindhard Model

\[ Q(E_R) = \frac{k g(\epsilon)}{1 + k g(\epsilon)} - \frac{q}{\epsilon} \]

- A small \( q \) value has no significant effect at the large recoil energy region.
- A positive \( q \) value allows a sharp cutoff in the energy given to electrons.
- A negative \( q \) value allows an enhancement in the energy given to electrons.


New Physics in CEvNS

• A light vector $Z'$

\[
\frac{d\sigma_{SM+Z'}}{dE_R} = \left(1 - \frac{q_{Z'}}{q_W}\right)^2 \frac{d\sigma_{SM}}{dE_R}
\]

\[q_{Z'} = \frac{3\sqrt{2} (N + Z) g'{}^2}{G_F (2ME_R + M_{Z'}^2)}\]

• A light scalar $\phi$

\[
\frac{d\sigma_{SM+\phi}}{dE_R} = \frac{d\sigma_{SM}}{dE_R} + \frac{d\sigma_{\phi}}{dE_R}
\]

\[\frac{d\sigma_{\phi}}{dE_R} = \frac{G_F^2}{4\pi} q_{\phi}^2 \frac{2ME_R}{E_{\nu}^2} MF^2(q)\]

\[q_{\phi} = \frac{(14N + 15.1Z) g_{\phi}^2}{\sqrt{2}G_F (2ME_R + M_{\phi}^2)}\]
• Both the light $Z'$ and scalar cases with the standard Lindhard model can fit the SM spectrum for a given set of QF parameters $k$ and $q$.

• This will lead to confusion in determining the nature of new physics.
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Suggestive evidence for coherent elastic neutrino-nucleus scattering from reactor antineutrinos  

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\textsuperscript{3}Pacific Northwest National Laboratory, Richland, Washington 99354, USA  
(Dated: February 22, 2022)

Solid (dotted) line shows the SM CEvNS prediction for the iron filter (Lindhard) QF.  

Blue (black) line are based on the data from the iron filter (photo-neutron) measurement.
Quenching factor sensitivity

\[ E_M \text{ [keV}_{ee}] \]

- \( m_{\nu} = 63.1 \text{ MeV, } g_{\nu} = 1.4 \times 10^{-4} \)
- \( m_{\phi} = 25.1 \text{ MeV, } g_{\phi} = 1.6 \times 10^{-5} \)
- \( \mu_\nu = 2.5 \times 10^{-10} \mu_B \)
- \( k = 0.157, q = -23.8 \times 10^{-5} \)
- \( k = 0.167, q = -22.2 \times 10^{-5} \)
- \( k = 0.157, q = 0 \)

\[ q/10^{-5} \]

\[ k \]

\[ \Delta_k^2 \]

\[ q/10^{-5} \]
• Assume the standard Lindhard QF model is valid.
• $1\sigma$ allowed region of light $Z'$ is also allowed by COHERENT due to

$$q_{Z'} = 2q_W \quad \Rightarrow \quad \frac{g_{Z'}}{m_{Z'}} = \sqrt{\frac{2G_F}{3(N + Z)} \left[ N - (1 - 4\sin^2\theta_W)Z \right]}$$
New Physics

- Marginalize over the \((k,q)\) of the modified Lindhard model.
- Constraints are qualitatively affected by the QF model.
Summary

- Recent direct QF measurement in Ge indicates a departure from the standard Lindhard model at low energies.

- This deviation can be parameterized by a negative $q$ in the modified Lindhard model.

- NCC-1701 data provide an independent probe of Ge quenching factor, and the best-fit point is consistent with the direct QF measurements.

- A precise measurement of the QF is essential to detect new physics at CEvNS.

Thanks!
Backup slides
“...it is usually assumed that the atomic electrons around the recoil nucleus immediately follow the motion of the nucleus. However, it takes some time for the electrons to catch up, which causes ionization and excitation of the recoil atom...”


A value of $P = 50\%$ are needed to obtain agreement of the data, being a factor of approximately seven above the integrated ionization probabilities calculated for Migdal shakeoff from atomic germanium in 1707.07258

CEvNS Signal $H_1$ \[ A_{0.2} e^{-(E-0.2)/\xi} \]

amplitude $A_{0.2}$ (counts / $10^3$ eV 3 kg day)

decay constant $\xi$ (keV$_{ee}$)

Rx-ON

Rx-OFF

arXiv: 2202.09672
## Fit Results

<table>
<thead>
<tr>
<th>scenarios</th>
<th>$k$</th>
<th>$q/10^{-5}$</th>
<th>model parameters</th>
<th>$\chi^2_{\text{min}}$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM w/ standard Lindhard</td>
<td>0.157</td>
<td>0</td>
<td>-</td>
<td>14.34/19</td>
</tr>
<tr>
<td>SM w/ modified Lindhard w/ fixed $k$</td>
<td>0.157</td>
<td>-23.8</td>
<td>-</td>
<td>8.28/18</td>
</tr>
<tr>
<td>SM w/ modified Lindhard w/ $0.147 \leq k \leq 0.167$</td>
<td>0.167</td>
<td>-22.2</td>
<td>-</td>
<td>8.14/17</td>
</tr>
<tr>
<td>light $Z'$</td>
<td>0.157</td>
<td>0</td>
<td>$m_{Z'} = 63.1 \text{ MeV}, g_{Z'} = 1.4 \times 10^{-4}$</td>
<td>9.09/17</td>
</tr>
<tr>
<td>light scalar</td>
<td>0.157</td>
<td>0</td>
<td>$m_{\phi} = 25.1 \text{ MeV}, g_{\phi} = 1.6 \times 10^{-5}$</td>
<td>7.77/17</td>
</tr>
<tr>
<td>neutrino magnetic moment</td>
<td>0.157</td>
<td>0</td>
<td>$\mu_{\nu} = 2.5 \times 10^{-10} \mu_B$</td>
<td>11.71/18</td>
</tr>
</tbody>
</table>

$$\frac{dR}{dE_M} = \frac{\int_{0}^{\infty} G(E_M, E_I, \sigma^2) \frac{dR}{dE_I} dE_I}{\int_{0}^{\infty} G(E_M, E_I, \sigma^2) dE_I}$$

$$N_i = t \int_{E_M^i}^{E_M^{i+1}} \frac{dR}{dE_M} dE_M$$

$$\chi^2 = \sum_i \left[ \frac{N_{\text{exp}}^i - N_{\text{th}}^i (1 + \alpha)}{\sigma_i} \right]^2 + \left( \frac{\alpha}{\sigma_{\alpha}} \right)^2$$