Exploiting electron parity violation

From Standard Model tests to dark matter detection predictions

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Summary

• Electroweak interactions
• Parity-violating electron scattering
• Coherent neutrino scattering
• Connection between parity-violating electron scattering and coherent neutrino scattering
• WIMP direct detection
Electroweak interactions

Electron scattering

$\beta^p_V = 0.04$

$\beta^n_V = -0.5$

Neutrino scattering

$Z^0 (G_F)$

Electromagnetic + Weak neutral

$\left[ \bar{f} q^f \gamma^\mu f \right] A_\mu$

$\alpha = \frac{g^2}{4\pi}$

$\sim 10^{-2}$

$G_F = \frac{\sqrt{2}}{8} \left( \frac{g_W}{m_W} \right)^2$

$\sim 10^{-5}$ GeV$^{-2}$

Currents

Vector

Axial - Vector

Couplings

Weak neutral

$\left[ \bar{f} \left( c_V^f \gamma^\mu - c_A^f \gamma^\mu \gamma^5 \right) f \right] Z^0_\mu$

$G_F = \frac{\sqrt{2}}{8} \left( \frac{g_W}{m_W} \right)^2$

$\sim 10^{-5}$ GeV$^{-2}$
Parity-violating electron scattering

Definition

Parity-violating (helicity) asymmetry:

\[ A = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \]

Polarized electron (clockwise) → Nuclear target

Polarized electron (anticlockwise)

Mirror

Mirror image

\[ q \approx 2E \sin(\theta/2) \]
Parity-violating electron scattering

Definition

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Parity-violating electron scattering

**Definition**

Parity-violating (helicity) asymmetry:

\[ A = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \]

Within plane wave Born approximation and for isospin-0 (N = Z), spin-0 targets, the ‘reference asymmetry’ is:

\[ A = A^\text{ref} \equiv -\frac{G_F}{\sqrt{2}\pi \alpha} |Q|^2 |a^e_A| \sin^2 \theta_W \approx 10^{-6} \]

**Assumptions**

- Only one photon and one Z$^0$ are exchanged.
- Electron wave functions are not distorted by the target charge.
- Target state is spin-0, isospin-0 (non isospin mixing).
Parity-violating electron scattering

Definition

Parity-violating (helicity) asymmetry:

\[ \mathcal{A} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \]

For \( N \neq Z \) nuclei:

\[ \mathcal{A} \approx -\frac{G_F}{\sqrt{2} 2\pi \alpha} |Q|^2 a_A^e \beta_n^V \frac{N}{Z} \frac{F_n}{F_p} \]
Parity-violating electron scattering

Applications

• Determination of the neutron radius and neutron skin of heavy nuclei (PREX, CREX experiments), isospin mixing, neutron-rich matter equation of state, …

• Extrapolation to properties of neutron stars: radius, transition density, size of crust, …
Parity-violating electron scattering

Applications

Nucleon densities  (Form factors)  PV asymmetry

Neutron skin thickness

$r_n - r_p$
Parity-violating electron scattering

Applications

Possible relationship between nuclear structure and neutron star structure through the equation of state of neutron-rich matter:

- The larger the **neutron skin thickness** of nuclei, the larger the **radius** of neutron stars.

- The larger the **neutron skin thickness** of nuclei, the smaller the **crust thickness** of neutron stars.

![Graph showing density profiles of proton and neutron densities in 208Pb.](image)
Parity-violating electron scattering

Applications

• Accurate evaluation of the weak mixing angle, the size and momentum-dependence of higher-order electroweak radiative corrections, …

Related to the current interest in low-energy, high-luminosity polarized electron beams for high precision parity-violating experiments: MESA@Mainz, FEL@JLab, Cβ@Cornell.

Accurate theoretical knowledge is required of the size and uncertainty of the nuclear and nucleon structure effects involved.
Parity-violating electron scattering

Analysis

• Computation of nuclear and nucleon structure effects on the parity-violating observables in electron scattering. Focus on a carbon 12 target (spin 0, $N = Z$).

• Estimation of the theoretical uncertainties related to the previous calculations.

• Search for the optimal kinematic conditions to achieve the required theoretical and statistical uncertainties.
Parity-violating electron scattering

Analysis
Parity-violating electron scattering

Absolute effect of feature $X$

Relative effect of feature $X$

$$
\Gamma^X = \frac{A^X - A^{\text{ref}}}{A^{\text{ref}}}
$$
Parity-violating electron scattering

Analysis

\[ \Gamma^X = \frac{A^X - A^{\text{ref}}}{A^{\text{ref}}} \]

\[ \Delta \Gamma^X = \Gamma^X_a - \Gamma^X_b = \frac{A^{X_a} - A^{X_b}}{A^0} = \frac{\Delta A^X}{A^0} \]
Parity-violating electron scattering

Analysis

- Distortion of the electron wave function due to the Coulomb field created by the nuclear charge distribution: from plane-wave (PW) to distorted-wave (DW) calculations.

- Isospin mixing in the nucleus due to the Coulomb interaction acting differently on protons and neutrons.

- Strangeness content of the nucleons modifying the isoscalar (but not the isovector) nuclear responses.

- Meson exchange currents among the nucleons affecting differently the isoscalar and the isovector nuclear responses.

- Inelastic transitions to excited nuclear states differing significantly from the ground state (e.g. different nominal isospin).
### Analysis

**Summary of sizes and uncertainties**

(150 MeV incident electron energy, 25° - 45° scattering angle range)

<table>
<thead>
<tr>
<th>Contribution to PV asymmetry</th>
<th>Relative size</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulomb distortion of projectile wave function</td>
<td>3 %</td>
<td>0.01 %</td>
</tr>
<tr>
<td>Nuclear isospin mixing (electromagnetic origin)</td>
<td>0.4 %</td>
<td>0.05 %</td>
</tr>
<tr>
<td>Nucleon strangeness content (mainly electric)</td>
<td>0 - 1 %</td>
<td>1 %</td>
</tr>
<tr>
<td>Meson exchange currents</td>
<td>&lt; 0.1 %</td>
<td>&lt; 0.1 %</td>
</tr>
<tr>
<td>Inelastic contributions</td>
<td>&lt; 0.1 %</td>
<td>--</td>
</tr>
</tbody>
</table>
Coherent neutrino scattering

Definition

• Weak neutral current process, neutrino in and neutrino out: only nuclear recoil can be detected.

• The target nucleus remains in its ground state (elastic scattering).

• The cross section is roughly proportional to $A^2$.

• Larger when the wavelength corresponding to the momentum transfer is similar to the nuclear size ($q \approx 70$ MeV for $^{12}$C).

• It is the only elastic contribution for even-even nuclear targets, and usually dominant for other targets.

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\nu,\nu}^{ref} = \frac{G_F^2}{2\pi^2} \left[ (a_A^\nu)^2 + (a_V^\nu)^2 \right] \varepsilon_{\nu}^2 \cos^2(\theta_\nu/2) f_{rec}^{-1} A^2 \sin^4 \theta_W
\]
Coherent neutrino scattering

Applications

- Determination of electroweak constants at low momentum transfer as well as higher-order corrections.
- Testing the universality of the weak interaction for charged and neutral leptons.
- Analysis of structure details of the target (e.g. axial structure).
- Astrophysical processes (e.g. stellar core collapse, supernova neutrinos).
- Extension to direct detection of certain types of dark matter particles.
Parity violating electron and coherent neutrino scatterings

• Relationship between coherent electron-nucleus and coherent neutrino-nucleus cross-sections in PWBA:

$$\left( \frac{d\sigma}{d\Omega} \right)_{(\nu,\nu)} = A^2_{(e,e)} \left( \frac{d\sigma}{d\Omega} \right)_{(e,e)}$$

Deviations from this prediction:
- Coulomb distortion.
- Effect of higher order corrections.
- Non-SM couplings of neutrinos to $Z^0$.

• Relationship between their relative uncertainties:

$$\mathcal{E} \left( \frac{d\sigma}{d\Omega} \right)_{(\nu,\nu)} \approx 2 \mathcal{E} A_{(e,e)}$$
Parity violating electron and coherent neutrino scatterings
WI(M)Ps: Weak interacting (massive) particles
- Weak-like interactions (like neutrinos): the current has vector and axial components.
- May have much heavier masses than Standard Model neutrinos.
- Examples: supersymmetric particles (neutralinos), sterile neutrinos.

\[ |\nu_a\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle \]
\[ |\nu_b\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle \]

\[ |\nu_1\rangle, |\nu_2\rangle, |\nu_3\rangle, |\nu_4\rangle \]

\[ \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}, \begin{pmatrix} \nu_s \\ - \end{pmatrix} \]
WIMP - $^{12}\text{C}$ elastic scattering differential cross sections as a function of momentum transfer $q$ (proportional to nuclear recoil energy), for several WIMP velocities $\beta$ and WIMP mass 100 MeV.

**WI(M)P direct detection**
Conclusions

Parity violation in electron scattering

Nuclear structure:
- radius, neutron skin, isospin mixing

Nucleon structure:
- form factors, strangeness content

Standard Model tests and parameters

Neutrino-nucleus coherent scattering

WI(M)P direct detection

Nuclear matter equation of state, neutron star radius and structure

References: