Determination of the helicity of neutrinos
Parity violation of the weak interaction

Rebekka Schmidt

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Neutrinos overview

- spin 1/2 particles
- colourless
- electrically neutral
  \[ \Rightarrow \] only weak interaction via massive vector bosons \((W^\pm, Z^0)\)
- 3 neutrinos, associated with \(e, \mu, \tau\)
- lepton number of each family conserved
- neutrinos are left handed and antineutrinos right handed
Helicity and handedness

- **helicity:**
  - projection of particle’s spin $\vec{S}$ along direction of motion $\vec{p}$

\[
\vec{s} \cdot \vec{p} \implies \vec{S} \uparrow \downarrow \vec{p} \quad \text{negative, left helicity}
\]

\[
\vec{S} \uparrow \uparrow \vec{p} \quad \text{positive, right helicity}
\]

- for massive particles: sign of helicity depends on frame

- **handedness:** Lorentz invariant analogue of helicity
  - two states: left handed (LH) and right handed (RH)
  - massless particles: either pure RH or LH, can appear in either states
  - massive particles: both LH+RH components
    - helicity eigenstate is combination of handedness states
  - for $E \to \infty$ can neglect mass
    - handedness $\equiv$ helicity
Helicity and handedness

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      $\Rightarrow$ helicity eigenstate is combination of handedness states

- for $E \rightarrow \infty$ can neglect mass $\Rightarrow$ handedness $\equiv$ helicity
Parity violation of the weak interaction

first hint that there are only LH neutrinos and RH antineutrinos

1956: T. D. Lee and C. N. Yang predict P violation

1957: Wu et al. observed maximum P violation
Wu-Experiment

Helicity: \[ \mathcal{H} = \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|} \]

- $^{60}\text{Co}$ spin 5
- $^{60}\text{Ni}^*$ spin 4
- $\bar{\nu}_e$ antineutrino $\langle \mathcal{H} \rangle = +1$
- $e^-$ electron $\langle \mathcal{H} \rangle = -\nu/c$
Wu-Experiment

parity transformation:
- polar vectors change sign: $\vec{p} \rightarrow -\vec{p}$
- axial vectors don’t change sign: $\vec{s} \rightarrow \vec{s}$

experiment:
- nuclear spins are aligned through magnetic field, measurement of the electrons
- reverse magnetic field for other scenario

result:
beta emission is preferentially in the direction opposite to the nuclear spin $\Rightarrow$ parity is violated
1957: experiment to determine the helicity of the neutrino (Goldhaber et al.)

used electron capture of the nucleus $^{152}Eu$:

$$^{152m}_{152}Eu + e^- \rightarrow ^{152}_{152}Sm^* + \nu_e \rightarrow ^{152}_{152}Sm + \gamma + \nu_e$$

$$\begin{array}{ccc}
0 & \frac{1}{2} & 1 - \frac{1}{2} \\
0 & -\frac{1}{2} & -1 & \frac{1}{2} & 0 & -1 & \frac{1}{2}
\end{array}$$

$\Rightarrow \vec{s}(\gamma) \uparrow \downarrow \vec{s}(\nu_e)$
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\[ \Rightarrow \bar{s}(\gamma) \uparrow \downarrow \bar{s}(\nu_e) \]

if neutrino and photon are „back-to-back“

\[ \Rightarrow H(\nu_e) = H(\gamma) \]
\[ Eu + e^{-} \rightarrow Sm^{*} + \nu_{e} \rightarrow Sm + \gamma + \nu_{e} \]

- energy of \( Sm^{*} \) is distributed on \( Sm \) and \( \gamma \)
  \( \rightarrow \) \( \gamma \) has to less energy to excite another \( Sm \) nucleus
- but: \( Sm^{*} \) gets a recoil when the \( \nu_{e} \) is emitted \( \rightarrow \) doesn’t decay in rest
- \( \gamma \) emitted in moving direction of \( Sm^{*} \) nucleus
  \( \rightarrow \) gets additional energy
  \( \rightarrow \) can be absorbed by another \( Sm \) nucleus
  \( \Rightarrow \) resonant absorption possible
measurement of helicity:
- Eu-source in iron magnet
- photons Compton scattered on electrons of Fe
- \[ \frac{d\sigma}{d\Omega(\uparrow\downarrow)} > \frac{d\sigma}{d\Omega(\uparrow\uparrow)} \]
- reverse magnetic field and count detected photons
  ⇒ polarisation of photons
  ⇒ \[ H(\nu) = -1.0 \pm 0.3 \]
⇒ neutrinos are left handed
Summary

- parity violation of weak interaction:
  - 1956 predicted by T. D. Lee and C. N. Yang
  - 1957 showed by Wu et al.

- Goldhaber-Experiment
  - experiment to determine the helicity of neutrinos
  - showed that neutrinos are LH and antineutrinos RH

- no evidence for RH neutrinos, LH antineutrinos