Parity non-conservation in beta decay

Parity was introduced first by E. Wigner in 1927, for describing symmetry of atomic quantum states against \( r \rightarrow -r \) transformation. Electromagnetic interaction conserves the parity. Strong interaction conserves the parity. It was assumed that the weak interaction also conserves the parity. However, in 1956 T.D.Lee and C.N.Yang showed, that there was no experimental evidence for parity conservation in weak interaction. They explained the so called „tau-theta puzzle“ assuming that parity is not conserved → Nobel-prize in 1957!

Why does this mean parity violation?

- Direction of electrons: \( p \) (momentum): vector \( \rightarrow -1 \) if mirrored
- Direction of angular momentum \( J = [r \times p] \): axial vector \( \rightarrow +1 \) if mirrored

If parity is not conserved in weak interaction, this should be seen also in nuclear \( \beta \)-decay!

Experimental proof: C.S.Wu et al. (1957)

\[
I = 5\hbar, \pi = + \\
I = 4\hbar, \pi = + \\
I = 2\hbar, \pi = + \\
I = 0\hbar, \pi = + \\
\]

Polarized \( ^{60}\text{Co} \) source:
small temperature \((\sim 3 \text{ mK})\),
strong magnetic field
\((\mu B) \gg kT\)

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/wu.gif
Angular momenta in Wu experiment

Explanation of the parity violation (complete violation)

Only right-handed antineutrinos (p↑↑s), and left handed neutrinos (p↑↓s) exist!

W. Pauli: „Cannot believe that God is left-handed!”

Antineutrinos have to fly in the direction of the J = 5h!
So electrons have to fly in opposite direction (Σp ~0)

Consequence for the H_b operator:
H_b = (H_bS + H_bV) + (H_bA + H_bT)

Finally, the interaction operator: H_b = H_bV + H_bA

The story of the neutrino

Early history:
1914: Chadwick discovered the continuous energy spectrum of 214Pb (RaB) using a magnetic spectrometer

Interpretation (Rutherford): monoenergetic electrons come out of the nucleus, but they loose energy in the matter

1927: Ellis and Wooster experiment: total energy released by 210Bi (RaE) β-decays, measured by a differential calorimeter, that could stop all electrons inside.

E_0 = 1050 keV as calculated from the mass difference

E_measured = 344±34 keV

Double beta decay

92Mo cannot beta-decay, since 92Nb is „higher” in energy. However, the energy of 92Zr is lower, so if the nucleus could „jump” ΔZ=2, then it was energetically favorable!

The ordinary double beta decay:  92X→ 92Y + 2e^- + 2ν_
It may occur in certain even-even nuclei.
It has been observed at 35 isotopes, with T_1/2~10^{18}-10^{23} years

The neutrinoless double beta decay:  92X→ 92Y + 2e^- 
It may occur only if the neutrino is its own antiparticle:
92X→ 92K + ν + e^- 

The neutrino emitted in the first, will induce the second reaction
It has not been observed yet. T_1/2>10^{25} years

Not only energy was „missing”

14C→ 14N + e^-  Angular momentum non-conservation?

6He→ 6Li + e^-  Cloud chamber photo
S. Szalay & Gy. Csikai (Hungary)

Momentum non-conservation?

Ideas for the solution of the puzzle:
N. Bohr, J.C. Slater, L.D.Landau: conservation laws are not valid in microscopic scale, only statistically! (Hmm…)

1930: W. Pauli: hypothesis of the „neutron”.
M<M_proton , neutral, spin=1/2
„We will never detect it directly” (Pauli)

1933: E. Fermi renamed it „neutrino”, after the discovery of Chadwick of the „massive” neutron (M=M_proton)
By that time it was known (Dirac) that fermions should have antiparticles. **neutrino = antineutrino?**

If **no** then we call them **Dirac neutrino**
If **yes**, we call them **Majorana neutrino**

**Three „family” of the leptons**

1936: C. D. Anderson: discovery of the muon (m\(^-\)) (m\(_m\)~200 m\(_e\))
1975: M. L. Perl (SLAC, USA): discovery of tau meson (m\(_T\)~3500 m\(_e\)) (Nobel-prize: 1995)
2000: DONUT experiment (Fermilab, USA) discovery of tau neutrino

**The lepton families (flavours)**

<table>
<thead>
<tr>
<th>Charged lepton</th>
<th>Mass</th>
<th>Neutral lepton</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron (e(^-))</td>
<td>1 m(_e)</td>
<td>electron neutrino ((\nu_e))</td>
<td>?</td>
</tr>
<tr>
<td>muon ((\mu^)</td>
<td>~200 m(_e)</td>
<td>muon neutrino ((\nu_\mu))</td>
<td>?</td>
</tr>
<tr>
<td>tau meson ((\tau^))</td>
<td>~3500 m(_e)</td>
<td>tau neutrino ((\nu_\tau))</td>
<td>?</td>
</tr>
</tbody>
</table>

... + their antiparticles!

**Leptonic charge**

The lack of **neutrinoless** double beta decay (and many other processes) led to the discovery of **leptonic charge conservation law**

It was discovered by 3 physicists in the same year (1953) independently:
- G. Marx (Hungarian) - 1953 January (published in German)
- J. B. Zeldovich (Soviet) - 1953 July (published in Russian)
- H.M. Mahmoud and E.J. Konopinsky (USA) - 1953 November (published in English)

\[ L = L_e + L_\mu + L_\tau \]

The „family” leptonic charge = 1 for the particles, -1 for the antiparticles, and 0 for the non-leptons.

**A conservation law exists for the total leptonic charge!**

(And for most reactions also for the family leptonic charge)

**Anti-neutrino detection** (Reines-Cowan experiment)

Very small interaction probability

\[ \bar{\nu} + p \rightarrow n + e^+ \]

Water (~400 l) big amount of interacting particles

\[ N = 6.6 \cdot 10^{22} \frac{1}{cm^2} \]

Easy detection of the reaction products low background

Detecting \(e^+ \rightarrow\) annihilation gammas (2 x 511 keV)

\[ \frac{1}{cm^2 \cdot s} \]

Detecting \(n \rightarrow\) high energy gammas following n-capture in CdCl\(_2\) Cd(n,\(\gamma\)) reactions

\[ \phi \approx 10^{13} \]

**Negative b-decay**

**Positive b-decay**

**Electron capture**

**Pion decay**

**Muon decay**

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Leptonic Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^- \rightarrow \mu^- + \bar{\nu}_\mu)</td>
<td>-1</td>
</tr>
<tr>
<td>(\mu^- \rightarrow e^- + \bar{\nu}<em>e + \nu</em>\mu)</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ 0 \rightarrow 1 + (-1) \]

\[ L_e \]

\[ L_\mu \]
B. Pontecorvo: use nuclei as target: $\nu^+ + ^{A}X \rightarrow ^{A}Y + e^-$

Problem: big amount of $X$ needed $\leftrightarrow$ few atoms of $Y$ created

How to separate and detect?

- $X$ and $Y$ must be very different chemically
- $Y$ should be radioactive

$\nu^+ + ^{37}Cl \rightarrow ^{37}Ar + e^-$  
$^{37}Ar + e^- \rightarrow ^{17}Cl + \nu$  
(T$_{1/2}$ = 35 days, e$^-$ capture, EC)

Source: Sun $^{4}\text{H} \rightarrow ^{4}\text{He} + 2e^+ + 2\nu + 26.22\text{ MeV}$

Production rate: $\frac{1}{13.11\text{ MeV}} = 4.8 \cdot 10^{11} \text{ J}$

Solar constant: $1361\text{ kW/m}^2 = 136.1\text{ J/(cm}^2\text{s)}$

The neutrino flux then: $\phi = 4.8 \cdot 10^{11} \cdot 136.1 = 6.53 \cdot 10^{13} \frac{1}{\text{cm}^2\text{s}}$
R. Davis, J. Bahcall „Homestake“ experiment

Results: 1 SNU = $10^{-36} \frac{1}{37\text{Cl} \cdot \text{s}}$

Expected value ~ 9 SNU
Measured value ~ 3 SNU → Solar neutrino puzzle

Attempts to solve the puzzle:
* Experimental error? NO! Several other neutrino experiments confirmed the results
* Error in the Sun model? (Pulsating Sun?)
* Neutrino oscillations? (Yeah!) 😊

Neutrino oscillation
Main idea: neutrinos have masses, $\nu_e, \nu_\mu, \nu_\tau$ are NOT mass-eigenstates! (B. Pontecorvo 1957)
The weak interaction selects according to the „flavours”
Creation according to flavours → mixed mass state
Propagation → according to masses → mixing changes
Detection (Davis) → according to flavours again

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

flavour eigenstates → mass eigenstates

MNS matrix (1962) (Maki, Nakagawa, Sakata)

For 3 neutrinos obviously $\Delta m^2_{21} + \Delta m^2_{31} + \Delta m^2_{32} = 0$

For 3 neutrinos obviously $\Delta m^2_{21} + \Delta m^2_{31} + \Delta m^2_{32} = 0$

Neutrino oscillation (contd.)

Simple example: 2 neutrinos $\nu_\mu = \begin{pmatrix} \cos \theta & \sin \theta \end{pmatrix} \nu_1 - \begin{pmatrix} -\sin \theta & \cos \theta \end{pmatrix} \nu_2$

The $\nu_\mu$ neutrino was created with $p$ momentum at $t = 0$.

Since $E_t = \sqrt{p^2 c^2 + m^2 c^4}$
at $t$ time we have: $|\nu_t| = \sqrt{\exp \left( \frac{-iE_t \theta}{\hbar} \cos \theta \nu_1 \right) + \exp \left( \frac{-iE_t \theta}{\hbar} \sin \theta \nu_2 \right)}$

The probability to detect a $\nu_\mu$ again after $L \sim c \cdot t$ distance:

$p(t \approx \frac{L}{c}) = 1 - \sin^2 2 \theta \cdot \exp \left( \frac{2 \pi L}{2 \hbar c} \Delta m^2 \right)$

Can be shown that: $\frac{\hbar^2}{2mc^2} \cdot \Delta m^2 = \frac{1.27 \text{ km}}{\text{MeV}} \cdot L$, where $\Delta m^2 = m^2_2 - m^2_1$ [eV]^2

$L [\text{m}], \ h [\text{pc} [\text{MeV}]]$
**Neutrino oscillation (contd.)**

Several experiments confirmed the existence of neutrino oscillations and the neutrino mass. Some of the key experiments include:

- **Super Kamiokande (Japan)**: This experiment detected neutrinos from the supernova burst of SN 1987A.
- **Kamland (Japan)**: Kamland uses a large underground detector to study neutrinos from nuclear power plants and the Sun.
- **CERN to Gran Sasso (Italy)**: This setup involves neutrino beams generated at CERN that are detected at Gran Sasso, offering a method to study the properties of neutrinos.

![Sun picture taken with ν](image)

- Data: 
  - GeV, 
  - Expected based on oscillation parameters determined by KamLAND

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**Nobel-prize in Physics 2015**

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

![Arthur B. McDonald and Takaaki Kajita](image)

- Arthur B. McDonald: Super-Kamiokande Collaboration, University of Wisconsin, Madison, USA
- Takaaki Kajita: Super-Kamiokande Collaboration, University of Tokyo, Japan

"Tävetsäkten av neutrinooscillationer, som visar att neutriner har massa"

The discovery of neutrino oscillations, which shows that neutrinos have mass.