Nuclear Physics
(5th lecture)

Content

- Parity violation in weak interaction, Wu experiment
- History of the neutrino, leptons' families. Leptonic charge
- Anti-neutrino detection (Reines-Cowan experiment)
- Neutrino detection (Davis experiment)
- Solar neutrino puzzle
- Neutrino oscillation, and neutrino masses

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!

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 $^{60}$Co source:
small temperature ($\approx 3$ mK),
strong magnetic field

$$\frac{n_+}{n_-} = e^{-\frac{2\mu B}{kT}}$$

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

Mirroring the coordinate axis is not a good symmetry!
Angular momenta in Wu experiment

Explanation of the parity violation (complete violation)

\[ \phi = \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{pmatrix} \]

Only right-handed antineutrinos ($p\uparrow\uparrow$), and left handed neutrinos ($p\uparrow\downarrow$) 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 ($\Sigma p \sim 0$)

Consequence for the $H_\beta$ operator:

$H_\beta = (H_{KS} + H_{\beta,V}) + (H_{\beta,A} + H_{\beta,T})$

Fermi, G.T.

Finally, the interaction operator: $H = H_{\beta,V} + H_{\beta,A}$

The story of the neutrino

Early history:

1914: Chadwick discovered the continuous energy spectrum of $^{210}\text{Pb}$ (RaB) using a magnetic spectrometer

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

1927: Ellis and Wooster experiment: total energy released by $^{210}\text{Bi}$ (RaE) $\beta$-decays, measured by a differential calorimeter, that could stop all electrons inside.

$E_0 = 1050$ keV as calculated from the mass difference

$E_{\text{measured}} = 344 \pm 34$ keV

Double beta decay

$^{92}\text{Mo}$ cannot beta-decay, since $^{92}\text{Nb}$ is „higher“ in energy. However, the energy of $^{92}\text{Zr}$ is lower, so if the nucleus could „jump“ $\Delta Z=2$, then it was energetically favorable!

The ordinary double beta decay: $^{A}\text{X} \rightarrow ^{A+2}\text{Y} + 2\text{e}^- + ^{2}\text{Ar}$

It may occur in certain even-even nuclei.

It has been observed at 35 isotopes, with $T_{1/2} \sim 10^{19}$-$10^{23}$ years

The neutrinoless double beta decay: $^{A}\text{X} \rightarrow ^{A}\text{Y} + 2\text{e}^-$

It may occur only if the neutrino is its own antiparticle:

$^{Z}\text{X} \rightarrow ^{Z}\text{K} + \nu + e^-$

The neutrino emitted in the first, will induce the second reaction

It has not been observed yet. $T_{1/2} > 10^{25}$ years
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 \((\mu^-)\) (\(m_\mu\sim200\ m_e\))
1962: Lederman, Schwartz, Steinberger: discovery of the \(\mu\)-neutrino (Nobel-prize 1988)
1975: M. L. Perl (SLAC, USA): discovery of the tau meson \((m_\tau\sim3500\ m_e\)) (Nobel-prize: 1995)
2000: DONUT experiment (Fermilab, USA) discovery of tau neutrino

Charged lepton Mass Neutral lepton Mass

electron \((e^-)\) \(1\ m_e\) electron neutrino \((\nu_e)\)?

muon \((\mu^-)\) \(~200\ m_e\) muon neutrino \((\nu_\mu)\)?

tau meson \((\tau^-)\) \(~3500\ m_e\) tau neutrino \((\nu_\tau)\)?

... + their antiparticles!

The lepton families (flavours)

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

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)

A few examples:

\[ \frac{\Delta}{\Delta} X \rightarrow Z \frac{\Delta}{\Delta} \ Y + e^- + \bar{\nu} \]

Negative \(\beta\)–decay

\[ \left[ \begin{array}{c} 0 \\ 0 \end{array} \right] \rightarrow \left[ \begin{array}{c} 0 \\\n +1 + (-1) \end{array} \right] \]

\(L_e\)

\[ \frac{\Delta}{\Delta} X \rightarrow Z \frac{\Delta}{\Delta} \ Y + e^+ + \nu \]

Positive \(\beta\)–decay

\[ \left[ \begin{array}{c} 0 \\ 0 \end{array} \right] \rightarrow \left[ \begin{array}{c} 0 \\\n +1 + (-1) \end{array} \right] \]

\(L_e\)

\[ \frac{\Delta}{\Delta} X + e^- \rightarrow Z \frac{\Delta}{\Delta} \ Y + \nu \]

Electron capture

\[ \left[ \begin{array}{c} 0 \\ 0 \end{array} \right] \rightarrow \left[ \begin{array}{c} 0 \\\n +1 + 1 \end{array} \right] \]

\(L_e\)

\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]

Pion decay

\[ \left[ \begin{array}{c} 0 \\ 0 \end{array} \right] \rightarrow \left[ \begin{array}{c} 1 \\\n +(-1) \end{array} \right] \]

\(L_\mu\)

\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]

Muon decay

\[ \left[ \begin{array}{c} 0 \\ 1 \end{array} \right] \rightarrow \left[ \begin{array}{c} 1 \\\n +0 + 1 \end{array} \right] \]

\(L_\mu\)

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)

Anti-neutrino detection (Reines-Cowan experiment)

Very small interaction probability

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

big amount of interacting particles

easy detection of the reaction products

low background

water (~400 l)

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

\(N = 6.6 \cdot 10^{-2} \left[ \frac{1}{cm^2} \right] \)

nuclear reactor (Savannah River)

Many \(\beta^-\) decays from the fission products

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

\[ \phi \approx 10^{13} \left[ \frac{1}{cm^2 \cdot s} \right] \]
Results:

1953: \(24 \pm 12\) counts/h
1956: \(2,88 \pm 0.22\) counts/h
1958: \(36.4 \pm 4\) counts/h

\[
\sigma_{\text{exp}} = 1.2 \pm 0.5 \cdot 10^{-41} \text{cm}^2 \\
\sigma_{\text{theory}} = 1.0 \pm 0.17 \cdot 10^{-41} \text{cm}^2
\]

Nice agreement!! ☺

Neutrino detection (Davis experiment)

The Reines-Cowan method does not work!

\[ V + n \rightarrow p + e^+ \]

No target can be prepared!

Detecting \(e^-\) not possible, electrons are everywhere

Detecting \(p\) not possible, protons are everywhere

B. Pontecorvo: use nuclei as target:

\[ \nu + ^{A}_{Z}X \rightarrow ^{A+1}_{Z+1}Y + e^- \]

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

\[ ^{37}_{18}\text{Ar} + e^- \rightarrow ^{37}_{17}\text{Cl} + \nu \quad (T_{1/2} = 35\text{ days, } e^-\text{ capture, EC}) \]

Source: Sun \(4_{1}^{1\text{He}} \rightarrow 4_{2}^{1\text{He}} + 2e^+ + 2\nu + 26.22\text{ MeV} \)

Production rate:

\[
\frac{1}{13.11\text{MeV}} = 4.8 \cdot 10^{11} \frac{1}{J}
\]

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

The neutrino flux then:

\[
\phi = 4.8 \cdot 10^{11} \cdot 136.1 = 6.53 \cdot 10^{13} \frac{1}{\text{cm}^2 \text{s}}
\]
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

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

flavour eigenstates mass eigenstates

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

For 3 neutrinos obviously $\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{13} = 0$

Neutrino oscillation (contd.)

Simple example: 2 neutrinos

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} v_e \\ v_\mu \end{pmatrix}$$

The $v_e$ neutrino was created with $p$ momentum at $t = 0$.

Since $E_i = \sqrt{p^2c^2 + m_i^2c^4}$

at $t$ time we have: $|v_\mu| = \exp\left(-\frac{iE_i t}{\hbar}\cos \theta v_e\right) + \exp\left(-\frac{iE_\mu t}{\hbar}\sin \theta v_\mu\right)$

The probability to detect a $v_e$ again after $L \sim c t$ distance:

$$P\left(t \approx \frac{L}{c}\right) = 1 - \sin^2 2\theta \cdot \sin^2 \left(\frac{(E_i - E_\mu) L}{2 \hbar c}\right)$$

Can be shown that: $\frac{(E_i - E_\mu) L}{2 \hbar c} = 1.27 \frac{\text{km}}{c} L$ [m], $\frac{\text{MeV}}{\text{MeV}}$
Neutrino oscillation (contd.)

Several experiments confirmed

Super Kamiokande (Japan)  
Sun picture taken with ν

Kamland (Japan)

CERN to Gran Sasso (Italy)

Nobel-prize in Physics 2015

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

Takaaki Kajita  
Super-Kamiokande Collaboration  
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald  
Sudbury Neutrino Observatory Collaboration  
Queen’s University, Kingston, Canada

Nobel-prize in Physics 2015

Nobel-prize in Physics 2015

NEUTRINER FRÅN KOSMISK STRÅLNING

Takaaki Kajita

SUDBURY NEUTRINO OBSERVATORY (SNO)

Arthur B. McDonald

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