CP Violation in the Leptonic Sector

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High Energy Physics

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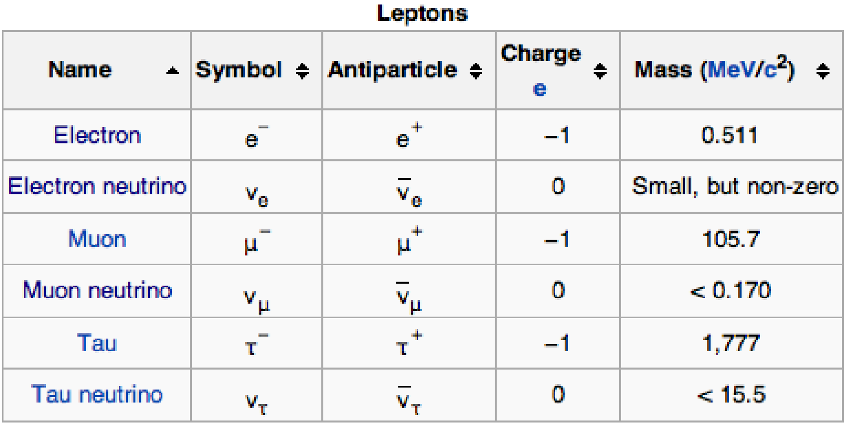
Leptons: Brief Overview

- Respect Pauli exclusion principle

Anti-Symmetric wave function

$$\Psi(r_1, r_2) = -\Psi(r_2, r_1) \tag{1}$$

Leptons: Brief Overview



Leptons

Name	Symbol	Antiparticle	Charge e	Mass (MeV/c^2)
Electron	e^-	e^+	−1	0.511
Electron neutrino	ν_e	$\bar{\nu}_e$	0	Small, but non-zero
Muon	μ^-	μ^+	−1	105.7
Muon neutrino	ν_μ	$\bar{\nu}_\mu$	0	< 0.170
Tau	τ^-	τ^+	−1	1,777
Tau neutrino	ν_τ	$\bar{\nu}_\tau$	0	< 15.5

CP Symmetry: Understanding the Concept

- **C interchanges particles and antiparticles.**
  So **C** conservation means that the rate for a process equals the rate for the same process with particles replaced by their respective antiparticles. C is violated in weak interactions, but conserved in E.M. and strong ones.

- **P changes $\vec{x} \to -\vec{x}$, if $\vec{x}$ is a vector.**
  On the other hand, pseudovectors, like angular momenta, are left unchanged. Therefore, **P** exchanges left-handed (LH) with right-handed (RH) particles and vice-versa.

- **CP performs the two operations together.**
  So, in particular it exchanges a right-handed e^- into a left-handed e^+, and a left-handed e^- into a right-handed e^+.

CP Violations

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- CP Violation was first discovered in the decay patterns of **Kaons**.
- Since this discovery, CP symmetry violation has already been observed in quark oscillations and incorporated into quark mixing theory
- If CP violation draws a clear distinction between matter and antimatter, then CP violation may be what caused our universe to be matter-dominated!
- However, more CP violation must be observed in order to explain the universe's matter dominance. Therefore, physicists are looking to find CP violation in other particles, such as **neutrinos**.

Neutrino Oscillations

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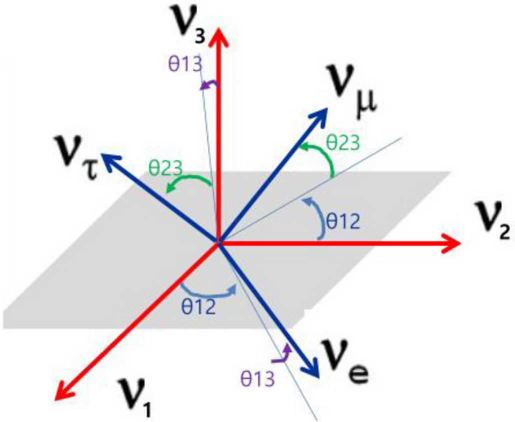

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Neutrino Oscillations

- PMNS Matrix

PMNS Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{2}$$

Neutrino Oscillations

- PMNS Matrix

PMNS Matrix parameterization

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \\ \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3)$$

Where $s_{ij} = sin\theta_{ij}$ and $c_{ij} = cos\theta_{ij}$. The phase factors α_1 and α_2 are physically meaningful only if neutrinos are Majorana particles (they dont enter into oscillation phenomena regardless). And the phase factor δ_{CP} is non-zero only if neutrino oscillation violates CP symmetry.

Neutrino Oscillations

- PMNS Matrix

PMNS Matrix parameterization

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \tag{4}$$

Neutrino Oscillations

- Transition probability $P(\nu_\alpha \to \nu_\beta)$

Transition probability

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>k} \mathcal{R}\left\{U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\right\} sin^2\left(\frac{\Delta_{jk} m^2 L}{4E}\right)$$
$$+ 2\sum_{j>k} \mathcal{I}\left\{U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\right\} sin\left(\frac{\Delta_{jk} m^2 L}{4E}\right) \quad (5)$$

Where $\Delta_{jk} m^2 = m_j^2 - m_k^2$.

Neutrino Oscillations

- (Anti) Transition probability $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

(Anti) Transition probability

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{j>k} \mathcal{R}\left\{U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\right\} sin^2\left(\frac{\Delta_{jk} m^2 L}{4E}\right) - 2\sum_{j>k} \mathcal{I}\left\{U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\right\} sin\left(\frac{\Delta_{jk} m^2 L}{4E}\right) \quad (6)$$

CP violation in neutrino oscillations

- The simplest measure of CP Violation would be the difference between the oscillation probabilities of neutrinos and anti-neutrinos, $P(\nu_\alpha \rightarrow \nu_\beta)$ and $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$, which is given by,

CP Violation measurement

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = 4 \sum_{j>k} \mathcal{I}\left\{ U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \right\} sin\left(\frac{\Delta_{jk} m^2 L}{4E} \right) \tag{7}$$

CP violation in neutrino oscillations

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CP Violation measurement

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = 16 J_{\alpha\beta} sin\left(\frac{\Delta_{21} m^2 L}{4E}\right) sin\left(\frac{\Delta_{32} m^2 L}{4E}\right) \times \times sin\left(\frac{\Delta_{31} m^2 L}{4E}\right) \quad (8)$$

CP violation in neutrino oscillations

- Where $J_{\alpha\beta} = \mathcal{I}\left\{U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\right\} = \pm J,$

Jarlskog Invariant

$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 sin\delta \tag{9}$$

The maximal value for J (with current data) is, $J_{CP}^{max} \approx 0.0333 \pm 0.0006$

Ongoing Experiments

- **T2K experiment**
  T2K (Tokai to Kamioka) is a long-baseline neutrino oscillation experiment in Japan that aims to study neutrino oscillations and search for CP violation. It utilizes an intense beam of muon neutrinos produced at the Japan Proton Accelerator Research Complex (J-PARC) and measures the oscillation of these neutrinos over a distance of 295 kilometers to the Super-Kamiokande detector. T2K provides crucial data on neutrino properties and is focused on measuring the mixing angle θ_{13} and determining the CP-violating phase δ.

Ongoing Experiments

- **NOνA experiment**
  NOνA (NuMI Off-Axis Electron Neutrino Appearance) is another long-baseline neutrino oscillation experiment, based in the United States. It uses the NuMI (Neutrinos at the Main Injector) beam from Fermilab to generate a beam of muon neutrinos. These neutrinos are detected over a distance of 810 kilometers at the NOνA detectors in northern Minnesota. NOνA aims to measure the oscillation of neutrinos and antineutrinos and investigate the mixing angles θ_{13} and θ_{23}. It also aims to study the mass ordering of neutrinos and search for CP violation.

Ongoing Experiments

- **DUNE experiment**
  DUNE (Deep Underground Neutrino Experiment) is a future international project for studying neutrino oscillations and other neutrino physics. It will employ a powerful neutrino beam produced at Fermilab, which will be directed towards massive liquid argon time projection chambers (LArTPCs) located at the Sanford Underground Research Facility in South Dakota, USA. DUNE will focus on precise measurements of the mixing angles θ_{13}, θ_{23}, θ_{12}, determining the neutrino mass hierarchy, investigating CP violation, and exploring other aspects of neutrino physics such as supernova neutrinos and nucleon decay.

Experimentally measured parameter values

- As of November 2022, the current best-fit values from NuFIT.org, from direct and indirect measurements, using normal ordering, are:

$$\begin{aligned}\theta_{12} &= 33.41^{\circ}{}^{+0.75^{\circ}}_{-0.72^{\circ}}\\ \theta_{23} &= 49.1^{\circ}{}^{+1.0^{\circ}}_{-1.3^{\circ}}\\ \theta_{13} &= 8.54^{\circ}{}^{+0.11^{\circ}}_{-0.12^{\circ}}\\ \delta_{\mathrm{CP}} &= 197^{\circ}{}^{+42^{\circ}}_{-25^{\circ}}\end{aligned}$$

- As of November 2022, the 3σ ranges (99.7% confidence) for the magnitudes of the elements of the matrix were:

$$|U| = \begin{bmatrix} |U_{\mathrm{e}1}| & |U_{\mathrm{e}2}| & |U_{\mathrm{e}3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{bmatrix} = \begin{bmatrix} 0.803 \sim 0.845 & 0.514 \sim 0.578 & 0.142 \sim 0.155 \\ 0.233 \sim 0.505 & 0.460 \sim 0.693 & 0.630 \sim 0.779 \\ 0.262 \sim 0.525 & 0.473 \sim 0.702 & 0.610 \sim 0.762 \end{bmatrix}$$

Q&A

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

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