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Nuclear Physics B 908 (2016) 279–301

NUCLEAR PHYSICS B

www.elsevier.com/locate/nuclphysb

Theory prospective on leptonic CP violation

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Received 4 February 2016; received in revised form 24 February 2016; accepted 25 February 2016

Available online 2 March 2016

Editor: Tommy Ohlsson

Abstract

The phenomenology of 3-neutrino mixing, the current status of our knowledge about the 3-neutrino mixing parameters, including the absolute neutrino mass scale, and of the Dirac and Majorana CP violation in the lepton sector are reviewed. The problems of CP violation in neutrino oscillations and of determining the nature – Dirac or Majorana – of massive neutrinos are discussed. The seesaw mechanism of neutrino mass generation and the related leptogenesis scenario of generation of the baryon asymmetry of the Universe are considered. The results showing that the CP violation necessary for the generation of the baryon asymmetry of the Universe in leptogenesis can be due exclusively to the Dirac and/or Majorana CP-violating phase(s) in the neutrino mixing matrix U are briefly reviewed. The discrete symmetry approach to understanding the observed pattern of neutrino mixing and the related predictions for the leptonic Dirac CP violation are also reviewed.

1. Introduction: the three-neutrino mixing

There have been remarkable discoveries in the field of neutrino physics in the last 18 years or so. The experiments with solar, atmospheric, reactor and accelerator neutrinos have provided compelling evidences for the existence of neutrino oscillations [1,2] – transitions in flight between the different flavour neutrinos ν_e, ν_μ, ν_τ (antineutrinos $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$) – caused by nonzero neutrino masses and neutrino mixing (see, e.g., Ref. [3] for review of the relevant data). The ex-

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http://dx.doi.org/10.1016/j.nuclphysb.2016.02.032

istence of flavour neutrino oscillations implies the presence of mixing in the weak charged lepton current:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{l=e,\mu,\tau} \overline{l_L}(x)\,\gamma_\alpha \nu_{lL}(x)\, W^{\alpha\dagger}(x) + \text{h.c.}\,,\ \ \nu_{l\mathrm{L}}(x) = \sum_{j=1}^{n} U_{lj}\,\nu_{j\mathrm{L}}(x)\,, \tag{1}$$

where $\nu_{lL}(x)$ are the flavour neutrino fields, $\nu_{j\mathrm{L}}(x)$ is the left-handed (LH) component of the field of the neutrino ν_j having a mass m_j, and U is a unitary matrix – the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) neutrino mixing matrix [1,2,4], $U \equiv U_{PMNS}$. All compelling neutrino oscillation data can be described assuming 3-neutrino mixing in vacuum, $n = 3$. The number of massive neutrinos n can, in general, be bigger than 3 if, e.g., there exist RH sterile neutrinos [4] and they mix with the LH flavour neutrinos. It follows from the current data that at least 3 of the neutrinos ν_j, say ν_1, ν_2, ν_3, must be light, $m_{1,2,3} \lesssim 1$ eV, and must have different masses, $m_1 \neq m_2 \neq m_3$.[1]

In the case of 3 light neutrinos, the 3×3 unitary neutrino mixing matrix U can be parametrised, as is well known, by 3 angles and, depending on whether the massive neutrinos ν_j are Dirac or Majorana particles, by one Dirac, or one Dirac and two Majorana, CP violation (CPV) phases [7]:

$$U = V\,P\,, \quad P = \text{diag}(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}})\,, \tag{2}$$

where $\alpha_{21,31}$ are the two Majorana CPV phases and V is a CKM-like matrix,

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}. \tag{3}$$

In eq. (3), $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, the angles $\theta_{ij} = [0, \pi/2]$, and $\delta = [0, 2\pi)$ is the Dirac CPV phase. Thus, in the case of massive Dirac neutrinos, the neutrino mixing matrix U is similar, in what concerns the number of mixing angles and CPV phases, to the CKM quark mixing matrix. The PMNS matrix U contains two additional physical CPV phases if ν_j are Majorana particles due to the special properties of Majorana fermions (see, e.g., Refs. [7–9]). On the basis of the existing neutrino data it is impossible to determine whether the massive neutrinos are Dirac or Majorana fermions.

The probabilities of neutrino oscillation are functions of the neutrino energy, E, the source-detector distance L, of the elements of U and, for relativistic neutrinos used in all neutrino experiments performed so far, of the neutrino mass squared differences $\Delta m^2_{ij} \equiv (m_i^2 - m_j^2)$, $i \neq j$ (see, e.g., Ref. [9]). In the case of 3-neutrino mixing there are only two independent Δm^2_{ij}, say $\Delta m^2_{21} \neq 0$ and $\Delta m^2_{31} \neq 0$. The numbering of neutrinos ν_j is arbitrary. We will employ the widely used convention which allows to associate θ_{13} with the smallest mixing angle in the PMNS matrix, and θ_{12}, $\Delta m^2_{21} > 0$, and θ_{23}, Δm^2_{31}, with the parameters which drive the solar (ν_e) and the dominant atmospheric ν_μ and $\bar{\nu}_\mu$ oscillations, respectively. In this convention $m_1 < m_2$, $0 < \Delta m^2_{21} < |\Delta m^2_{31}|$, and, depending on sgn($\Delta m^2_{31}$), we have either $m_3 < m_1$ or $m_3 > m_2$. The

[1] At present there are several experimental inconclusive hints for existence of one or two light sterile neutrinos at the eV scale, which mix with the flavour neutrinos, implying the presence in the neutrino mixing of additional one or two neutrinos, ν_4 or $\nu_{4,5}$, with masses m_4 ($m_{4,5}$) ~ 1 eV (see, e.g., Ref. [5]). For a discussion of these hints and of the related implications see, e.g., Ref. [6].