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Nuclear Physics B 908 (2016) 436–455

NUCLEAR PHYSICS B

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Neutrino oscillations and the seesaw origin of neutrino mass

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Received 29 January 2016; received in revised form 8 March 2016; accepted 21 March 2016

Available online 25 March 2016

Editor: Tommy Ohlsson

Abstract

The historical discovery of neutrino oscillations using solar and atmospheric neutrinos, and subsequent accelerator and reactor studies, has brought neutrino physics to the precision era. We note that CP effects in oscillation phenomena could be difficult to extract in the presence of unitarity violation. As a result upcoming dedicated leptonic CP violation studies should take into account the non-unitarity of the lepton mixing matrix. Restricting non-unitarity will shed light on the seesaw scale, and thereby guide us towards the new physics responsible for neutrino mass generation.

1. Introduction

Particle physics has seen two historic discoveries in less than twenty years: the confirmation of the mechanism of electroweak symmetry breaking [1] and the discovery of neutrino oscillations [2–6], both deservedly honored with the Nobel prize. The unification paradigm [7,8] and the good behavior of the electroweak breaking sector, including naturalness, perturbativity and

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http://dx.doi.org/10.1016/j.nuclphysb.2016.03.027

stability [9], have so far provided a strong theoretical motivation for new physics. Other hints are the understanding of flavor and the unification with gravity, in addition to the challenges posed by cosmological observations associated to dark matter, dark energy and inflation. Last, but not least, the need to account for non-zero neutrino mass [10,11] plays a key role in the quest for new physics [12].

The most popular mechanism of neutrino mass generation ascribes the smallness of neutrino mass as resulting from the exchange of heavy messenger particles, such as right-handed iso-singlet neutrinos and/or iso-triplet scalar bosons, known as the seesaw mechanism [12]. When formulated at low-scale this naturally implies new effects in neutrino propagation that go beyond the oscillatory behavior, as explained below. In particular, future neutrino experiments will face the challenge of disentangling "conventional" CP violation with that associated to the non-unitarity of the lepton mixing matrix, which in turn results as an indirect effect of the extra neutral heavy right-handed neutrinos.

In what follows, we briefly review current neutrino oscillation parameters and describe novel effects associated to right-handed neutrino admixture in the charged current weak interaction, expected in low-scale seesaw schemes, purely in the context of the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ paradigm. We also recompile current limits on right-handed neutrino mass and mixing parameters.

2. Three neutrino mixing and oscillations

Generic neutrino mass schemes require interactions associated to new Yukawa couplings that do not commute with those of the charged leptons, leading to the phenomenon of mixing in the charged current weak interactions, analogous to the CKM mixing of quarks [13]. However, as we will see its structure can be richer.

2.1. Lepton mixing matrix for Dirac neutrinos

The mixing of leptons arising from the non-simultaneous diagonalizability of the Dirac neutrino and charged lepton mass matrices is given by an arbitrary unitary matrix

$$U = \omega_0(\gamma) \prod_{i<j}^{3} \omega_{ij}(\eta_{ij}) \,, \tag{1}$$

where each of the ω factors is effectively 2×2, characterized by an angle and a corresponding CP phase, e.g.

$$\omega_{13} = \begin{pmatrix} c_{13} & 0 & e^{-i\phi_{13}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\phi_{13}} s_{13} & 0 & c_{13} \end{pmatrix} , \tag{2}$$

while $\omega_0(\gamma)$ is an arbitrary diagonal unitary matrix. In complete analogy with the standard model quark sector we can use the phase redefinition freedom for neutral and charged leptons to show that only one independent CP phase remains for the three Dirac neutrinos. To find this rephasing invariant parameter we use the conjugation property [14]

$$P^{-1}\, U\, P = \omega_{23}(\theta_{23}; \phi_{23} - \beta)\; \omega_{13}(\theta_{13}; \phi_{13} - \alpha)\; \omega_{12}(\theta_{12}; \phi_{12} + \beta - \alpha) \,, \tag{3}$$

with $P = diag(e^{i\alpha}, e^{i\beta}, 1)$, which allows us to identify [15],

$$\delta \leftrightarrow \phi_{13} - \phi_{12} - \phi_{23} \,. \tag{4}$$