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Review

Analysis of neutrino mass, mixing and flavor change

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A B S T R A C T

Established results on neutrino mass, mixing and flavor change (as of 2009) are briefly reviewed. Status and prospects of unknown neutrino properties (smallest mixing angle, Dirac/Majorana nature, absolute masses and their hierarchy) are also discussed.

1. Introduction

Neutrino Physics has witnessed a dramatic revolution in the past decade, after the discovery of atmospheric ν_μ oscillations in 1998. Such a breakthrough, as well as further decisive results on ν masses and mixings, have greatly raised the level interest in this field, with $O(10^3)$ "neutrino" preprints released per year, as shown in Fig. 1. These results have established a solid framework for neutrino flavor physics, but certainly they have not exhausted the discovery potential in this field: several problems remain open, and their solution will generate future peaks of interest, although perhaps on a longer timescale.

In particular, the rapid pace experienced in the past few years should not make us forget that neutrino physics is, in general, an exercise in patience. As a matter of fact, the three most basic neutrino questions have been formulated long ago in the past century:

- How small is the neutrino mass?
  (W. Pauli, E. Fermi, '30*s*);
- Can a neutrino turn into its own antiparticle?
  (E. Majorana, '30*s*);
- Do different ν flavors change ("oscillate") into one another?
  (PMNS: B. Pontecorvo; Maki, Nakagawa and Sakata, '60*s*).

However, only the last question has been positively solved, while hard work is still going on to answer the others. In this Talk, the current status of the field (as of 2009) will be reviewed, by using the above questions as a template, and by emphasizing contributions presented at this School. For more extensive and detailed overviews and bibliographies, the reader is referred to [1–5], as well as to the book [6] and to the website [7].

2. Can different ν flavors oscillate into one another? (PMNS)

The short answer is a resounding: Yes, they can! We have learned, from the results of beautiful experiments, that the neutrino flavor states (ν_α) mix with neutrino mass states (ν_i),

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U(\nu_1, \nu_2, \nu_3)^T, \quad (1)$$

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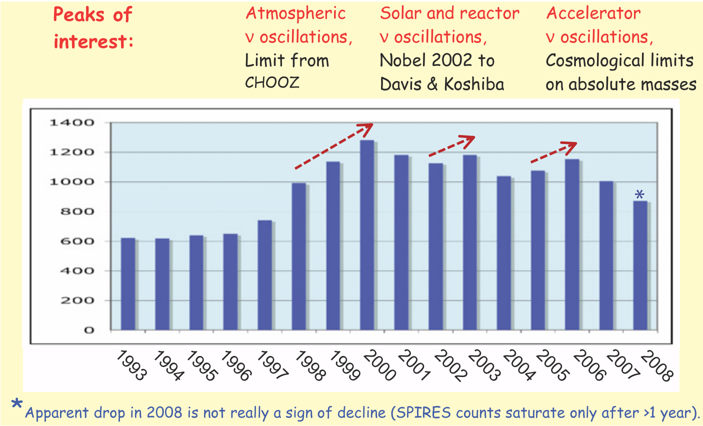

Fig. 1. Yearly distribution of preprints with "neutrino(s)" in the title, for the period 1993–2008, from the SPIRES database. Relevant peaks of interest are also indicated.

via a unitary matrix U, parametrized in terms of mixing angles θ_{ij} and a CP phase δ as:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{2}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

In general, the oscillation amplitudes are governed by the θ_{ij}'s, while the oscillation phases are determined by the squared mass differences δm^2 and $\Delta m^2 \gg \delta m^2$, hereafter defined as

$$(m_2^2, m_2^2, m_3^2) = \frac{m_1^2 + m_2^2}{2} + \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm\Delta m^2\right), \tag{3}$$

where the case $+\Delta m^2$ refers to the "normal" (quark-like) hierarchy with $m_3 > m_{1,2}$, while the case $-\Delta m^2$ refers to the "inverted" hierarchy with $m_3 < m_{1,2}$.

Assuming standard interactions, the mass-mixing parameters $(\delta m^2, \pm\Delta m^2, \theta_{ij}, \delta)$ completely define the ν flavor evolution, even in complicated cases involving forward scattering on fermion backgrounds (provided that their density profile is known). In general, the Hamiltonian H of ν flavor evolution is then the sum of three terms,

$$H = H_{\text{vacuum}} + H_{\text{matter}} + H_{\nu\nu}, \tag{4}$$

where the first one (H_{vacuum}) is kinematical, while the second one (H_{matter}) embeds effects of neutrino interactions in matter (e.g., in the Earth or in the Sun), and the third one ($H_{\nu\nu}$) describes neutrino–neutrino interactions (only relevant in high-density conditions such as core-collapse supernovae [8,9]).

A more detailed answer to Pontecorvo's question is then: We know several of the oscillation parameters governing H, but not all of them. Indeed, there are robust upper and lower limits on the squared mass differences δm^2 and Δm^2, as well as on the two angles θ_{12} and θ_{23}; however, nothing is known about the mass spectrum hierarchy [sign (Δm^2)] or the CP Dirac phase (δ). [Nonstandard neutrino interactions [10], not discussed herein, would obviously lengthen the list of unknowns.]

Eq. (2) shows that, in order to access the leptonic CP violation phase δ [11], the mixing angle θ_{13} must be nonzero. At present, this angle is bounded from above by the celebrated CHOOZ reactor neutrino data [12] (plus additional, subdominant data from a variety of different experiments [1]), and the possibility that $\theta_{13} = 0$ is still open, although perhaps slightly disfavored (see below).

Fig. 2 shows updated results on the mass-mixing parameters, as derived from a global analysis of world ν oscillation data [13]. The results are shown in terms of standard deviations n_σ from the best fit (where $n_\sigma = \sqrt{\Delta\chi^2}$ after χ^2 marginalization). Table 1 summarizes the same results in numerical form.

Known oscillation parameters. The parameters $(\delta m^2, \theta_{12})$, which drive oscillations in the (ν_1, ν_2) sector, are constrained by solar and (long-baseline) reactor neutrino experiments in the ν_e disappearance channel. In this sector, there is room for several improvements in the next future, as new data (or analyses of acquired data) will be released by the Super-Kamiokande [14], SNO [15] and Borexino [16] solar neutrino experiments, as well as by the KamLAND reactor ν experiment [17]. Their combination will not only reduce the $(\delta m^2, \theta_{12})$ uncertainties, but will also allow better checks of the low-energy behavior of the solar neutrino survival probability, of the standard solar model, and of models of the Earth (via geoneutrinos).

The parameters $(\Delta m^2, \theta_{23})$, which drive oscillations in the (ν_2, ν_3) sector, are constrained by atmospheric and (long-baseline) accelerator neutrino experiments in the ν_μ disappearance channel. Updated results have been presented here