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A view of neutrino studies with the next generation facilities

L. Stanco

INFN-Padova, Via Marzolo, 8, Padova I-35131, Italy

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ABSTRACT

Neutrino physics is nowadays receiving more and more attention as a possible source of information for the long-standing investigation of new physics beyond the Standard Model. The rather recent measurement of the third mixing angle θ_{13} in the standard mixing oscillation scenario encourages the pursuit of what is still missing: the size of any leptonic CP violation, absolute neutrino masses and the characteristic nature of the neutrino. Several projects are currently running and they are providing impressive results. In this review, the phenomenology of neutrino oscillations that results from the last two decades of investigations is reviewed, with emphasis on our current knowledge and on what lesson can be taken from the past. We then present a critical discussion of current studies on the mass ordering and what might be expected from future results. Our conclusion is that decisions determining the next generation of experiments and investigations have to be strictly based on the findings of the current generation of experiment. In this sense it would be wise to wait a few years before taking decisions on the future projects. In the meantime, since no direct path forward is evident for the future projects, the community must be committed to their careful evaluation.

1. Introduction

The current scenario of the Standard Model (SM) of particle physics, being arguably stalled by the discovery of the Higgs boson, is *desperately* looking for new experimental inputs to provide a more comfortable theory. In parallel, experiments on neutrinos so far have been an outstanding source of novelty and unprecedented results. In the last two decades several results were obtained by studying atmospheric, solar or reactor neutrinos, or more recently with neutrino productions from accelerator-based beams. Almost all these results have contributed to strengthen the flavour-SM. Nevertheless, relevant parts like the values of the leptonic CP phase and the neutrino masses are still missing, a critical ingredient being the still undetermined neutrino mass ordering. On top of that the possibility of lepton flavour violation (if e.g. neutrinos are Majorana particles), is a very open issue, experimentally strongly pursued.

Even if the Standard Model can be easily extended with right-handed neutrinos to introduce Dirac mass terms, notwithstanding the lightness of the neutrino masses points to very small and unnatural Yukawa couplings. The latter issue is likely overcome by considering a Majorana neutrino mass and some choices of see-saw mechanisms. This peculiarity of neutrinos, compared to the other charged fermions, originates from the fact that they are neutral particles. The possible Majorana nature of neutrinos would correspond to lepton-flavour violation and a real portal for new physics beyond the SM. It is

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E-mail address: luca.stanco@pd.infn.it

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intriguing and wishful that studies on neutrinos could uncover some of the solutions to the open questions in fundamental physics. However, it might even happen that all our hopes are shattered in the end, and a coherent picture of SM will continue to hold, i.e. three flavours with no Majorana mass and a *natural* mass hierarchy, together with a tiny leptonic CP-phase.

Nevertheless, there are already some measurements that do not fit the standard 3-flavour neutrino-framework hinting instead at the possible existence of one (or more) *sterile* neutrino. That is a very wide issue, as well as one experimentally strongly pursued, too. If the existence of the dark matter and its possible interplay to neutrinos are additionally taken into consideration, thus the present picture turns out to be very stimulating.

From 2012 neutrino-oscillation physics entered a new era, as many applicable measurements were collected in the meantime. From one side, phenomenological fits were continuously improved by inputs given by those measurements. A coherent picture could be expected to emerge for the four most relevant missing pieces, namely, the CP-phase, the mass ordering, the octant of the largest mixing angle θ_{23}, and the presence or not of new sterile-like states at the eV mass scale. In any case the phenomenological scenario will be tested by the ensemble of inputs providing either a coherent or not-coherent picture. From the other side, many new experimental proposals were put forward, even if some of them not yet fully funded. In the context of the strategy the neutrino community is requested to take for the future, all of these proposed future projects must be carefully evaluated and perhaps even rejected in the event that the currently running experiments and approved projects will be able to confirm and complete the *standard* scenario by the year 2020–2025 (or less).

It would be unconceivable even to think to include in this short review descriptions of all the facts today known about neutrinos together with an exhaustive discussion of the whole set of experiments and proposals for the near future. Therefore a concise attitude is adopted, either referring to the bibliography or not including on purpose many results/studies/projects not so relevant to the mainstream of the discussion, which is instead focussed on the major issues according to the judgement of the author. The paper is organised as follows. In the next section an overview of the acquired phenomenological scenario for neutrinos is presented, while in the following one a critical discussion on the future determination of the mass ordering/hierarchy (MH) is depicted. A brief description of the major on-going experiments and fully funded proposals, useful to the mainstream, follows. In the last section some final considerations and conclusions are drawn. Several issues are just mentioned and not developed, as attempted measurements of individual neutrino masses, and the studies on the production and detection of the solar and supernova neutrinos.

2. Neutrino phenomenology in the last two decades and nowadays

The most famous *hunter* of neutrinos is probably Raymond Davis, Jr.. From the late sixties, with collaborators he looked at neutrinos coming from the Sun [1]. It took almost three decades to collect about 2000 solar electron-neutrino candidates in the Homestake experiment, much less (about 1/3) than what predicted by John N. Bahcall and collaborators (see, e.g., Ref. [2] for a discussion). Even if the neutrino deficit w.r.t. the solar models was unveiled quite soon [3], the dispute was finally settled by the confirmation of the neutrino oscillation. That was reached by the observation of the oscillations in both the atmospheric-neutrino sector by Super-Kamiokande (SK) in 1998 [4] through the $\nu_\mu$disappearance[1] and the solar sector by SNO in 2002 [5] through the measurement of the neutral current (NC) interactions, equally sensitive to all the neutrino flavours. The NC measurement confirmed the predictions of the solar model, and therefore the rightness of the deficit by Davis and Bahcall as due to a flavour changing of neutrinos from the Sun.

However, the just evident neutrino mass mixing was again puzzled by the simultaneous null result of CHOOZ in 1998 [6] that looked at neutrino oscillations at a very short distance (1 km) from an anti-$\nu_e$reactor flux. The puzzle on flavours was clarified in 2002 after the KamLAND [7] measurement of the reactor-neutrino flux at an averaged distance of 180 km from several nuclear power plants. KamLAND showed evidence of the spectral distortion as function of L/E (distance over neutrino energy) providing insights of the 3-flavour structure. In Fig. 1 the (later) beautiful result by KamLAND is reported, with almost two complete oscillation cycles observed.

To better explain the general picture it is necessary to go back to the initial idea of Pontecorvo, who in 1957 introduced the concept of neutrino oscillation [9], further elaborated by Z. Maki, M. Nakagawa and S. Sakata in 1962 [10] and Pontecorvo himself in 1968 [11]. However, one had to wait until the measurement of KamLAND for a clear understanding of the mismatch between the diagonalisation of the charged lepton mass matrix and that of the neutrino mass matrix, similarly to what happens in the quark sector with the CKM matrix [12]. The mismatch is described by a unitary matrix, U_{PMNS} to honour the pioneering authors, that mixes the 3 flavour states $\nu_\alpha,\ \alpha = e, \mu, \tau,$ of the weak interactions with the 3 mass eigenstates $\nu_i,\ i = 1, 2, 3$:

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

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[1] The correct inheritance of the physics measurements and results on atmospheric neutrinos is more articulated than here reported. More experiments were actually involved, see e.g. [24].