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Next-generation atmospheric neutrino experiments

Antoine Kouchner *

Laboratoire AstroParticule et Cosmology (APC), Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris, France

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ABSTRACT

A short review on the next-generation experiments aiming to study the neutrinos produced in cosmic-ray induced atmospheric showers is presented. The projects currently proposed rely on different complementary detection techniques, from the successful water Cherenkov and magnetized tracko-calorimeter techniques to the more innovative Liquid Argon technology. As all of the proposed detectors must be deeply buried to mitigate the atmospheric muon background, many experiments are expected to be placed deep underground. Following the neutrino telescope approach, the largest ones will be located deep under the sea/ice. Several future projects are part of a wider physics program which includes a neutrino beam. For such cases, the focus is put on the expected performances with only using atmospheric neutrinos.

The main physics thread of the review is the question of the determination of the ordering of the neutrino mass eigenstates, referred to as the neutrino mass hierarchy. This falls into the broader context of the precise measurement of the neutrino mixing parameters. The expected reach of the future planned detectors in this respect is also addressed.

1. Introduction

Important progress has been made in the past two decades on determining the fundamental properties of the neutrino. A variety of experiments using solar, atmospheric, reactor and accelerator neutrinos, spanning energies from the MeV to the GeV, have provided compelling evidence for neutrino oscillations, implying the existence of non-zero neutrino masses (see e.g. Refs. [1,2] for recent reviews on the subject).

In the standard 3ν scheme, the mixing of the neutrino flavour eigenstates (ν_e, ν_μ, ν_τ) into the mass eigenstates (ν_1, ν_2, ν_3) is described by the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix U which is a product of three rotation matrices (related to the mixing angles θ_{12}, θ_{13} and θ_{23}) and a diagonal matrix containing the complex CP phase[1] δ:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (1)$$

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

Oscillation experiments are not sensitive to the absolute value of the neutrino masses but they provide measurements of the squared-mass splittings $\Delta m^2_{ij} = m^2_i - m^2_j$ ($i, j = 1, 2, 3$). In the 3ν scheme, there are two independent squared-mass differences; one is associated to the mass splitting arising from solar observations $\Delta m^2_{21} \simeq 7.5 \times 10^{-5}$ eV^2, while the other was first obtained from the atmospheric neutrino sector $|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}$ eV^2.

At present, the values of all mixing angles and squared-mass differences can be extracted from global fits of available data with a precision better than 15% [3–5]. While $\sin^2\theta_{12}$ and $\sin^2\theta_{13}$ are known with a fractional error of 5.4% and 8.5% respectively, the largest remaining uncertainty currently relates to the mixing angle θ_{23}, with an error of ∼10% on $\sin^2\theta_{23}$. It is in particular worth noticing that the octant of this angle (i.e. whether θ_{23} is smaller or larger than $\pi/4$) is currently unknown. This is particularly relevant in the context of the determination of the NMH by atmospheric detectors. In general, the impact of the current parameter uncertainties is briefly discussed at the end of Section 2.1.

The recent observation of $\overline{\nu}_e$ disappearance in several short-baseline reactor experiments [6–8] has provided the first high-significance measurement of the mixing angle θ_{13}. The relatively large value of this parameter, $\sin^2(2\theta_{13}) \simeq 0.1$, is an asset for the subsequent searches for the remaining major unknowns in the neutrino sector, and in particular for the determination of the neutrino mass hierarchy (NMH).

The ordering of neutrino mass eigenstates is indeed not determined so far. While $\Delta m^2_{21} > 0$ is fixed by matter effect resonance in the Sun, two solutions remain possible for Δm^2_{31}: the normal

* Tel.: +33 0157276156.
E-mail address: kouchner@apc.univ-paris7.fr.

[1] We have omitted here the two additional Majorana phases ξ and ζ which are irrelevant in oscillation phenomena.

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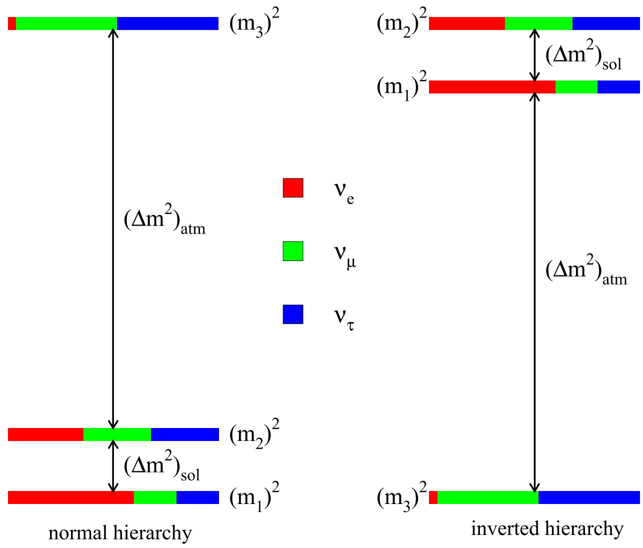

Fig. 1. Scheme of the two distinct neutrino mass hierarchies. The colour code indicates the fraction of each flavour (e, μ, τ) present in each of the mass eigenstates (ν_1, ν_2, ν_3) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: From Ref. [2].

hierarchy (NH: $m_1 < m_2 < m_3$) and the inverted hierarchy (IH: $m_3 < m_1 < m_2$), as can be seen from Fig. 1.

From a theoretical point of view, the determination of the NMH is of fundamental importance to constrain the theoretical models that seek to explain the origin of mass in the leptonic sector and the differences in the mass spectra of all elementary particles. More practically, it has also become a primary experimental goal because the NMH can have a strong impact on the potential performances of next-generation experiments with respect to the determination of other unknown parameters such as the CP phase δ (related to the presence of CP-violating processes in the leptonic sector), the absolute value of the neutrino masses, and their Dirac or Majorana nature (as probed in neutrinoless double beta decay experiments, or $0\nu\beta\beta$).

While the combination of $0\nu\beta\beta$ and direct neutrino mass experiments with cosmological constraints on $\Sigma_\nu m_\nu$ might have an indirect sensitivity to the NMH, most of the efforts currently focus on the determination of NMH via neutrino oscillation experiments (see e.g. Section 3.1 of Ref. [2] for an overview of the subject). One option uses medium-baseline (~50 km) reactor experiments such as JUNO and RENO-50, which probe the ν_e survival probability via vacuum oscillations in the low energy (~ MeV) regime [9]. These experiments may be sensitive to the NMH through the interference effects arising from the combination of the fast oscillations driven by Δm^2_{31} and Δm^2_{32}.

Another appealing strategy consists in probing the $\nu_\mu \leftrightarrow \nu_e$ oscillations (either via the study of the ν_μ survival probability or through the observation of ν_e appearance), which are directly sensitive to the Δm^2_{31} splitting. As will be detailed in the next section, this option requires long oscillation baselines and matter effects that essentially affect the ν_e-component of the propagation eigenstates. This is the oscillation channel that upcoming (such as NOνA [10] in combination with T2K [11]) and next-generation (such as CHIPS [12], LBNE [13] and LBNO [14]) accelerator neutrino experiments will be concentrating on. It is also the most relevant one for atmospheric neutrino experiments. Comparing the three approaches, one can say in short that:

- Reactor experiments could start earlier than other projects, but they require a challenging accuracy both in the relative energy resolution and in the absolute energy scale calibration.
- Accelerator-based experiments would achieve the ultimate precision on both the NMH and oscillation parameters, but are foreseen on a longer timescale.
- Atmospheric neutrino experiments can run in intermediate time scale with a good sensitivity as it will be further developed in this paper. Nonetheless, for these experiments, angular and energy resolutions are also crucial.

A more detailed comparison of the potential future projects to measure the NMH and the corresponding timelines can be found in Refs [15,16].

While the physics program of atmospheric neutrino detectors covers a large range of topics including nucleon decay searches, studies of solar neutrinos, supernovae neutrinos as well as high-energy neutrinos from cosmic origin, or even indirect searches for dark matter, in this paper, the NMH will be the main thread of the discussion. The paper is therefore organized in the following way: in Section 2, general considerations about the phenomenology of matter effects related to the question of the NMH are briefly presented, together with some remarks on the statistical approach for expressing the sensitivity to the NMH. The future projects based on the water Cherenkov technique are presented in Section 3, starting with underground detectors and followed by deep-sea(ice) projects. Future projects of magnetized iron trackers are presented in Section 4. For completeness, we also shortly mention, in Section 5, the potentials brought by future Liquid Argon Time Projection Chamber (LAr TPC) in the study of atmospheric neutrinos.

2. General considerations

2.1. Matter effects

In the 3ν framework, the $\nu_\mu \leftrightarrow \nu_e$ transition probability in vacuum can be approximated by the following formula:

$$P_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\, \sin^2 2\theta_{13}\, \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \qquad (2)$$

where E_ν is the neutrino energy and L stands for the oscillation baseline. For atmospheric neutrinos, the baseline is the distance between the neutrino production point in the atmosphere and the interaction point in the detector. For upward going neutrinos through the Earth sphere, this distance is proportional to the cosine of the zenith angle $\cos\theta$. Relation (2) establishes the direct link between the transition probability and the value of θ_{13}; it also shows that the $\nu_\mu \leftrightarrow \nu_e$ transition in vacuum is at first order insensitive to the sign of Δm^2_{31}.

This sign can however be revealed once matter effects come into play along the neutrino propagation path. Contrary to the other flavours, the ν_e component can indeed undergo charged-current (CC) interactions with the electrons in matter and consequently acquire an effective potential $A = \pm\sqrt{2}G_F N_e$, where N_e is the electron number density of the medium, G_F is the Fermi constant and the $+(-)$ sign is for ν_e $(\overline{\nu}_e)$. In the case of neutrinos propagating in a medium with constant density, the $\nu_\mu \leftrightarrow \nu_e$ transition probability now reads[2]

$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\, \sin^2 2\theta^m_{13}\, \sin^2\left(\frac{\Delta^m m^2_{31} L}{4E_\nu}\right), \qquad (3)$$

[2] This expression is obtained under the assumption $\frac{\Delta m^2_{12} L}{4E_\nu} \ll 1$, valid for atmospheric neutrinos ($E_\nu \geq \mathcal{O}$ (GeV)) and $L = \mathcal{O}(10^3$ km).