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The neutrino properties and mass determination

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Summary. — The determination of mass pattern and hierarchy is still one of the main issues of neutrino physics, relevant both for elementary-particle physics and astrophysics. The recent results in this field are briefly discussed, together with the main aspects of theoretical analysis and the perspectives of future medium baseline reactor antineutrino experiments and in particular of the JUNO experiment, that will start data taking in a few years from now.

The long-standing problem of neutrino mass determination has great relevance both for elementary-particle physics, astrophysics and cosmology. The data from different sources (atmospheric, solar, reactor and accelerator neutrinos) proved the original Pontecorvo's idea of flavor oscillation and, therefore, they clearly indicated the need to go beyond the Standard Model (SM), in which neutrino is described as a massless left-handed fermion. Two different theoretical scenarios are still possible: neutrino is a Majorana fermion, coinciding with its antiparticle, or the mass content of the theory must be enlarged, including a sterile right-handed neutrino. Different possible models, beyond the SM can accomodate a neutrino mass term and the study of oscillation and mass patterns offers a unique opportunity to test these models and discriminate between them.

After 2002, when the SNO and the first KamLAND results (combined with the previous radiochemical experiments and SuperKamiokande) definitely solved the long-standing solar-neutrino problem [1], the main issue in the oscillation pattern was the determination of the θ_{13} mixing angle. Ten years later the three Short Baseline (SBL) reactor experiments (Double Chooz, Daya Bay and RENO) [2] proved that the mixing angle between the first and the third neutrino generation is small but significantly different from zero ($\theta_{13} \simeq 8°$–$9°$), confirming the hints coming by the Long Baseline (LBL) accelerator experiments (mainly T2K and MINOS) [3] and by global phenomenological fits [4]. This opened the way to neutrino experiments looking for leptonic CP violation and aiming to determine the exact neutrino mass hierarchy. In fact, the possible CP violation effects should be proportional to $\sin^2(2\theta_{13})$ and, in a very similar way, the amplitude of corrections to oscillation probabilities sensitive to the neutrino mass hierarchy depends upon the same quantity.

The ordering of the mass eigenvalues is one of the main open issues of neutrino physics. From oscillation experiments one can extract the differences of the squared mass eigenvalues ($\Delta m^2_{ij} = m^2_i - m^2_j$), but no direct indications about the real mass scale. Besides, at present, two different possible mass patterns are still compatible with the data coming from the different neutrino experiments: the so-called normal hierarchy, NH, (in which the third mass eigenvalue is the highest one, separated from the other 2 eigenvalues by the $\Delta m^2_{\rm atmospheric}$ mass gap) and the inverted hierarchy, IH, (in which the mass gap between the third and the two other mass generations is always the one ruling atmospheric oscillations, but the third mass eigenvalue is the lightest one, that is $m_2 > m_1 > m_3$). The determination of the right mass hierarchy would be fundamental, not only do discriminate between different possible extensions of the Standard Model, but also to estimate the discovery potential of various experiments. This is particularly true for the experiments searching for neutrinoless double-beta decays ($0\nu2\beta$), essential to establish the neutrino nature (Dirac or Majorana fermion) and eventually to find the mass scale. In case of inverse mass ordering to test the existence of $0\nu2\beta$ it should be sufficient to reach values of the neutrino effective mass of the order of a few hundredths of eV (depending upon the value of the Majorana phases), accesible to the future generation of experiments. In case of normal ordering, instead, the mass scale would be at least one order of magnitude lower and the search for $0\nu2\beta$ would be extremely challenging, if not impossible. The analysis is even more tricky, because in case one adds an additional sterile neutrino, passing from the 3 to the 3 + 1 pattern, the situation is essentially reversed and the NH and the IH cases are exchanged, as recently shown in [5].

Quite recently important hints about the mass ordering have been obtained by the analysis of the LBL data, and mainly of the ones obtained by the NOνA experiment, that studied the ν_e appearance and the ν_μ disappearance signals. By checking the consistency between these data and the reactor experiments results, one gets a general indication in favor of the normal hierarchy, with a statistical significance that can reach $3\,\sigma$, but is strongly dependent upon the region considered for the CP violation parameter δ [6, 7]. In the near future significant improvements are expected for the LBL sensitivity (in particular a 13 times larger exposure is foreseen for both NOνA channels) and, in principle, additional inputs could come also from new data analyses of SuperKamioKande and other atmospheric neutrino experiments and by next global fits. However, it is highly probable that the final answer on the mass hierarchy will come only by future dedicated experiments, with neutrino beams from reactors (JUNO [8], RENO50 [9]), LBL accelerators (LBNF/DUNE [10]) and atmospheric (PINGU and ORCA) [11].

The JUNO (Jiangmen Underground Neutrino Observatory) [8] is a multipurpose neutrino reactor experiment, under construction close to Kaiping, in the South of China. The detector, a huge, 20 ktons, liquid scintillator (Linear Alkyl-Benzene), will operate underground with over 700 m overburden and will receive reactor antineutrinos mainly from two different nuclear power plants, with a total of 10 cores in the original project. The average distance from the reactor to the detector is around 53 km. This medium baseline is optimized in such a way that, for typical antineutrino energies of a few MeV, one is in the region of the maximum of oscillation in the 2-1 sector, corresponding also to the maximum sensitivity to the higher order corrections to the oscillation probability depending upon the mass hierarchy, as is shown in fig. 1.

In addition to its main goal, the determination of the mass hierarchy, JUNO will investigate, starting from 2020, other important issues [8, 12]. It should perform a measurement, at 1% or subpercent level, of some mass and mixing oscillation parameters, as summarized in table I. The JUNO experiment could analize also the neutrinos coming

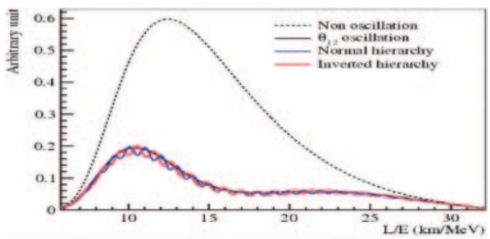

Fig. 1. – The reactor antineutrino spectrum as a function of the ratio L/E between the baseline and the $\bar{\nu}_e$ energy. One can see (for both mass hierarchies) the fast oscillating correction terms superimposed to the general oscillation pattern. Taken from [8].

from extraterrestrial and terrestrial sources, taking advantage from its huge mass and the very good energy resolution, which will be a technical characteristic crucial also to make possible the mass hierarchy discrimination. The detection of Supernova (SN) burst neutrinos and of diffuse SN background could give answers to physical and astrophysical questions, like the knowledge of the mechanisms ruling stars formation and evolution, the SN collapse and explosion and the related production of the heavy chemical elements. Also for solar neutrinos, JUNO measurements (mainly of ^{7}Be and ^{8}B ν_e) could be relevant for still unresolved problems, like the determination of solar abundancy, related to the solar metallicity problem, and the detailed study of oscillation probability as a function of ν_e energy, particularly in the transition zone between the vacuum dominated and the matter enhanced regions, corresponding to the lower end of the ^{8}B ν_e spectrum [1]. The success of these analyses will require, in addition to a good energy resolution, also the capability of reaching levels of radiopurity comparable with the Borexino ones. The measurement of geoneutrinos at JUNO could contribute, together with the KamLAND and Borexino data, to the determination of the Th and U abundance in the Earth, shedding light on the relative relevance of the radiogenic contribution to the heat flow of the Earth and contributing to discriminate between different geological models. The main experimental issue for this measurement will be the capability to disentangle the geoneutrino signal from the very high background due to reactor antineutrinos; hence the sensitivity to this signal could be particularly interesting during the first period of run of the experiment, when the power of some of the reactor cores could be lower than the designed one.

Concerning the mass hierarchy study, the $\bar{\nu}_e$ survival probability can be written as

$$\begin{aligned} P_{ee} = 1 - \sin^2(2\theta_{12})\, c_{13}^4 \, \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \\ - \sin^2(2\theta_{13}) \left[c_{12}^2 \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right] \end{aligned}$$

with $c_{ij} = \cos(\theta_{ij}), s_{ij} = \sin(\theta_{ij})$ and $\Delta m^2_{ji} = m^2_j - m^2_i$. The last term of P_{ee} can be written in the form: $\frac{1}{2}\sin^2(2\theta_{13})[1-(1-\sin^2(2\theta_{12})\sin^2(\Delta_{21}))^{1/2}\cos(2|\Delta_{ee}|\pm\phi)]$, introducing the notations: $\Delta_{ji} = (\Delta m^2_{ji} L)/(4E)$ and $\Delta m^2_{ee} = (\cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32})$(1). The

(1) For a detailed discussion on the theoretical aspects and the subtlelties connected to the better expression to use for oscillation probability, see also [13], in addition to [8].

Table I. – *Present accuracy and expected improvements at JUNO for some parameters.*

Parameter	Current accuracy	JUNO
Δm^2_{21}	4%	0.6%
$\lvert\Delta m^2_{32}\rvert$	4%	0.6%
$\sin^2\theta_{12}$	5%	0.7%

angle ϕ is defined in such a way that $\sin(\phi)$ and $\cos(\phi)$ correspond to combinations of the mass and mixing parameters Δm^2_{21} and θ_{12}. The sign of ϕ in the last term of the oscillation probability changes according to the mass hierarchy ($+1$ for NH and -1 in case of IH). Therefore, the phase of the fastly oscillating term (superimposed to the general oscillation pattern) leads to a contribution of opposite sign in the cases of the two different hierarchies and the number of detected inverse β decay events depends also on the mass hierarchy, in addition to the other oscillation parameters. By fitting the data as a function of oscillation parameters (taking into account also all other neutrino experiments) and comparing the values of the χ^2 minima for the best fit points in the NH and the IH cases, it is possible to discriminate the two hierarchy cases. For a poor energy resolution, a solution with the wrong mass hierarchy risks to be indistinguishable from the right hierarchy solution, but for an energy resolution equal to or better than $\frac{3\%}{\sqrt{E}}$ it should be possibile to discriminate the 2 mass hierarchies at a 3–4 σ confidence level [8].

Differently from LBL experiments looking for mass hierarchy, JUNO and RENO50 plan to study vacuum (instead of matter induced) oscillations and, hence, they will not sufffer from the uncertainty on Earth density profile and the CP-violating phase ambiguity. Moreover, they do not depend on the θ_{13} value (affecting only the amplitude of the corrections they are looking for) and depend only mildly on 3-4 flavor pattern.

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