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The neutrino mass ordering and the JUNO experiment

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Summary. — Neutrino mass hierarchy has a significant impact on model building and on present and future experiments. It can be investigated in medium baseline reactor experiments, like JUNO, whose characteristics and physics program are discussed here.

1. – The neutrino mass hierarchy

We do not know yet the neutrino absolute mass scale and the only information we can extract from experiments are the differences of the squared mass eigenvalues. The two possible scenarios still compatible with data are known as Normal and Inverted Hierarchies (NH, IH). In the first case the 3rd mass eigenvalue is the highest one, separated from the others by a larger mass gap, corresponding to the atmospheric and LBL accelerator value (for updated values of oscillation parameters see [1]) and the "solar" Δm^2 is $\Delta m^2_{21} = m^2_2 - m^2_1 = \Delta m^2_{31} - \Delta m^2_{32}$. In the IH case, instead, $m_3 < m_1 < m_2$ and the relation becomes $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$. Establishing the real hierarchy is fundamental for model building and for the discovery potential of the experiments on neutrinoless double β decays and/or leptonic CP violation [2]. The study of this puzzle, by looking at the hierarchy dependence of $\bar{\nu}_e$ inverse β decay at medium baseline reactors, as suggested in [3] and made possible by the relatively large value of $\sin^2(2\theta_{13})$, is the main goal of JUNO (Jiangmen Underground Neutrino Observatory) experiment [4]. The $\bar{\nu}_e$ survival probability is given by: $P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta \mathrm{m}^2_{21}\mathrm{L}}{4\mathrm{E}}\right) - P_{13}$, where P_{13} denotes the contribution sensitive to mass hierarchy (see [4]):

$$P_{13} = \sin^2(2\theta_{13})\left[\cos^2(\theta_{12})\,\sin^2\left(\frac{\Delta \mathrm{m}^2_{31}\mathrm{L}}{4\mathrm{E}}\right) + \sin^2(\theta_{12})\,\sin^2\left(\frac{\Delta \mathrm{m}^2_{32}\mathrm{L}}{4\mathrm{E}}\right)\right] =$$
$$= \frac{1}{2}\sin^2(2\theta_{13})\left[1 - \sqrt{1 - \sin^2(2\theta_{12})\,\sin^2\left(\frac{\Delta \mathrm{m}^2_{21}\mathrm{L}}{4\mathrm{E}}\right)}\,\cos\left(2\left|\frac{\Delta \mathrm{m}^2_{ee}\mathrm{L}}{4\mathrm{E}}\right| \pm \phi\right)\right].$$

The phase factor ϕ (defined so that $\sin(\phi)$ and $\cos(\phi)$ are combinations of the 1-2 oscillation parameters) is positive in case of NH and negative for IH. Therefore, the spectrum is characterized by fastly oscillating terms, with opposite phases for the two hierarchy cases, superimposed to the general oscillation pattern and to distinguish the right hierarchy a large detector and a good energy resolution are needed. In addition to this, the JUNO baseline from the detector to the main $\bar{\nu}_e$ reactor sources (10 nuclear cores in 2 different power plants) is optimized to be in the region (53 km) of the maximum 1-2 oscillation.

2. – The JUNO physics and potentialities

The JUNO experiment [4] will soon become operative in the south of China, with an underground ($\geq$700 m of rock overburden) detector made up by 20 ktons of liquid scintillator (LAB+PPO+bis-MSB), with a very high photon yield ($\simeq$ 1200 p.e./MeV), contained in an acrylic sphere of 35.4 m of diameter, sustained by a steel structure and surrounded by large (20$''$) and small (3$''$) photomultipliers. The inverse β decay $\bar{\nu}_e + p \rightarrow e^+ + n$, with $E_{\bar{\nu}} \geq 1.8\,\mathrm{MeV}$, will produce a coincidence signal of an e^+ and a 2.2 MeV γ ray from the neutron capture. By means of a χ^2 analysis taking into account, in addition to JUNO data, the results of all neutrino experiments, one can distinguish between the two possible mass hierarchies and the difference between the χ^2 values for the NH and IH best fit points is a statistical indicator of the experiment discrimination power. JUNO is designed to reach a very good energy resolution ($\sigma(E)/E \leq 3\%/\sqrt{E}$) and this should guarantee (after 6 years of data taking with the nominal reactor $\bar{\nu}$ flux) the mass hierarchy determination at 3-4 σ of C.L., with the advantage, with respect to the LBL accelerator and atmospheric experiments, that the result does not suffer from uncertainty on the Earth density profile and ambiguity on CP violation phase and it does not depend on the θ_{13} value and only mildly on the possible addition of sterile neutrinos. For a detailed discussion about the rich JUNO physics program see [2, 4]. JUNO should improve significantly the determination of $\Delta m^2_{21}, \Delta m^2_{31(2)}$ and $\sin^2(\theta_{12})$, reaching the subpercent level; it could study SuperNova neutrinos and extract important information on geoneutrinos (it is expected to detect in its 1st year more events than the ones collected by that time by KamLAND, Borexino and SNO+). It will also investigate the ^{7}Be and the ^{8}B contributions to solar neutrino spectrum, with the aim to improve the flux determination (interesting also for the solar metallicity problem) and check the consistency of the LMA solution, by looking at the spectrum shape in the transition region between the low energy vacuum oscillation and the higher energies, where the MSW mechanism dominates. The search for possible anomalies in this pattern and the comparison between the oscillation parameters extracted by JUNO and the values from other experiments (like HyperKamiokande) will also offer the opportunity of searching for eventual Non Standard Neutrino Interactions.

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