PROCEEDINGS OF SCIENCE

JUNO's Sensitivity to the Neutrino Mass Ordering

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The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kt liquid scintillator detector equipped with 17612 20-inch PMTs as well as 25600 3-inch PMTs located 700 m underground in southern China. It features a broad physics program with a primary goal of determining the neutrino mass ordering to 3σ in about 6 years. With an unprecedented energy resolution better than 3% at 1 MeV, it will measure the spectrum of antineutrinos emitted from two nuclear power plants located 53 km from the detector. For the success of JUNO's neutrino mass ordering determination and its oscillation parameter precision measurement program, an accurate knowledge of the emitted reactor neutrino spectrum is crucial. Therefore, a satellite detector with 2.8 tons of gadolinium-doped liquid scintillator will be constructed in a distance of 30 m from one of the reactor cores to provide a precise measurement of the unoscillated spectrum with an energy resolution better than 2% at 1 MeV. This contribution will present studies on the sensitivity of the JUNO detector to determine the neutrino mass ordering in combination with its satellite detector called TAO.

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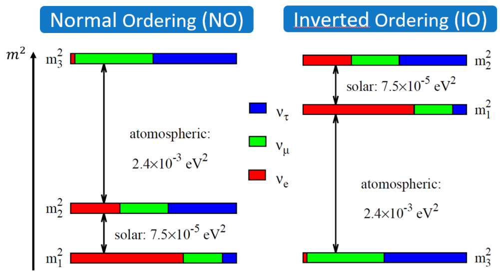
1. Physics Motivation

Neutrinos are electrically neutral fermions of very low mass. While the exact values of the three neutrino masses m_1, m_2, and m_3 are not known, it is known that $m_2 > m_1$. However, it is not known if $m_3 > m_2$ or $m_3 < m_1$, which gives two options for the neutrino mass ordering (NMO), the first being called normal ordering (NO) and the second inverted ordering (IO). This is illustrated in the left part of figure 1. Regarding neutrino oscillations, the survival probability of electron antineutrinos depends on the actual NMO which can be observed when measuring the neutrino spectrum with a high resolution detector. This is the main goal of the Jiangmen Underground Neutrino Observatory. The right plot in figure 1 exemplarily shows the dependency of the spectrum measured with JUNO after 6 years on four oscillation parameters for both NMOs.



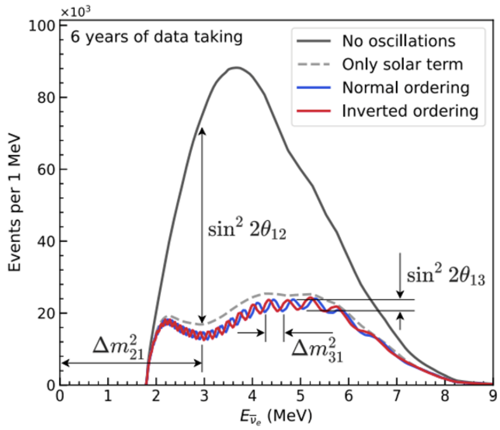


Figure 1: The left figure illustrates the differences of the squared neutrino masses and how they are arranged in the case of normal or inverted ordering. The plot on the right shows the measured JUNO spectrum for 6 years of data taking for the case of no oscillation (black), solar term only (gray dashed), and with all oscillation terms for the assumption of NO (blue) and IO (red). Figure adapted from [1].

2. Detector Design

The JUNO detector [1] is located at a distance of 53 km from two nuclear power plants with a total of 8 reactor cores and a combined thermal power of 26.6 GW. Its central detector consists of an acrylic sphere with a diameter of 35.4 m filled with 20 kt of LAB-based liquid scintillator. The acrylic sphere is surrounded by 17612 20-inch photomultipier tubes (PMTs) and 25600 3-inch PMTs mounted on a stainless steel supporting structure. The central detector will be surrounded by a cylindrical water Cherenkov muon veto filled with 34 kt of ultra pure water equipped with 2400 20-inch PMTs. The JUNO detector is designed to have an energy resolution equal or better than 3% at 1 MeV.

To provide a reference of the unoscillated reactor neutrino spectrum, a satellite detector is constructed. The Taishan Antineutrino Observatory (TAO) [2] will be located at a distance of 44 m and 217 m resp. from the Taishan reactor cores. It features an acrylic vessel filled with 2.8 tons of

Gd-loaded liquid scintillator. The sphere is surrounded by a copper shell with a Silicon photomuliplier array of 10 m^2 (4000 pcs.). To reduce dark noise, the detector will be cooled down to $-50°$ C to achieve an energy resolution better than 2% at 1 MeV.
In both detectors, the reactor antineutrinos are detected via inverse beta decay (IBD)

$$\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n} \quad , \tag{1}$$

where the electron antineutrino interacts with a free proton in the detector and produces a positron and a neutron. The positron deposits its energy in the scintillator and annihilates with an electron creating two 511 keV photons which together produce the prompt signal while the neutron thermalizes and is captured by hydrogen (JUNO) or gadolinium (TAO) releasing 2.2 MeV or 8 MeV photons respectively which gives a delayed signal around 200 μs later. The coincidence of prompt and delayed signal gives a unique signature to identify the IBD signal [1], [2].

3. Sensitivity Analysis

The expected antineutrino spectrum measured in the JUNO and TAO detectors is calculated taking into account [3]

- the emitted reactor antineutrino spectrum $S(E_\nu)$
- the survival probability $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}(E_\nu)$ for electron antineutrinos for the distances from the reactors to the detectors depending on the NMO
- the detector response containing
  - the IBD cross section $\sigma_{\mathrm{IBD}}(E_\nu)$
  - the energy leakage matrix (*TAO only*)
  - the liquid scintillator non-linearity (LSNL) which is assumed to be the same in both detectors
  - the energy resolution of the detectors
  - the IBD event selection efficiency
- and the expected backgrounds at the detector locations.

For both NMOs an Asimov dataset X of the expected measured spectrum is generated. The χ^2-function, which is being minimized, is defined as

$$\chi^2 = [X - \mu(\theta, \eta)]^T \, V^{-1} \, [X - \mu(\theta, \eta)] + \left(\eta - \eta^0\right) V_\eta^{-1} \left(\eta - \eta^0\right) \tag{2}$$

where V is the covariance matrix (containing statistical errors and bin-to-bin uncertainties) and $\mu(\theta, \eta)$ the fit model for the expected signal with the three free oscillation parameters θ (Δm^2_{31}, Δm^2_{21}, $\sin^2 2\theta_{12}$) and 73 constrained nuisance parameters η with the corresponding covariance matrix V_η.
For the combined JUNO+TAO analysis, the reactor antineutrino spectrum for the isotope i is parametrized as a piecewise exponential in every energy segment j by

$$S_{ij}(E^\nu) = n_j k_{ij} \mathrm{e}^{-b_{ij}(E^\nu - E^\nu_j)} \tag{3}$$

with $E^\nu \in (E^\nu_j, E^\nu_{j+1})$. The parameters k_{ij} are defined by the antineutrino yield of the input model, b_{ij} are chosen that the whole function is continuous, and n_j are additional free parameters that account for the ratio of the observed to the predicted number of events in each energy segment j. Since the parameters n_j appear in both the JUNO and TAO model, possible deviations of the observed spectrum from the input spectrum model are corrected by the fit.
The NMO discriminator is finally given by the difference between the two minimum χ^2 values for the IO and NO hypothesis fit to the Asimov dataset X with specific NMO

$$\Delta\chi^2_{\text{min}} = \chi^2_{\text{min}}(\text{IO}) - \chi^2_{\text{min}}(\text{NO}) \quad . \tag{4}$$

4. Results for the NMO Sensitivity

From three independent analysis groups within the JUNO collaboration a consistent result for JUNO's median sensitivity to the NMO was obtained to be 3σ for an exposure of 6 years$\times$26.6 GW_{th} with an energy resolution of 2.9% @ 1 MeV for the assumption of a true NO. The left plot in figure 2 shows the expected NMO sensitivity as a function of the exposure for both mass orderings in the cases of statistic uncertainties only as well as with all systematic uncertainties. Besides exposure and systematic uncertainties also the energy resolution highly affects the NMO sensitivity. The right plot in figure 2 shows the contour of $|\Delta\chi^2_{\text{min}}|$ as a function of exposure and energy resolution at 1 MeV for the assumption of a true NO.

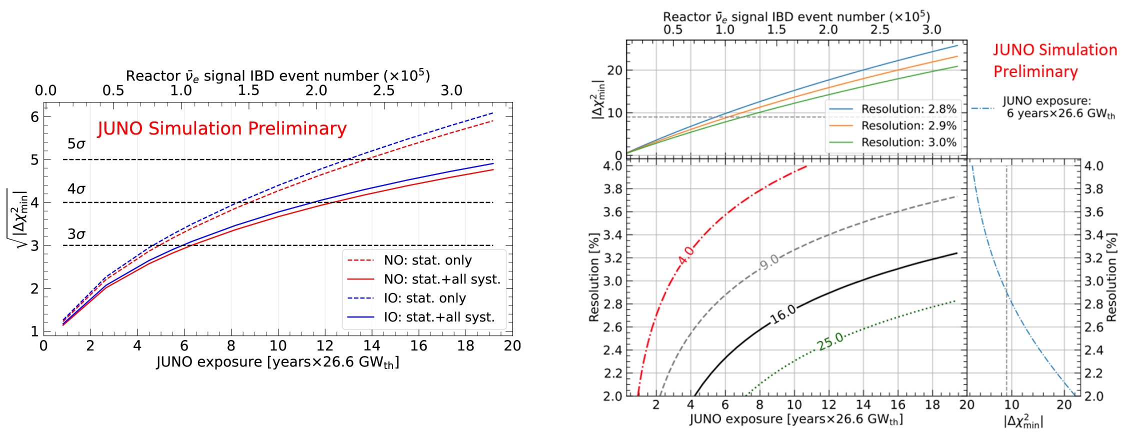


Figure 2: The left plot shows the NMO sensitivity as a function of the exposure for true NO and IO. The dashed line shows the expected sensitivity for statistics only and the solid line if all systematic uncertainties are taken into account. Due to the higher statistics in case of a true IO caused by the shifted oscillation probability compared to NO, the median sensitivity will be larger in case of true IO. The plot on the right displays the contour of $|\Delta\chi^2_{\text{min}}|$ as a function of exposure and energy resolution at 1 MeV for the assumption of a true NO. The red, gray, black, and green lines correspond to 2σ, 3σ, 4σ, and 5σ significance. The upper panel in the right plot shows the $|\Delta\chi^2_{\text{min}}|$ as a function of the exposure for an energy resolution of 2.8%, 2.9%, and 3.0% at 1 MeV. The panel on the right shows the $|\Delta\chi^2_{\text{min}}|$ as a funtion of the energy resolution at 1 MeV for an exposure of 6 years $\times$ 26.6 GW_{th}.

5. Conclusions

Taking into account all systematics in a combined JUNO+TAO analysis, JUNO's median sensitivity to the NMO will be 3σ for about 6 years $\times$ 26.6 GW_{th} exposure. This result was obtained by three independent analysis groups and a paper on these results will be published soon.

References

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