JUNO's Sensitivity to Neutrino Mass Ordering
Чувствительность эксперимента JUNO к упорядоченности масс нейтрино

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Jiangmen Underground Neutrino Observatory (JUNO) это сцинтилляционный детектор с массой мишени 20 кт, который строится на юге Китая. Одной из основных целей эксперимента является определение упорядоченности масс нейтрино. Для этого измерения JUNO будет использовать электронные антинейтрино от восьми ядерных реакторов, расположенных на расстоянии 52,5 км от детектора. Для разрешения быстрой осцилляционной картины в спектре и определения упорядоченности масс нейтрино JUNO будет необходимо иметь энергетическое разрешение σ равное 3% при энергии 1 МэВ и неопределенность энергетической шкалы менее 1%. Данная статья посвящена последним результатам анализа чувствительности JUNO к упорядочению масс нейтрино.

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator detector that is under construction in southern China. One of the main goals of the experiment is to determine the neutrino mass ordering. For this measurement, JUNO will use electron antineutrinos from eight nuclear reactors located at an optimized baseline of 52.5 km. To resolve fast oscillatory pattern in the spectrum and determine the neutrino mass ordering, JUNO will need energy resolution σ of 3% at 1 MeV and energy scale uncertainty lower than 1%. This paper covers recent results of JUNO's sensitivity analysis for neutrino mass ordering.

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Introduction

In the last few decades neutrino physics has advanced remarkably. Currently we have precise measurements of several key parameters: $\sin^2\theta_{12}$ (4.2% uncertainty), Δm^2_{21} (2.4% uncertainty), $|\Delta m^2_{31}|$ (1.1% uncertainty), $\sin^2\theta_{13}$ (3.2% uncertainty), and $\sin^2\theta_{23}$ (3.6% uncertainty) [1]. However, some questions remain, such as the so-called Neutrino Mass Ordering (NMO). While

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it was shown by solar oscillation experiments that $\Delta m^2_{21} > 0$ [2], there are still two possible scenarios for the sign of Δm^2_{31}. One possibility, Normal Ordering (NO), is that the third neutrino mass eigenstate m_3 is the heaviest (i. e. $\Delta m^2_{31} > 0$), another possibility, Inverted Ordering (IO), is that m_3 is the lightest one (i. e. $\Delta m^2_{31} < 0$). Determining the neutrino mass ordering is essential for improving our knowledge of the fundamentals of particle physics. It can have a significant impact on cosmology, flavor physics, and the search for neutrinoless double beta decay.

JUNO experiment

The Jiangmen Underground Neutrino Observatory (JUNO) detector is currently under construction in southern China. 20 kton of organic liquid scintillator inside a 35.4 m diameter acrylic sphere will be used as a target. The JUNO's photodetection system will include 17612 large 20-inch photomultipluer tubes (LPMTs) and 25600 small 3-inch photomultipluer tubes (SPMTs) [3]. One of the primary goals of the experiment is to determine the NMO. JUNO will accomplish this by studying the fast oscillation pattern in the oscillated antineutrino spectrum at a baseline of 52.5 km.

JUNO will detect electron antrineutrinos from 8 nuclear reactors with total thermal power of 26.6 $\mathrm{GW_{th}}$ via Inverse Beta Decay (IBD) reaction $\bar{\nu}_e + p \to e^+ + n$. The positron rapidly deposits its energy into the liquid scintillator and then annihilates, forming a prompt signal on a timescale of a few nanoseconds. At the same time, a neutron scatters in the liquid scintillator before being captured by a hydrogen or carbon nucleus with probabilities of 99% and 1%, respectively. The gamma signal from nuclear relaxation with an energy of 2.22 MeV or 4.95 MeV respectively forms a delayed signal approximately 220 μs after the initial IBD reaction. The energy signature along with temporal and spatial correlations of prompt-delayed pairs allows for the effective separation of the signal from background events.

Figure 1 shows the expected JUNO antineutrino spectra for 6 years of data taking for two NMO scenarios, assuming perfect energy resolution. To resolve oscillatory peaks, precisely define their positions, and determine the NMO, JUNO must achieve an energy resolution σ better than 3% at 1 MeV and an energy scale uncertainty of less than 1%.

Additionally, JUNO will have a satellite detector called TAO (Taishan Antineutrino Observatory) located near one of the reactors. The main goal of TAO is to provide a precisely measured reference antineutrino spectrum for JUNO, making the determination of the neutrino mass ordering model-independent [5].

JUNO's Detector Response

The JUNO energy response model incorporates three effects: energy transfer in the IBD reaction, liquid scintillator non-linearity, and energy resolution.

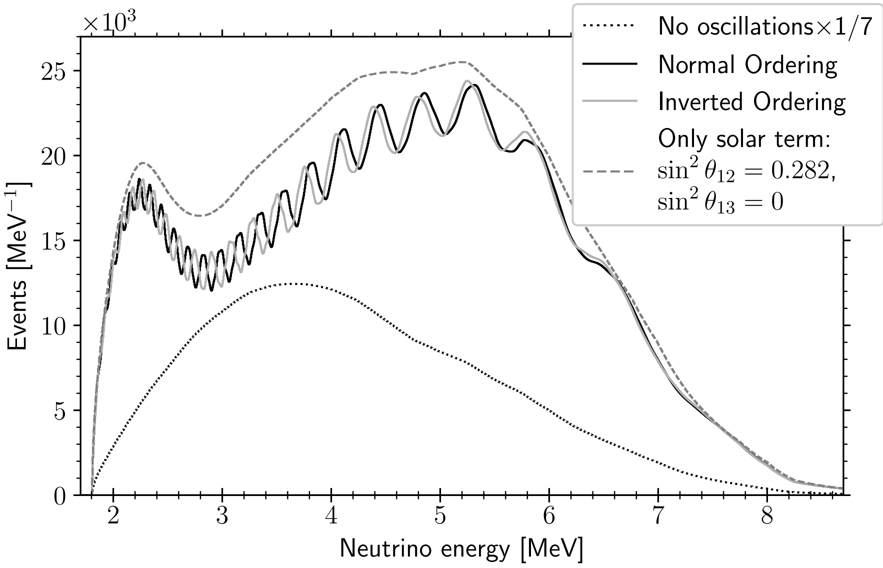

Fig. 1. The expected antineutrino spectra at the JUNO detector after 6 years of data taking, assuming perfect energy resolution [4]. It shows scenarios with (solid and dashed lines) and without (dotted line) oscillations, where black and gray solid lines represent normal and inverted ordering, respectively. For improved visibility, the dotted line is scaled down by a factor of 7.

Energy transfer in the IBD reaction is calculated by integrating the IBD differential cross-section over the positron scattering angle and energy. The kinetic energy of the positron along with the two 0.511 MeV annihilation photons is assumed to be fully deposited in the detector and is defined as E_{dep}. Approximatly, E_{dep} equals $E_\nu - 0.782$ MeV.

Due to liquid scintillator quenching and Cherenkov radiation effect, relation between E_{dep} and visible energy in the detector under assumption of perfect energy resolution E_{vis} is not linear. Thus, detector non-linearity function is introduced and defined as a ratio $E_{\mathrm{vis}}/E_{\mathrm{dep}}$.

Subsequently, the visible energy E_{vis} undergoes further smearing due to the finite energy resolution of the detector, parameterized by the following equation:

$$\frac{\sigma_{E_{\mathrm{rec}}}}{E_{\mathrm{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\mathrm{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\mathrm{vis}}}\right)^2}, \tag{1}$$

where $a = 2.61\%\ \sqrt{\mathrm{MeV}}$ is the term driven by the Poisson statistics of the total number of detected photoelectrons, $c = 1.20\%$ MeV is dominated by the PMT dark noise, and $b = 0.64\%$ is dominated by the detector's spatial non-uniformity.

Figure 2 illustrates the energy spectrum at various stages of applying detector response effects, along with the nonlinearity and energy resolution curves [6].

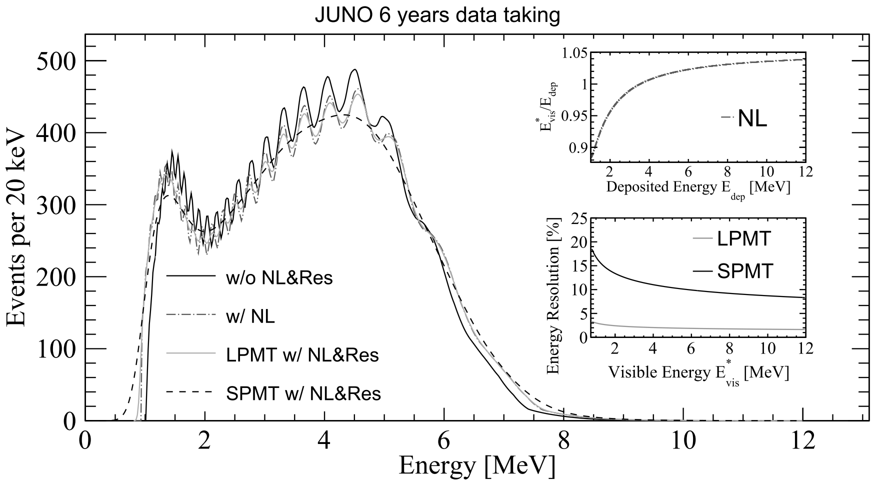

Fig. 2. Impact of detector response on the IBD spectrum [6]. The upper right inset illustrates the liquid scintillator nonlinear energy response. The lower right inset displays the energy resolution as a function of visible energy for LPMT and SPMT systems. The main panel presents the deposited energy spectrum from IBD reactions over 6 years of JUNO data under various conditions: without detector nonlinearity and energy resolution (black solid), with nonlinearity only (dark grey dash-dotted), and with both effects for LPMT (light gray solid) and SPMT (black dashed) systems. Fast oscillations are not distinguishable in the SMPT system due to low energy resolution. The fast oscillation pattern driven by Δm^2_{31} is not distinguishable in the SPMT system due to insufficient energy resolution.

In this work, the sensitivity to neutrino MO is estimated in a Gaussian limit, where median sensitivity is defined as $n = \sqrt{|\Delta\chi^2_{\rm min}|}$, where $\Delta\chi^2_{\rm min}$ is a difference between minimized χ^2 function under assumption of Normal Ordering (NO) and Inverted Ordering (IO) respectively:

$$\Delta\chi^2_{\rm min} = \min\chi^2_{\rm IO} - \min\chi^2_{\rm NO}. \tag{2}$$

Data without fluctuations (Asimov data) is used for the analysis.

The result of the analysis is shown in the Figure 3. After about 7.1 years of data taking with assumption of 11/12 duty factor for the reactors, JUNO will reach 3σ median sensitivity to NMO [4]. Dominant sources of uncertainty are due to the residual backgrounds, limited precision of the reference antineutrino spectrum, and detector non-linearity effects.

Conclusion

JUNO will reach 3σ median sensitivity to NMO after about 7.1 years of data taking, which corresponds to an exposure of 6.5 years $\times$ 26.6 $\mathrm{GW_{th}}$. The result is obtained considering events from reactor antineutrinos only.

Funding

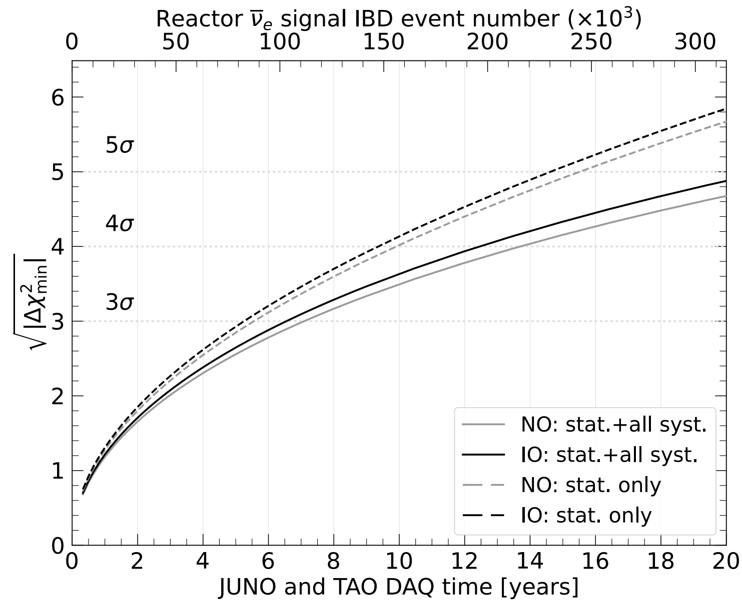

Fig. 3. Evolution of the NMO discriminator $\Delta\chi^2_{\min}$ over JUNO and TAO data taking time for both Normal Ordering (NO, black) and Inverted Ordering (IO, gray) scenarios [4]. Horizontal gray dotted lines indicate 3σ, 4σ, and 5σ significance levels. Solid lines represent results including full systematic uncertainties, while dashed lines show statistical-only cases.

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