Neutrino Oscillation Physics at JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment being built in China. The primary physics goal is to determine the neutrino mass hierarchy and precisely measure the neutrino oscillation parameters by detecting reactor antineutrinos at a baseline of 53 km from Taishan and Yangjiang reactor power plants with a nominal thermal power of 36 GW. The detector is designed to reach a target mass of 20 kt liquid scintillator and an energy resolution of $3\%/\sqrt{E}$. JUNO is planning to start data taking around 2020. The principle to determine the mass hierarchy is based on the precision measurement of reactor antineutrino oscillation. The sensitivity of mass hierarchy determination is studied with the standard chi-square fit. The impacts on the mass hierarchy sensitivity from the energy resolution, matter effects, neutron recoiling and other systematic uncertainties are discussed. In addition, the precision of the measurement of neutrino oscillation parameters are studied. Three oscillation parameters, Δm^2_{21}, Δm^2_{ee} and $\sin^2\theta_{12}$, can be measured with a precision better than 1%.

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1. Introduction

In the three-flavor neutrino oscillation framework, the latest known mixing angle θ_{13} was found to be about 0.09 which is relatively larger than the expectations before. The precision of $\sin^2 2\theta_{13}$ can reach to 3% by continuous running of Daya Bay in the next few years. The next generation neutrino oscillation experiments focus on the determination of the neutrino mass hierarchy (the sign of mass-squared difference, Δm_{31}^2 and Δm_{32}^2) and the CP violating phase. Among these experiments, atmospheric [1, 2] and accelerator [3, 4, 5] neutrino experiments are proposed to measure the matter effect for the determination of mass hierarchy. Another possibility is to use the oscillation interference effect between Δm_{31}^2 and Δm_{32}^2 by reactor antineutrinos [6, 7, 8, 9, 10].

The Jiangmen Underground Neutrino Observatory (JUNO) was proposed [11, 12, 13] to measure the reactor antineutrino spectrum from Taishan and Jiangmen reactor power plants with a 20 kt liquid scintillator (LS) detector. The primary goal is to determine the mass hierarchy and to precisely measure the neutrino oscillation parameters by precise measuring the oscillation spectrum with a $3\%/\sqrt{E_{vis}}$ energy resolution. A candidate site is located at Jiangmen in South China, with baselines around 53 km from Taishan and Yangjiang nuclear power plants. The JUNO experiment has other rich physics potentials, including the detection of supernova neutrinos, geo-neutrinos, solar neutrinos and atmospheric neutrinos, and can probe the sterile neutrinos and exotic physics like nucleon decays.

2. Mass Hierarchy Determination

In the propagation of the reactor antineutrinos, the survival probability can be written as

$$P_{ee} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \cos^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{31} - \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{32}, \quad (2.1)$$

where $\Delta_{ij} = 1.27 \Delta m_{ij}^2 L/E$, Δm_{ij}^2 is the neutrino mass-squared difference $(m_i^2 - m_j^2)$ in eV^2, θ_{ij} is the neutrino mixing angle, L is the baseline length from reactor to detector in meter, and E is the $\overline{\nu}_e$ energy in MeV. In the liquid scintillator detector, the reactor antineutrinos can be detected via coincident signals of inverse β decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$.

Reactor antineutrinos are mainly generated by Taishan and Yangjiang reactor power plants with a nominal thermal power of 36 GW. The baselines and the related reactor power of each reactor core are listed in Table 1. A thermal power of 26.6 GW will be available in 2020 when JUNO

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline(km)	52.76	52.63	52.32	52.20	215	265

Table 1: List of the baselines and reactor power for the Yangjiang (YJ) and Taishan (TS) reactor power plants, as well as the remote reactors of Daya Bay (DYB) and Huizhou (HZ), at the candidate site. Taken from [13]

experiment plans to taking data. Remote reactors (> 200 km), such as Daya Bay and Huizhou reactor power plants, give a very small contribution to the total reactor antineutrino spectrum. The experiment site was selected to minimize the baseline difference between Yangjiang and Tainshan reactor cores, optimizing the sensitivity. At the candidate site, the JUNO experiment will collect more than hundred thousand IBD signals over 6 year of data, assuming an 80% effective detection efficiency which relies on the event selection efficiency, live time ratio and reactor full power ratio.

To study the mass hierarchy sensitivity, we define a standard χ^2 function to fit the simulated reactor antineutrino spectrum to the input spectrum in the normal hierarchy (NH) and inverted hierarchy (IH) cases respectively,

$$\chi^2 = \sum_i \frac{(T_i - F_i(1+\varepsilon_{ik}))^2}{T_i} + \sum_i \frac{\varepsilon_{ik}^2}{\sigma_k^2}, \qquad (2.2)$$

where T_i is the input spectrum assuming the true case is NH or IH, and F_i is the fitted spectrum. The ε_{ik} is the pull parameters for the systematic uncertainty of σ_k. As expected, the spectrum can fit the input spectrum better if the truth mass hierarchy is used. Assuming NH is the truth, we try two fits using NH spectrum and IH spectrum respectively and get two corresponding minimal χ^2, namely $\chi^2_{\min}(\text{NH})$ and $\chi^2_{\min}(\text{IH})$. A discriminator can be defined as

$$\Delta\chi^2 = \chi^2_{\min}(\text{IH}) - \chi^2_{\min}(\text{NH}), \qquad (2.3)$$

A median sensitivity [14], approximatly $\sqrt{\Delta\chi^2}\sigma$, is often used when comparing the sensitivity of different experiments.

To optimize the candidate site for JUNO experiment, the ideal case with two reactors was studied. The sensitivity as a function of the baselines of the two reactors is shown in the left panel of Fig. 1. The sensitivity reaches maximal around 50 km, which is approximately at the oscillation maximal baseline for Δm_{21}^2 driven oscillation. The baseline difference of the two reactors is very important as shown in right panel of Fig. 1. If the baseline difference is close to 2 km, where is the baseline for the maximal Δm_{32}^2 driven oscillation, the sensitivity will be eliminated due to the interference of the reactor antineutrino spectra. As a result, the current candidate site is optimized to achieve the equal mean baselines from Taishan power plant and Yangjiang power plant.

Energy resolution is crucial for JUNO experiment because the mass hierarchy sensitivity is determined by the fast oscillation frequency driven by Δm_{32}^2 and Δm_{31}^2, which is about 1/30 of the slow oscillation frequency driven by Δm_{21}^2. The importance of the energy resolution and the event statistics is illustrated in Fig. 2. At the nominal luminosity with an energy resolution of $3\%/\sqrt{E}$, a sensitivity of $\Delta\chi^2 = 11$ will be obtained. If the energy resolution reaches $2.6\%/\sqrt{E}$ and $2.3\%/\sqrt{E}$, a $\Delta\chi^2$ sensitivity of 16 and 25 can be achieved, respectively.

The uncertainties on $\sin^2 2\theta_{13}$, $\sin^2 \theta_{12}$, and Δm_{21}^2 have slight impacts to the sensitivity. However, the uncertainty of effective mass-squared difference $\Delta m_{\mu\mu}^2$ (combination of Δm_{31}^2 and Δm_{32}^2) from a prior measurement has large impact to the sensitivity. A sensitivity of $\Delta\chi^2 \simeq 18$ will be achieved by using a 1% uncertainty of $\Delta m_{\mu\mu}^2$, as shown in Figure 3.

As a summary of the mass hierarchy determination, the impacts of different effects on the sensitivity is listed in Table 2. Matter effects, always treated as a small effect in reactor antineutrino experiments due to low energy, have been considered for the JUNO experiment [15]. A reduction of 0.6 for the mass hierarchy sensitivity is found after considering the matter effects.
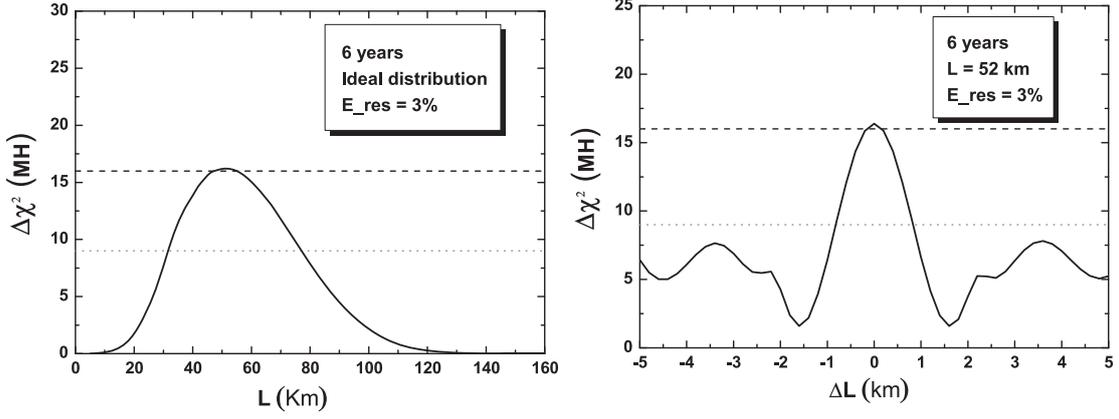
Figure 1: Sensitivity of mass hierarchy determination as the function of the baseline (left panel) and function of the baseline difference of two reactors (right panel). Taken from [13].
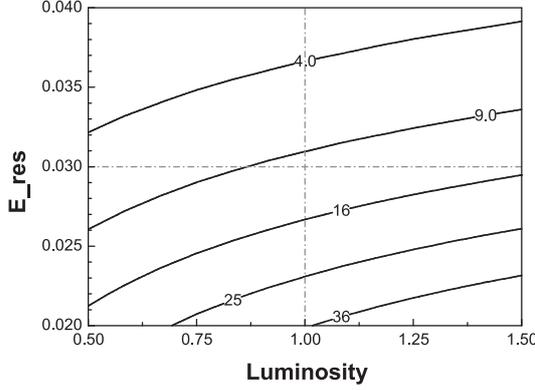

Figure 2: The $\Delta\chi^2$ contours as the function of the event statistics (luminosity) and the energy resolution, where the vertical dashedÍCdotted line stands for the nominal running of six years with.Taken from [13].
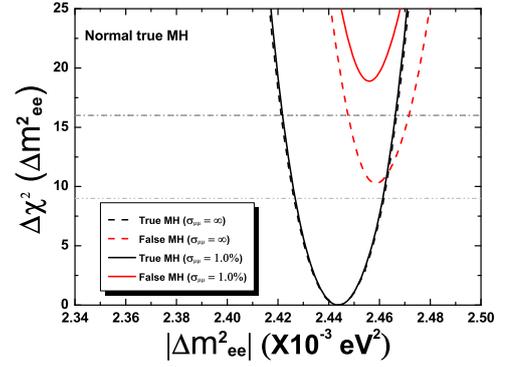
Figure 3: Mass hierarchy sensitivity of JUNO. The solid and dashed lines are for the analyses with and without the prior measurement of $\Delta m^2_{\mu\mu}$. Taken from [13].

3. Precision Measurement of Oscillation Parameters

Thanks to the large target mass and good energy resolution, JUNO could be the first to observe an oscillation pattern containing two independent oscillation frequencies and multiple oscillation cycles. Therefore JUNO will have an unprecedented precision measurement of Δm^2_{21}, Δm^2_{ee} and $\sin^2\theta_{12}$ better than 1%.

The precision of the oscillation parameter measurements were studied using the standard chi-square fit using Eq. 2.2. In this study, effects of important systematic errors, including the bin-to-bin (B2B) energy uncorrelated uncertainty, the energy linear scale (EL) uncertainty and the energy non-linear (NL) uncertainty, and background (BG) were taken into account. In Table 3, we show the precision of $\sin^2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$ from the nominal setup to those including additional

	Stat.	Core dist.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$|\Delta m_{\mu\mu}^2|$
Size	52.5 km	Tab. 1	Tab. 1	1%	6.3%	0.4%	1%
$\Delta\chi_{MH}^2$	+16	−3	−1.7	−1	−0.6	−0.1	+(4 − 12)

Table 2: Different contributions for the mass hierarchy determination. The first column is the statistical-only scenario with the equal baseline of 52.5 km, the second column considers the real distribution (dist.) of reactor cores, the third column defines the contribution of remote DYB and HZ nuclear power plants, the fourth column stands for the reduction of the reactor shape uncertainty, the fifth and sixth columns are the contributions of the background statistical and shape uncertainties, the seventh column is the enhanced sensitivity from additional information of $|\Delta m_{\mu\mu}^2|$. Taken from [13]

	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm_{21}^2	0.24%	0.27%	0.29%	0.44%	0.59%
$|\Delta m_{ee}^2|$	0.27%	0.31%	0.31%	0.35%	0.44%

Table 3: Precision of $\sin^2\theta_{12}$, Δm_{21}^2 and $|\Delta m_{ee}^2|$ from the nominal setup to those including additional systematic uncertainties one by one from left to right column. Taken from [13]

systematic uncertainties one by one. Note the energy-related uncertainties are more important because the sensitivity is mostly from the spectrum distortion due to neutrino oscillations. We can achieve the precision level of 0.5%−0.7% for the three oscillation parameters $\sin^2\theta_{12}$, Δm_{21}^2 and $|\Delta m_{ee}^2|$. Therefore, precision tests of the unitarity of the lepton mixing matrix is feasible at unprecedented precision levels.

4. Summary

The JUNO experiment is aimed at neutrino mass hierarchy determination and precision measurement of the oscillation parameters. Using a 20 kt liquid scintillator target, a $3\sigma - 4\sigma$ sensitivity after six years of data taking, with a $3\%/\sqrt{E_{vis}}$ energy resolution, can be reached. Additionally, three mixing parameters can be measured with a precision better than 1%. The JUNO project was approved in 2013 and is planned to start operation in 2020.

5. Acknowledgement

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