Neutrino Oscillation Studies in JUNO

Wenjie Wu***, on behalf of the JUNO collaboration**

School of Physics and Technology, Wuhan University, Wuhan 430072, China
E-mail: wuwenjie@ihep.ac.cn

Neutrino oscillation is the first observed phenomenon beyond the Standard Model, which can be interpreted in the framework of three neutrino mixings. It is governed by three mixing angles, two mass-squared differences, and one Dirac CP violation phase. The neutrino mass ordering, CP violation phase and the octant of θ_{23} remain unknown and could be measured by next-generation neutrino oscillation experiments. Jiangmen Underground Neutrino Observatory (JUNO) consists of a 20 kiloton liquid scintillator detector, which primarily aims to determine the neutrino mass ordering by measuring the reactor antineutrino oscillation pattern at a baseline of about 53 km. A $3-4\sigma$ significance to resolve mass orderings could be reached after 6 years of operation benefiting from its unprecedented 3% energy resolution at 1 MeV. Besides, JUNO is able to perform measurements at an accuracy of better than 1% to oscillation parameters $\sin^2\theta_{12}, \Delta m_{21}^2$ and Δm_{32}^2. In this talk, neutrino oscillation studies in JUNO will be reviewed.

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*Speaker.

1. Introduction

Neutrino oscillation originates from the mixture between the mass and flavor eigenstates of neutrinos, which can be described by the PMNS matrix. In the framework of three generations of neutrinos, six parameters are involved in neutrino oscillation. $\sin^2\theta_{12}, \sin^2\theta_{23}, \sin^2\theta_{13}, \Delta m_{21}^2$ and $|\Delta m_{31}^2|$ have been measured at the precision of 4.5%, 5.2%, 3.4%, 2.4% and 2.6% [1, 2, 3, 4, 5]. The sign of Δm_{31}^2, the octant of θ_{23} and the leptonic CP violation phase δ remain unknown. The sign of Δm_{31}^2 raises the question that whether ν_3 is heavier (Normal ordering) or lighter (Inverted ordering) than ν_2.

The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose reactor neutrino experiment [6]. It aims to determine the neutrino mass ordering and precisely measure the oscillation parameters. The central detector of JUNO contains 20 kiloton liquid scintillator (LS) within an acrylic sphere with inner radius of 17.7 m. Double calorimeter system consists of 18,000 20-inch PMTs and 25,000 3-inch PMTs which are mounted on the stainless steel latticed shell and immersed in the water buffer. Benefiting from the highly transparent LS and high photocathode coverage, JUNO can achieve an unprecedented energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$.

2. Measurement of neutrino mass ordering in JUNO

In the framework of three generations of neutrinos, the survival probability of $\overline{\nu}_e$ in vacuum can be written as [6, 7]

$$
\begin{aligned}
P_{\overline{\nu}_e \to \overline{\nu}_e} &= 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\
&= 1 - 2s_{13}^2 c_{13}^2 + 2s_{13}^2 c_{13}^2\sqrt{1 - 4s_{12}^2 c_{12}^2\sin^2\Delta_{21}}\cos\left(2|\Delta_{32}| \pm \phi_{ee}\right) - 4c_{13}^4 s_{12}^2 c_{12}^2\sin^2\Delta_{21} \quad (2.1)\\
&= a_0 + a_1(\xi)\cdot\cos\left[\left(2|\Delta m_{32}^2| \pm \Delta m_{\phi_{ee}}^2\right)\cdot\xi\right] - P_\odot(\xi),
\end{aligned}
$$

where

$$
s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij},\ \xi = \frac{L}{4E},\ \Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E},\ \Delta m_{\phi_{ee}}^2 = \frac{4E\phi_{ee}}{L},
$$

$$
\phi_{ee} = \tan^{-1}\left(\frac{\cos^2\theta_{12}\sin 2\Delta_{21}}{\cos^2\theta_{12}\cos 2\Delta_{21} + \sin^2\theta_{12}}\right).
$$

The $\pm$ sign of Equation 2.1 is decided by the MO with plus sign for the normal MO and minus sign for the inverted MO. The interference of Δm_{31}^2 and Δm_{32}^2 gives a beat pattern to the fast oscillation term of survival probability, as shown in Figure 1. The extra effective mass-squared difference $\Delta m_{\phi_{ee}}^2$ is relevant to the distortion of the energy spectrum giving a specific baseline. Figure 2 shows $\Delta m_{\phi_{ee}}^2$ as a function of baseline and visible prompt energy $E_{\mathrm{vis}} \simeq E_n - 0.8$ MeV [7]. Therefore, the advancement or retardation of the oscillation phase contains useful MO information.

In the sensitivity study, the benchmark is assuming a 20 kt LS detector and the total thermal power of the two reactor complexes as 36 GW$_{\mathrm{th}}$ with the nominal running time of 6 years, 73% efficiency and an energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$. The χ^2 test shows that a sensitivity of $\Delta\chi_{\mathrm{MO}}^2 \simeq 16$ can be obtained in the ideal case as shown in Figure 3. The decomposition of systematics from reactor and backgrounds are shown in Table 1. The sensitivity could be enhanced with
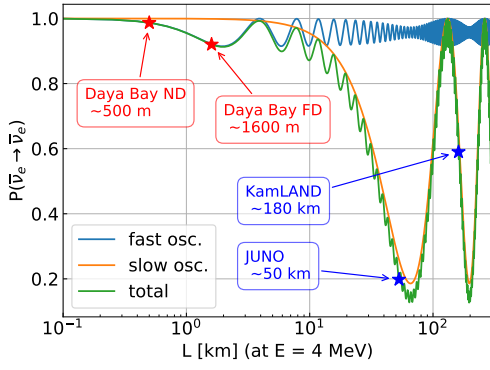
Figure 1: Survival probability of $\overline{\nu}_e$ with energy of 4 MeV.
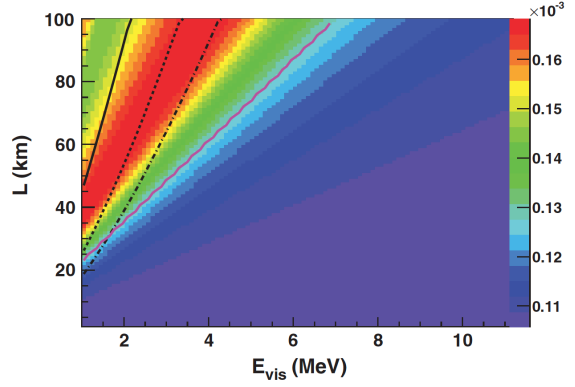
Figure 2: $\Delta m^2_{\phi_{ee}}$ as a function of baseline L and visible prompt energy E_{vis} [7].

additional information from the measurement of $|\Delta m^2_{\mu\mu}|$ in long-baseline muon-neutrino oscillation experiments. The enhancement of $\Delta\chi^2_{MO}$ ranges from 4 to 12 for the 1% relative precision of $|\Delta m^2_{\mu\mu}|$ considering the whole parameter space of the CP phase.
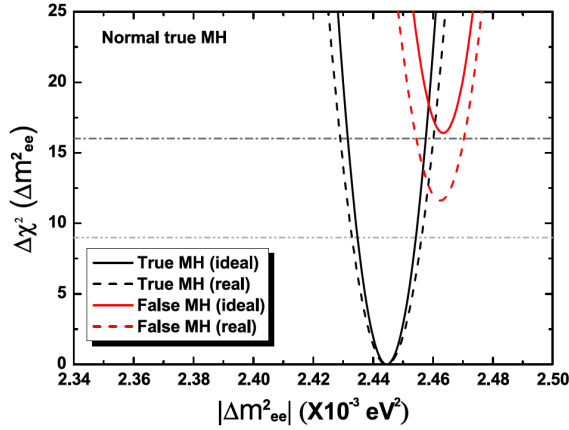
Figure 3: The comparison of the MO sensitivity for the ideal and real distribution of the reactor cores. The real distribution including DYB and HZ NPPs gives a degradation of $\Delta\chi^2_{MO} \simeq 5$ [6].

	Ideal	Core distr.	DYB and HZ	Reactor (shape)	B/S (rate)	B/S (shape)	$|\Delta m^2_{\mu\mu}|$
Size	52.5 km	Real	Real	1%	6.3%	0.4%	1%
$\Delta\chi^2_{MO}$	16	-3	-1.7	-1	-0.6	-0.1	+(4-12)

Table 1: Different contributions to the MO sensitivity [6].

3. Precision measurement in JUNO

Besides the determination of the neutrino MO, JUNO is expected to give a precise measurement of three oscillation parameters, including $\sin^2 2\theta_{12}, \Delta m^2_{21}$ and $\Delta m^2_{32}(\Delta m^2_{31})$. The precision measurement of neutrino oscillation parameters is a powerful tool to test the standard three-flavor

neutrino model. Current precision of oscillation parameters from individual experiments and a global fit are shown in Table 2. With the nominal setup described in the MO sensitivity study, the expected accuracy for the three relevant parameters of JUNO are 0.24%, 0.27% and 0.54% respectively. After considering additional systematic uncertainties from rector neutrino spectrum, detector energy scale and backgrounds, the precision can reach 0.59%, 0.44% and 0.67% respectively. With such high precision of oscillation parameters, JUNO can help in probing the unitary of the PMNS matrix to the level of 1%.

	Δm_{21}^2	$\|\Delta m_{31}^2\|$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA
Individual 1σ	2.4% [4]	2.6% [5]	4.5% [1]	3.4% [3]	5.2% [2]
Nu-FIT 4.1 [8]	2.7%	1.3%	4.2%	2.9%	3.6%
JUNO (statistics)	0.24%	0.27%	0.54%	-	-
JUNO (w/ systematics)	0.59%	0.44%	0.67%	-	-

Table 2: Precision for oscillation parameters from individual experiments and a global fit. And the expected precision for three relevant oscillation parameters of JUNO.

4. Summary and Prospect

JUNO could largely advance the neutrino physics with its unprecedented energy resolution and high statistics. The sensitivity study shows that a $3 - 4\sigma$ significance to determined neutrino MO can be reached after six years of operation. In addition, JUNO can measure $\sin^2 2\theta_{12}, \Delta m_{21}^2$ and $\Delta m_{32}^2 (\Delta m_{31}^2)$ to world-leading precisions. JUNO will be the first experiment to simultaneously observe an oscillation pattern containing two independent frequencies and more than two oscillation cycles.

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