Potential impact of sub-structure on the determination of neutrino mass hierarchy at medium-baseline reactor neutrino oscillation experiments

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Abstract In the past decade, the precise measurement of the lastly known neutrino mixing angle θ_{13} has enabled the resolution of neutrino mass hierarchy (MH) at medium-baseline reactor neutrino oscillation (MBRO) experiments. Recent calculations of the reactor neutrino flux predict percent-level sub-structures in the $\bar{\nu}_e$ spectrum due to Coulomb effects in beta decay. Such fine structure in the reactor spectrum has been an issue of concern for efforts to determine the neutrino MH for the MBRO approach, the concern being that the sub-dominant oscillation pattern used to discriminate different hierarchies will be obscured by fine structure. The energy resolutions of current reactor experiments are not sufficient to measure such fine structure, and therefore the size and location in energy of these predicted discontinuities has not been confirmed experimentally. There has been speculation that a near detector is required with sufficient energy resolution to resolve the fine structure. This article studies the impact of fine structure on the resolution of MH, based on predicted reactor neutrino spectra, using the measured spectrum from Daya Bay as a reference. We also investigate how a near detector could improve the sensitivity of neutrino MH resolution based on various assumptions of near detector energy resolution.

1 Introduction

The neutrino mixing angle θ_{13} has been measured precisely and was found to be larger than previously expected by

the current generation of short-baseline reactor neutrino and long-baseline accelerator neutrino experiments [1–5]. The large value of θ_{13} allows for the measurement of a leptonic CP-violating phase and the resolution of neutrino mass hierarchy (MH). Particularly, it opens a gateway to determine the MH from (approximately) vacuum oscillation in medium-baseline reactor neutrino oscillation (MBRO) experiments [6–15]. These experiments are designed to resolve the neutrino MH via precise spectral measurement of reactor $\bar{\nu}_e$ oscillations. A large liquid-scintillator detector (~ 10 – 20 ktons) with excellent energy resolution ($3\%/\sqrt{E/\text{MeV}}$), located ~ 50 km from the reactor core(s) is expected to be able to observe the sub-dominant oscillation pattern and thus discriminate the MH by measuring the resulting spectral distortions [13, 14]. However, there has been concern that the fine structure predicted to exist in the reactor neutrino spectrum might constructively or destructively interfere with the spectral distortions used to determine the MH.

In parallel, reactor neutrino experiments have also measured the reactor antineutrino flux and spectrum with unprecedented statistics at distances from dozens of meters to ~ 2 km from reactor sources. Together with the results from previous experiments, a neutrino deficit was found relative to predictions [16]. Current experiments also found an excess of events with respect to predictions in the region of 4–6 MeV prompt energy, which came to be known as the “bump” or “shoulder” [17–19]. Recently, it was also found that predictions of the (unoscillated) reactor antineutrino spectrum [20, 21] is inconsistent with the latest experimental measurements in the ratio between ^{235}U and ^{239}Pu yields [22–24]. In addition to the larger scale shape discrepancy, attempts to predict reactor antineutrino flux and spectrum using ab initio approaches predict percent-level sub-structures in the $\bar{\nu}_e$ spectrum due to Coulomb effects in beta decay [25, 26]. After

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the “bump” is found, Ref. [27] is one of the earliest articles which examined the impact of undetermined reactor antineutrino spectrum on the sensitivity of MH resolution, but the impact of fine structure was not discussed in details at that time. Recently, Ref. [28] concludes that the undetermined structure of reactor antineutrino spectrum will not lead to significant impact based on an approach using Fourier transforms. In this paper, we would like to estimate the scale of fine structure and the corresponding impact on mass ordering resolution based on direct calculation of χ^2 sensitivities. Our analysis indicates that fine structure would not significantly affect the resolution of neutrino MH, as found in [28].

In this context, we present numerical simulations to investigate the potential impact of fine structure in the reactor neutrino flux on the determination of the MH. We start with the simplest arrangement for a MBRO experiment, namely, one powerful source and one single large detector with a baseline of 52.5 km. We also investigate whether a near detector can provide significant improvement on MH sensitivity, and the effect on this sensitivity from different values of near detector energy resolution.

This paper is organized as follows. In Sect. 2, we review the discrepancies between reactor flux measurements and conventional predictions. Then, in Sect. 3, we present our estimation of the scale of fine structure and our simulation of MH resolution sensitivity, with additional shape uncertainties due to fine structure taken into account. In Sect. 4, we present our study concerning the proposed near detector. Finally, a summary of our results and perspectives are concluded in Sect. 5.

2 The undetermined reactor spectrum and discrepancies between experiments and conventional predictions

The conventional method of predicting reactor neutrino flux is based on measurements of electron spectra from the beta decays of fission daughters. These spectra are fit with fake beta branches from high energy bins to low, subtracting each “virtual branch” spectrum before fitting the next energy bin [20]. Those virtual branches are then converted to $\bar{\nu}_e$ spectra via the relation $E_0 - E_{\bar{\nu}_e} = T_\beta$, where E_0 is the available energy for the beta decay. Beta-conversion antineutrino spectra of ^{235}U , ^{239}Pu , ^{241}Pu from Huber [20] and ^{238}U spectra from Mueller [21] have been the most widely-used in reactor neutrino experiments. The conversion method was favored because corresponding uncertainties were well-defined and associated with the conversion procedure. Such predictions of the β decay spectrum estimate that the uncertainties of $\bar{\nu}_e$ would be around a few percent. However, the recent measurements at Daya Bay [23, 24] suggest that a 7.8% larger ^{235}U yield and a 7% (9%) discrepancies of ^{235}U (^{239}Pu) spectra at

4–6 MeV energy region from the Huber–Mueller prediction may be the primary contributors to the reactor antineutrino anomaly [16] and shoulder in the reactor neutrino spectrum [29], respectively.

Another method of predicting reactor neutrino spectra is the summation method described in Refs. [22, 25, 26, 29, 30]. To generate a summation prediction, one first calculates beta decay spectrum for every contributing isotope. Following that normalize each total beta spectrum to the cumulative yield of its corresponding isotope. The cumulative yield (Y_c) is the probability that the isotope appears as a result of either a fission, or the decay of the other fission products, and therefore represents the fraction of the reactor neutrino spectrum which decays from that isotope will contribute. In principle, the result should be the true reactor neutrino spectrum though still not exact due to some approximations used in correcting for various effects. However, the dominant uncertainty and bias comes from the underlying data (Q values, transition probabilities, energy levels, and cumulative fission yields). Besides the uncertainties, the bias in the underlying measurements is a larger concern for the method. The most well understood of these is the pandemonium effect [31], which overestimates feeding to lower energy levels. Recent experiments conducted by the IGISOL collaboration have addressed this bias for a few isotopes, which contribute strongly to the reactor neutrino spectrum [32–34], and these results are included in our analysis. However, additional biases likely remain, such as results which suffer from the pandemonium effect, but have not yet had new experiments measure the structure data to greater precision.

The majority of fissioning isotopes in Pressurized Water Reactors (PWRs) are ^{235}U and ^{239}Pu . As discussed above, the conversion method predicts the ^{239}Pu rate more accurately than the summation method, but predicts the ^{235}U spectrum poorly. Whereas the summation method overestimates the flux from both, and the associated uncertainties are poorly defined [22]. Nevertheless, summation calculations which incorporate the most recent data have found better agreement with overall flux [35]. In any case regardless of the quality of overall flux prediction, we are forced to use the summation method in this analysis because we aim to estimate the fine structure in the spectrum. Each beta decay has a sharp discontinuity at its endpoint. When all the individual beta decay spectra are summed fine structure emerges. Because the conversion method uses fake beta branches, fine structure can only be predicted by the summation method, therefore the summation method is used exclusively in this paper.

The origin of the discontinuities which give rise to fine structure is as follows. The beta spectrum from the beta decay of a free neutron will go to zero at zero kinetic energy. However, when an isotope decays into another, the electron is generated quite close to the positively charged nucleus. Therefore, the effect of this charge on the negatively charged

electron needs to be accounted for in the available final states. This results in a relatively soft electron energy spectrum, which importantly does not go to zero at zero kinetic energy. If we recall the relationship $E_0 = T_\beta + E_{\bar{\nu}_e}$, which tells us that if many electrons are created with zero kinetic energy, we should also see many neutrinos created with an energy equal to E_0 , the maximum available energy. This implies a sharp discontinuity at the endpoint of each neutrino spectrum corresponding to each beta decay branch. When the neutrino spectra of these beta branches are summed together, the discontinuities at the end of each generate fine structure in the total reactor neutrino spectrum, which is found to be at the few percent level [36], as shown in Ref. [25]. The size of the fine structure is dominated by the relative Fission Yields between isotopes. Large buildups of discontinuities also occur which can combine together to form what appears to be a single large discontinuity. More details and discussions of fine structure in reactor spectra can be found in Refs. [26, 36, 37].

Recent short baseline reactor neutrino experiments such as Daya Bay, cannot measure fine structure as their detectors have only $\approx 8\%$ energy resolution.¹ However, the future MBRO experiments such as JUNO [14] and RENO-50 [13], are expected to have finer detector energy resolution (around 3%) and thus are expected to observe more fine structure in the spectrum. However, it has been speculated that undetermined fine structure could give rise to unexpected variation in the measured spectrum which happens to mimic one or another MH, and therefore either reinforce the correct MH, or wash out its signal, resulting in either an artificially low or artificially high sensitivity. For this to be true the fine structure would need to be at approximately the scale of the sub-dominant oscillation pattern, and would have to fall in the right places and at the right magnitudes to mimic the MH signal. In the following, we treat the scale of the fine structure as an additional shape uncertainty because we expect to see fine structure but do not assume that the exact shape of fine structures could be predicted perfectly. The next section will discuss the impact of fine structure on MH resolutions in details.

3 The potential impact of fine structure on the resolution of neutrino MH

3.1 The conventional simulations of the MBRO experiments

Future MBRO experiments are expected to identify the neutrino MH with $\Delta\chi^2 > 9$. A large liquid-scintillator detector

Fig. 1 Expected reactor neutrino energy spectrum observed by a detector with 3% energy resolution locating at 52.5 km. The red (blue) curve corresponds to the NH(IH) assumption. In our simulation, the NH (and also IH) spectrum is generated based on the Daya Bay measured spectrum (un-oscillated) [38], which will be discussed in details in the following sections. A medium-baseline reactor neutrino oscillation experiment(s) is expected to observe the subdominant θ_{13} oscillation and distinguish the tiny differences between the blue and red curves [13, 14]

(20 ktons) is expected to be able to observe the sub-dominant oscillation pattern and thus extract the MH signal from the predicted spectral distortion, as illustrated in Fig. 1. To distinguish between normal hierarchy (NH) and inverted hierarchy (IH), we quantify the sensitivity of MH resolution by employing a least-squares method, calculating the difference between the (assumed) true event rate and the fitting event rates.

In our simulation, we assume the ideal detector is 20 ktons with 3% energy resolution,² located 52.5 km from the reactor core at medium-baseline reactor neutrino oscillation experiment(s). The electron antineutrino survival probability is given by [9, 12, 14]:

$$\begin{aligned}
 P_{\bar{\nu}_e} &= 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) \\
 &\quad - \sin^2(2\theta_{13}) \left[\cos^2(\theta_{12}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \right. \\
 &\quad \left. + \sin^2(\theta_{12}) \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) \right] \\
 &= 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) - \frac{1}{2} \sin^2(2\theta_{13})
 \end{aligned}$$

¹ However a bin to bin measurement has been attempted in order to attempt to measure a large buildup of discontinuities [26].

² In our simulation, the energy resolution is applied on the visible energy (E_{vis}) of the IBD events, where $E_{\text{vis}} \approx E_\nu - (m_n - m_p) - m_e \simeq E_\nu - 0.783$.

$$\times \left[1 - \sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)} \right. \\ \left. \times \cos\left(\frac{2|\Delta m_{ee}^2 L|}{4E} \pm \phi\right) \right]. \quad (1)$$

where Δm_{ee}^2 is the effective mass-squared difference [39,40]. The values of Δm_{ee}^2 and ϕ in Eq. (1) are given by:

$$\Delta m_{ee}^2 = \cos^2\theta_{12}\Delta m_{31}^2 + \sin^2\theta_{12}\Delta m_{32}^2, \quad (2)$$

$\sin\phi$

$$= \frac{\cos^2\theta_{12}\sin\left(2\sin^2\theta_{12}\frac{\Delta m_{21}^2 L}{4E}\right) - \sin^2\theta_{12}\sin\left(2\cos^2\theta_{12}\frac{\Delta m_{21}^2 L}{4E}\right)}{\sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)}}, \quad (3)$$

$\cos\phi$

$$= \frac{\cos^2\theta_{12}\cos\left(2\sin^2\theta_{12}\frac{\Delta m_{21}^2 L}{4E}\right) + \sin^2\theta_{12}\cos\left(2\cos^2\theta_{12}\frac{\Delta m_{21}^2 L}{4E}\right)}{\sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)}}. \quad (4)$$

In Eq. (1), the positive sign corresponds to NH and negative sign corresponds to IH respectively. In our simulations, the values of the oscillation parameters are assumed to be $\Delta m_{21}^2 = 7.53 \times 10^{-5} \text{ eV}^2$, $\Delta m_{ee}^2 = 2.56 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{12} = 0.851$, $\sin^2 2\theta_{13} = 0.083$ [41].

We quantify the sensitivity of the MH measurement by employing the least-squares method, which is also used in JUNO Yellow Book [14] and Refs. [42,43]. This method is based on a χ^2 function given by:

$$\chi^2 = \sum_i^{N_{\text{bins}}} \frac{[T_i - F_i(1 + \eta_R + \eta_d + \eta_i)]^2}{T_i} \\ + \left(\frac{\eta_R}{\sigma_R}\right)^2 + \left(\frac{\eta_d}{\sigma_d}\right)^2 + \sum_i^{N_{\text{bins}}} \left(\frac{\eta_i}{\sigma_{s,i}}\right)^2 \quad (5)$$

where T_i is measured neutrino event in the i th energy bin, and F_i is the predicted number of neutrino events with oscillations taken into account (the fitting event rate). η with different subscripts are nuisance parameters corresponding to reactor-related uncertainty (σ_R), detector-related uncertainty (σ_d) and shape uncertainty (σ_s). In Refs. [14,42,43], σ_R is assumed to be 2% and σ_d is assumed to be 1%. Since MH determination mainly depends on shape analysis, these uncertainties are minor and we follow the same assumptions in our analysis. Shape uncertainties ($\sigma_{s,i}$) are modified by adding the scale of potential substructure in the spectrum as additional shape uncertainties. The values of shape uncertainties are crucial to the MH resolution. In our analysis, we do not follow the assumption in Refs. [14,42,43], which assume σ_s to be constant at 1%. We treat the shape uncertainties as

energy dependent, $\sigma_s = \sigma_s(E_\nu)$ and related to the scale of fine structure. This is one of the main differences between the conventional analyses and ours.

Without loss of generality, in our simulations, the NH is assumed to be the true MH. The number of bins used N_{bins} is 200, equally spaced between 1.8 and 8 MeV. In this article, we focus on the potential impact of unknown structure in the reactor neutrino flux, and neglect the potential impact of detector non-linearity [14,42], actual reactor distribution [14,42], and matter effects [44]. The capability to resolve the MH is then given by the difference between the minimum χ^2 value for IH and NH:

$$\Delta\chi^2 \equiv |\chi_{\text{min}}^2(\text{IH}) - \chi_{\text{min}}^2(\text{NH})| \quad (6)$$

In the next two subsections, we will focus on treatment of the fine structure as an additional shape uncertainty and evaluate its effects on the sensitivity of MH resolution.

3.2 Our analysis method

To study the impact of fine structure on the discrimination of neutrino MH, we estimate the scale of such structure (especially in the energy range between $E_\nu = 2\text{--}6 \text{ MeV}$), treat it as additional shape uncertainty in the $\Delta\chi^2$ calculation and investigate how this affects the sensitivity. We define the scale of the fine structure relative to a hypothetical measured spectrum smeared out with an energy resolution of 8%. In particular, this scale is determined by taking the ratio of the unaltered spectrum to the smeared spectrum. Therefore, the scale of fine structure can only be determined with reference to a choice of energy resolution for the smeared spectrum. For the purposes of this analysis, we choose 8%, which is the energy resolution of the Daya Bay detectors. We take the measured spectrum from Daya Bay, which is currently the most precise reactor neutrino measurement, as the nominal (un-oscillated) spectrum in our simulation. We start with the measured spectrum from Daya Bay (26 bins) [38] and obtain a smooth spectrum, then estimate the sensitivity of MH resolution by calculating Eqs. (5) and (6) with this smooth Daya Bay spectrum used to estimate both T_i and F_i . Of course, fine structure is absent due to the finite (8%) detector energy resolution, so we need to estimate the scale of this missing fine structure and add it to Eq. (5) as an additional shape uncertainty.

3.2.1 Estimation of fine structure

Scale of fine structure is a potentially imprecise term so we should make it clear what our working definition is. Our “scale” here is a ratio of a spectrum with a certain energy resolution applied (which has the effect of smearing out the jaggedness) to a spectrum with perfect energy resolution. Since the Daya Bay measured spectrum is taken as the ref-

Fig. 2 Comparison of “the (un-oscillated) spectrum with fine structure” to the “smooth (un-oscillated) spectrum after smearing”. The red curve corresponds to the expected smooth spectrum (the smeared out spectrum with 8% energy resolution). The blue curve shows the original jagged spectrum without smearing

erence spectrum in our simulation, we are interested in the scale of unobserved fine structure with an 8% energy resolution detector. Therefore, the summation spectrum we use is smeared out with 8% energy resolution and 26 bins. Then we compare the original jagged spectrum with the smeared spectrum to estimate the scale of fine structure which is unobserved by Daya Bay. Figure 2 shows the comparison of the original jagged spectrum with the smeared spectrum. The red curve corresponds to the smeared out spectrum with 8% energy resolution. The blue curve represents the original jagged spectrum, which is a summation spectrum we generated, based on the cumulative yield datasets from the Evaluated Nuclear Data File (ENDF) [45,46] and Joint Evaluated Fission File (JEFF) [47]. Total absorption spectroscopy (TAS) nuclear structure data is included where available. Our spectrum using ENDF yield data is identical to Ref. [25] but with TAS data replacing previous structure data where available. Unless noted, all results are based on ENDF cumulative yields.

Based on the ratio of the blue curve to the red curve in Fig. 2, we attain the scale of fine structure,³ which is shown as the red curve in Fig. 3. Our estimation shows that the

³ Here, the scale of fine structure is calculated by the ratio of the jagged spectrum to the smooth spectrum without oscillation. To make a com-

Fig. 3 Comparison of our estimated scale of fine structure (red) with the ratio between IH and NH (blue). The IH and NH spectra are shown in Fig. 1, which are generated based on the Daya Bay measured (un-oscillated) spectrum

scale of substructure could be large at high energy ($E_\nu > 7$ MeV), but is relatively small in the range of $E_\nu = 2$ –6 MeV, compared with the ratio of spectra corresponding to the IH and NH.⁴ Since the determination of neutrino MH in medium-baseline reactor neutrino oscillation experiments is mainly dependent on this energy region, the sensitivity of such an experiment is expected to be mostly unaffected by the undetermined fine structure in the spectrum. The following subsections will investigate this more quantitatively.

3.2.2 Fine structure as additional shape uncertainty

Thus far, we have measured the scale of the fine structure at each point in the spectrum. However, each bin needs a single value treated as additional shape uncertainty because the same number applies across each bin. Because the bins are sufficiently narrow, the middle value is used. We treat the deviation from 1 at the middle of each bin as an additional shape uncertainty. It is because the deviation reveals the estimated scale of fine structure, which is absent in our reference spectrum (the measurement from Daya Bay). Therefore, the red curve in Fig. 3 is considered as the uncertainty of our reference spectrum, which leads to additional shape uncertainty in our simulation. There is a clear excess at low energy in the smooth spectrum. This is likely due to the effect of energy resolution causing events from higher energies to be detected in lower energy bins due to the sharp increase in rate from

parison, we also calculate the scale of fine structure between two spectra with oscillation in Appendix A.

⁴ As mentioned before, we attain the IH and NH spectra from our fitter, which uses the Daya Bay measured spectrum as the nominal un-oscillated spectrum in the simulations.

Fig. 4 Comparison of our estimated scale of fine structure (red) with the current uncertainties of the Daya Bay measured (black) spectrum [23]. We also plot the expected shape uncertainty (1%) in the literatures [14, 42, 43] (blue dashed lines) as well as the smoothed and symmetrized uncertainty from [27] as a comparison (the dashed green curve)

1.8 to 3 MeV. Since we are treating the scale of fine structure as a shape uncertainty, this can be left in and will only make the result more conservative.

Besides, we also compare the scale of our estimated fine structure with different assumptions of shape uncertainties, as shown in Fig. 4. We want to investigate whether the scale of fine structure is actually comparable or even smaller than other shape uncertainties. The scale of fine structure could lead to additional shape uncertainties in the analysis of neutrino MH. However, if we find out that the shape uncertainties are actually dominated by other systematic uncertainties, we believe that the fine structure would not give rise to significant impact on MH resolution sensitivity. In Fig. 4, we compare our estimated scale of fine structure with the conventional assumption of 1% shape uncertainty [14, 42, 43]. Moreover, we also compare the estimated scale of fine structure with the current uncertainties of the Daya Bay measurement [23], since we also need to consider the shape uncertainty from our reference spectrum, which is based on the Daya Bay measurement. We believe that instead of simply assuming the shape uncertainties of all energy bins are 1%, considering the corresponding uncertainties of our reference spectrum could be more realistic.

Fig. 4 shows that according to our estimation, the scale of fine structure which Daya Bay fails to measure is smaller than the current experimental uncertainties of the Daya Bay measurement in the range $E_\nu = 2$ to 8 MeV. The red curve representing scale of unmeasured fine structure does not exceed the shape uncertainty of the Daya Bay measurement [23]. In our simulations, we consider both the shape uncertainties due to the uncertainties of the Daya Bay measurement, and also

additional shape uncertainties due to fine structure.⁵ As mentioned before, we have to consider the intrinsic uncertainties of Daya Bay spectrum, which are the error bars plotted in Fig. 28(a) in Ref. [23], since it is taken as the reference spectrum in our analysis of neutrino MH sensitivities at MBRO experiment.

We sum these two different kinds of shape uncertainties in quadrature to calculate the total shape uncertainties of each bin. Specifically, in Eq. (5), $\sigma_{s,i}^2 = \sigma_{\text{sub},i}^2 + \sigma_{\text{DYB},i}^2$. We also calculate a result using the conventional assumption of 1% shape uncertainty summed in quadrature with the scale of fine structure in each bin.

3.3 The results of our simulations

Figure 5 shows the comparison of our results with the estimated sensitivities of different considerations of shape uncertainties. As mentioned in the previous subsection, the uncertainties of the Daya Bay measurement [38] are taken into account and the corresponding sensitivities are shown as red curves in Fig. 5. The dashed red curve corresponds to the case “ $\sigma_{s,i}^2 = \sigma_{\text{DYB},i}^2$ ”, and the solid one represents the scenario “ $\sigma_{s,i}^2 = \sigma_{\text{sub},i}^2 + \sigma_{\text{DYB},i}^2$ ”, with the additional shape uncertainties due to fine structure taken into account. On the other hand, the sensitivities of considering the conventional assumption of 1% shape uncertainty [14, 42] are also shown as the blue curves in Fig. 5. The dashed blue curve shows the MH sensitivity with just 1% shape uncertainties in each energy bin, while the solid one corresponds to the case that additional uncertainties due to fine structure are also considered.

For both the red curves and blue curves, the minima of the dashed and solid curves are close to each other. It implies that the consideration of fine structure does not significantly affect neutrino MH resolution. The difference between the assumption of 1% shape uncertainty and Daya Bay spectrum shape uncertainty is much larger than the difference between the results with and without fine structure. With the current Daya Bay spectrum uncertainty taken into account, the sensitivity of our simulation is given by $\Delta\chi^2 = 7.87$ (8.05) with (without) shape uncertainty from fine structure. With the conventional assumption of 1% shape uncertainty [14, 42], we find $\Delta\chi^2 = 11.65$ (12.01) with (without) fine structure. The effect on these results from fine structure is small when

⁵ In our analysis of MH sensitivities, we consider the uncertainty of each bin in Fig. 9 of [23] as the shape uncertainties of our reference spectrum. In our analysis of MH sensitivity, we have 200 bins, while the Daya Bay measurement just contains 26 bins. Thus we assume the first 9 of our 200 bins have the same uncertainty as the first Daya Bay bin, and the 10th to 17th bins of ours have the same uncertainty as the second Daya Bay bin, etc. Then, in each of our 200 bins, we further include the additional shape uncertainties due to the estimated scale of fine structure.

Fig. 5 Sensitivity of MH resolution using shape uncertainty from fine structure (solid lines) and without (dashed lines). NH is assumed to be the true MH. The curves on the left side correspond to the fitting of NH and curves on right side correspond to the assumption of IH (false MH). The blue curves represent the conventional assumption of 1% shape uncertainties (named as “CS” in the legend) for each bin; The red curves correspond to intrinsic uncertainties from the Daya Bay measurement (named as “DYB” in the legend). The green curves are the results based on shape uncertainties reported in Ref. [27]

compared to the difference between different assumptions of shape uncertainty. Additionally, because our treatment of fine structure is conservative, we are over-estimating its impact.

The result based on uncertainties reported in Ref. [27] is also shown as a comparison and the corresponding MH sensitivity is lowest. It is because it has not considered fine structure but using the 1σ uncertainty bands estimated in Ref. [25].⁶ Reference [27] has also studied the potential impact of shape uncertainties. Our simulations are based on reference spectrum from Daya Bay measurement and our estimation of additional shape uncertainties suggests a better sensitivity than the result based on the discussion from Ref. [27], as our suggested shape uncertainties are smaller, which are based on the estimation of potential fine structure.⁷

In order to account for possible variation in the spectrum, we generate 100 spectra based on both the JEFF and ENDF databases with all inputs varied randomly within their uncer-

ainties. Figure 6 shows the sensitivities of MH resolution based on the random samples generated from the ENDF (red) and JEFF (blue) datasets. The left panel shows results based on Daya Bay shape uncertainties, while the right panel shows results based on the conventional assumption of 1% shape uncertainty. However, both panels show that different summation spectra give similar $\Delta\chi^2$ values. The spread in results from each alternate spectrum is far narrower than the spread between results with and without shape uncertainty from fine structure. Bias in the underlying data is not contained in the published uncertainties, but the minimal effect from varying the spectra indicates that the true spectrum is unlikely to give results which will appreciably diminish the sensitivity of MH resolution.

3.4 Estimated fine-structure from summation spectra from the literature

In this section, we repeat the analysis using two spectra from Refs. [25, 26], also based on the summation method. As employed in the previous simulations, we use the Daya Bay measured spectrum as a reference spectrum. Then smeared out the summation spectra with 8% energy resolution and estimate the scale of (unobserved) fine structure based on the ratio of the original jagged spectrum to the smeared out spectrum. Again, even the exact shape of these two summation spectra are so different, we find that the corresponding scales of (unobserved) fine structures are similar and smaller than 1–2% over the low energy range ($E_\nu = 2\text{--}6\text{ MeV}$). The comparison of these two fine structures is shown in Fig. 7.

As we would expect from the similarity between the scale of fine structure obtained from each summation spectrum, the sensitivity of MH resolution is only slightly affected by these summation spectra. Results based on the estimated fine structures from Refs. [25] and [26] are shown in Fig. 8. The $\Delta\chi^2$ based on the spectrum from [25] is 7.90, while the $\Delta\chi^2$ based on the spectrum from [26] is 7.80. Both results use Daya Bay shape uncertainty and have very similar $\Delta\chi^2$ values to that obtained from our own spectrum ($\Delta\chi^2 = 7.87$). This suggests that the choice of summation spectra does not significantly affect the sensitivity of neutrino MH resolution, and reinforces the conclusion that introducing fine structure as additional shape uncertainty only slightly degrades sensitivity. As showed in Fig. 5, in both panels of Fig. 8, the sensitivities of the conventional assumption of 1% uniform shape uncertainties are much larger, regardless of whether we include shape uncertainty from fine structure.

4 MH discrimination with a near detector

In this section, we consider the scenario that using the spectrum measured by a proposed near detector (such as JUNO-

⁶ The authors of Ref. [27] do not consider the large scale structure or fine structure. They provide conservative results which are based on the estimated uncertainties of the summation calculation in Ref. [25]. Nevertheless, as discussed in Sect. 2, the summation method cannot provide well-defined uncertainties. Moreover, we believe that the large scale structure would not affect the determination of neutrino MH. Thus in our simulations we estimate the scale of fine structure and treat it as additional shape uncertainties.

⁷ Please note that the sensitivity represented by the green curves in Fig. 5 is better than the exact result in Ref. [27], since we have not considered detector non-linearities. We want to focus on the discussion of potential structure within the reactor neutrino spectrum, thus non-linearity is not discussed in this article.

Fig. 6 Sensitivities from spectra with inputs varied within their uncertainties based on ENDF (red) and JEFF (blue). The left panel shows results based on Daya Bay shape uncertainties and the right shows results based on 1% shape uncertainty

Fig. 7 The estimated scale of fine structure from two additional summation spectra generated by Dwyer [25] (green curve) and Sonzogni [26] (red curve)

TAO [48]), rather than the existing measurement from Daya Bay, as the reference spectrum in our simulation of MH resolution.

4.1 Motivations of a near detector

The results from previous sections suggest that fine structure is not likely to significantly degrade the sensitivity of MH resolution. However, it is still worthwhile to examine the potential effect of a near detector on MH discrimination in terms of its ability to measure fine structure. In fact, building an additional detector for MBRO experiments has been recently discussed in the literatures [43, 49, 50]. Particularly, the JUNO experiment [14] is planning to build a near detector 30–35 m from a European pressure water reactor (EPR)

of 4.6 GW thermal power, JUNO-TAO [48]. Such detector is designed to be with target mass around 1 ton and the energy resolution is expected to be $\sim 1.5\%/\sqrt{E/\text{MeV}}$. With such an excellent energy resolution, the JUNO-TAO detector or any other near detector could improve the measurement on the undetermined fine structure and provide a more precise reactor neutrino spectrum.

Taking the spectrum measured by a near detector as a reference spectrum will help cancel correlated systematic uncertainties, such as reactor neutrino shape uncertainties and also uncertainties due to the non-linear detector energy response correction [51]. However, building an identical far and near detector is not feasible because any far detector capable of determining the MH is quite large with a unique geometry, and there will therefore be many uncorrelated uncertainties to deal with. Additionally, if a near detector starts data taking after the far detector, this could introduce additional uncorrelated uncertainties. In our simulations, the proposed near detector is not used to cancel the correlated uncertainties, and we do not implement any model of detector nonlinearity. Our analysis focuses instead on determining the benefit of a near detectors ability to constrain the fine structure and thus reducing the uncertainty of the reference spectrum, which leads to smaller shape uncertainties in our simulation of the neutrino MH resolution at the original far detector.

Similar to the proposal of JUNO-TAO, we assume a small detector with 1 ton target-mass, located 33 m from the reactor core. In reality, there are several reactor cores located at different positions. Therefore, one small detector located near just one reactor will observe a slightly different spectrum than the original far detector due to differing fuel compositions between reactors. Such differences will generate more uncorrelated uncertainties. However, in this paper, we focus

Fig. 8 Same as Fig. 5, but fine structure is estimated based on the summation spectra from the literature instead of our own generated samples. Left: Results with fine structure based on the spectrum in Ref. [25]; Right: Results with fine structure based on the spectrum from Ref. [26]

on the ideal case: one powerful reactor, one large far detector and one small near detector.

4.2 The energy resolution of the near detector

We first assume the systematic uncertainties of the near detector (ND) are same as the far detector: 1% detector-related uncertainty [14,42,43]. The baseline is set to be just 33 m. We assume sufficient exposure time for this mass and baseline that statistical uncertainty is negligible. Without loss of generality, we assume our summation spectrum (ENDF with additional TAS data) is the true spectrum which will be measured by a near detector. We use this spectrum to estimate the unobserved fine structure in the near detector. This spectrum is used to calculate the values of T_i in Eq. (5), which is the expected event rates measured in the far detector with 3% energy resolution. The near detector (measured) spectrum is taken as the reference spectrum, which is smoothed according to several different energy resolutions and used to calculate the values of F_i in Eq. (5). In other words, we fit the far detector data based on the smooth spectrum measured by the ND.⁸

The results of this approach, shown in Fig. 9, shows that as we would expect from results reported in the previous section, detector uncertainty is more important to MH sensitivity than energy resolution. The lack of impact on sensitivity from

Fig. 9 Sensitivity of MH resolution as the energy resolution of the near detector increases and for different detector uncertainty of ND. The near detector provides the reference spectrum, which is smoothed according to the energy resolution of the ND. Similar to our previous simulations based on the Daya Bay measurement in Sect. 3, the detector uncertainty of ND is treated as part of the shape uncertainty in the resolution of MH

⁸ In principle, we are repeating our previous analysis in Sect. 3. The difference is that in the previous section, we used the Daya Bay measurement as our nominal spectrum. In this section, we are assuming the true spectrum is our generated summation spectrum and apply the smearing effects based on different assumptions of the near detector energy resolution. The smoothed spectrum (which is based on our generated summation spectrum) is treated as the nominal spectrum in our simulation of MH determination in far detector

energy resolution of ND, indicates that MH sensitivity is not appreciably affected by the fine structure predicted by current summation predictions, which is consistent with the results in our previous section. On the other hand, the detector uncertainty of ND could be important as it represents the uncertainty of the reference spectrum, which would be treated as shape uncertainty in our analysis of the data collected in far detector. More details about the detector uncertainty of ND will be discussed in Appendix B.

5 Conclusion

In order to resolve the neutrino MH with MBRO experiments, it was argued that a precise measurement of the fine structure of the reactor antineutrino spectrum should be achieved. To study the impact of fine structure on neutrino MH determination, we have used different summation spectra to estimate the potential scale of the un-observed fine structure in the Daya Bay measurement and also a proposed near detector. All of these spectra predict similar scales of fine structure, which are small over the low energy range ($E_\nu = 2\text{--}6\text{ MeV}$) even with $8\%/\sqrt{E/\text{MeV}}$ energy resolution. Our simulations show that the impact of such fine structure on MH resolution is insignificant,⁹ especially when compared to the intrinsic uncertainties of the reference spectrum. Compared to the unobserved fine structure, the detector uncertainty of the proposed near detector (or the systematic uncertainties of the Daya Bay measured spectrum) could be more important to the discrimination of the neutrino MH.

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Appendix A: Estimation of fine structure with oscillated spectrum

In Sect. 3.2, we estimate the scale of fine structure by comparing the jagged un-oscillated spectrum (with fine structure) with the smooth un-oscillated spectrum. Since the fine struc-

⁹ Recently, there is study suggesting that varying the central values of the oscillation parameter could give rise to significant impact on the sensitivities of neutrino MH resolution [52]. We believe that more precise measurements on the oscillation parameters could be more important than determining the fine structure for the future MBRO experiment(s).

Fig. 10 Estimating the scale of fine structure in two different scenarios. Compare the jagged and smooth spectrum (i) without considering oscillation effect (red curve), (ii) with the oscillation effect on the spectra taken into account (blue curve). The magnitudes and shapes of these two curves are very similar

ture is due to the sharp discontinuities at the endpoint of each neutrino spectrum corresponding to each beta decay branch, the scale of fine structure is related to the reactor neutrino flux and thus we believe that we should compare the spectrum without oscillation effects.

In order to provide a prudent and completed analysis, in this appendix, we also examine the case of comparing the oscillated jagged spectrum with the oscillated smooth spectrum to estimate the scale of fine structure. Figure 10 shows our estimations of fine structure with two different considerations: (i) The red curve represents the ratio between the jagged un-oscillated spectrum (with fine structure) to the smooth spectrum, which is same as the red curve in Fig. 4; (ii) The blue curve in Fig. 10 corresponds to the ratio between the oscillated spectrum with sawtooth structure to the smooth oscillated spectrum based on Daya Bay measurement.¹⁰

Our analyses show that the estimated scale of fine structure based on un-oscillated and oscillated spectrum are almost the same. However, as mentioned before, the fine structure is due to the sharp discontinuities. We believe that the uncertainties of reference spectrum should be determined by the conditions of the near detector, but irrelevant to the oscillation effect. Therefore in our simulation, we consider the red curve in Fig. 10 as our estimated scale of fine structure and also the additional shape uncertainties in our simulation of neutrino MH determination.

¹⁰ We obtained both the jagged and smooth spectra from our fitter, which considers both the oscillation effects and also tiny resolution effect, assuming the detector resolution to be around 0.0001%.

Appendix B: The detector systematic uncertainty of near detector

Section 4.2 clearly shows that with respect to the determination of neutrino MH, the systematic uncertainties of ND could make larger impact than the ND energy resolution. This is because the systematic uncertainties of the ND represent the uncertainties of the reference spectrum. The uncertainties of the detector energy nonlinearity response are energy dependent. Such uncertainties of the ND could lead to energy dependent uncertainties of the reference spectrum, which are propagated to the shape uncertainties of the analysis in FD.¹¹ However, because in this article we want to focus on the uncertainties due to the undetermined shape of reactor flux and the ways in which an extra detector provide a precise reference spectrum. The sources of the nonlinearities and methods to reduce corresponding uncertainties are not discussed. More details about the studies of nonlinearity can be referred to reference [14]. On the other hand, the benefits of an extra detector in canceling the uncertainties of nonlinearity are discussed in Ref. [51]. However, different with our assumption, the authors of that reference assume the original medium baseline detector and the proposed extra detector are identical and the correlated uncertainties can be canceled. We believe that the correlation of the nonlinearities between the ND and FD require more careful and detailed studies and Monte Carlo simulations, which are beyond the scope of this article.

Here, we just assume the overall detector uncertainties are consistent with all energy bins in the ND measurement, similar to the assumption of shape uncertainties in Refs. [14, 42, 43]. Please keep in mind that the detector uncertainties of ND would give rise to additional shape uncertainties of the measurement in FD, since the ND uncertainties correspond to the uncertainties of reference spectrum in our simulations. Figure 11 shows the sensitivity of neutrino MH determination vs the detector uncertainty. The latter is treated as additional shape uncertainty in our simulation of the MH resolution at far detector. Since the energy resolution of the ND barely makes impact on the MH resolution, we just assume an ND energy resolution of 3% in Fig. 11.

Figure 11 shows that the sensitivity of MH resolution is strongly dependent on the systematic uncertainties of the ND measurement. Our analyses show that for MH resolution, the intrinsic uncertainties of the reference spectrum could be more important than resolving the fine structure of the reactor flux, since the scale of the unobserved fine structure is expected to be smaller than 1%. In the future, if a near detector is really built, the corresponding systematic uncertainties

Fig. 11 MH discrimination sensitivity for different near detector uncertainties. The energy resolution of ND is fixed to be 3%

of non-linearity, detection efficiency, background estimation, etc could be important.

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¹¹ Moreover, the nonlinearity of the FD itself is also expected to make significant impacts on the neutrino MH determination, as it could distort the antineutrino spectrum and thus is crucial.

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