Experimental study of decoherence effect at Daya Bay

Chan-Fai (Steven) Wong†‡ on behalf of M. -C. Chu§, M. Dolgareva†, M. Gonchar†, D. Naumov†, D. Taichenachev†, K. Treskov†, K. M. Tsui‡, W. Wang†

1 Sun Yat-Sen University, GuangZhou, China
2 Department of Physics, The Chinese University of Hong Kong, N.T., Hong Kong
3 Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia
4 RCCN, ICRR, University of Tokyo, Kashiwa-no-ha Kashiwa City, Chiba, Japan

E-mail: † wongchf@mail.sysu.edu.cn

Abstract. The last unknown neutrino mixing angle has been successfully measured by the Daya Bay, RENO and Double Chooz experiments. The used oscillation probability formula is based on the plane-wave model. A wave-packet model is necessary for a self-consistent description of neutrino oscillations. The oscillation probability formula in the wave-packet model describes effects missing in the plane-wave approximation, such as delocalization, decoherence and dispersion which all depend on a single unknown parameter $\sigma_p$ - momentum dispersion of the neutrino wave-packet. The survival probability formula in the wave-packet model was used to fit the Daya Bay data. The high-statistics data set of reactor $\bar{\nu}_e$ interactions in the Daya Bay experiment allows us to study the neutrino oscillation in the wave-packet model and provide the first experimental constraint of $\sigma_p$. Some results of our study are reported in this paper.

1. Introduction

Unprecedented precision in measurement of neutrino mixing parameters has been achieved in the Daya Bay Experiment, which has determined $\sin^2(2\theta_{13}) = 0.084\pm0.005, |\Delta m^2_{23}| = (2.42\pm0.11) \times 10^{-3} \text{ eV}^2$ [1]. A plane-wave (PW) model [2, 3, 4] adopted to derive the $\bar{\nu}_e$ survival probability was used to estimate the oscillation parameters, which is not self-consistent and leads to a number of paradoxes [5, 6]. A wave-packet (WP) description leads to modifications of the PW oscillation formula [5, 6, 7, 8, 9, 10, 11, 12]. We provide an experimental search for a possible loss of coherence in the quantum state of reactor neutrinos, which follows from the WP treatment. Fits of the data within PW and WP models would yield in general two different sets of the best fit values of the oscillation parameters. As we show in what follows, certain domains of the neutrino wave packet relative momentum dispersion $\sigma_{rel}(\equiv \sigma_p/p \simeq \sigma_E/E)$ biases the true values of the oscillation parameters. Therefore, an analysis within the WP model is also important in order to ensure unbiased estimates of the oscillation parameters. This paper provides an examination of the wave-packet effect on neutrino oscillations based on the Daya Bay data [1].

2. Analysis

In one space dimension $^1$, the produced neutrino state is described by a wave packet $|\bar{\nu}_\alpha(t,L)\rangle = \sum_{k=1}^3 V_{\alpha k} \int \frac{dp}{2\pi} f(p)e^{-ip\phi_k(p)}|\nu_k(p)\rangle$, where $\phi_k(p) = E_k t - pL, E_k = \sqrt{p^2 + m_k^2}$. $V_{\alpha k}$ is an element

$^1$ While the neutrino wave function evolves actually in the three-dimensional space the transverse part of the wave function leads essentially to $1/L^2$ flux suppression [13], where $L$ is the distance traveled by neutrino, and does not affect significantly the oscillation pattern. Therefore we simplify the consideration by examining one-dimensional wave packet of neutrino.
of the PMNS-matrix. \( f(p) \) is the wave function of neutrino in the momentum space, which is assumed to be Gaussian with \( f(p) = \left( \frac{2\pi}{\sigma_{p,\text{prod}}} \right)^3 \exp \left[ -\frac{(p-p_\nu)^2}{4\sigma_{p,\text{prod}}} \right] \). Projection of \( |\tilde{\nu}_\alpha(t,x)\rangle \) onto a detection state \( |\tilde{\nu}_\beta\rangle \) similarly defined allows us to calculate the transition amplitudes and the probability which depends on the effective momentum dispersion \( \sigma_p \) given by \( \sigma_p^2 = \frac{1}{\sigma_{p,\text{prod}}} + \frac{1}{\sigma_{p,\text{det}}} \). \( \sigma_{p,\text{prod}} \) and \( \sigma_{p,\text{det}} \) represent the momentum dispersion at the production and detection of neutrinos respectively.

The neutrino flavor transition probability can be found to be

\[
P_{\alpha\beta}(L) = \frac{3}{4\pi} \sum_{k,l=1}^{3} \frac{V_{k\beta}V_{l\alpha}^\dagger V_{k\alpha}V_{l\beta}^\dagger}{\sqrt{1 + \left(L/L_{kl}^\text{coh}\right)^2}} \exp \left[ -\frac{\left(L/L_{kl}^\text{coh}\right)^2}{1 + \left(L/L_{kl}^\text{coh}\right)^2} - D_{kl}^2 - i\varphi_{kl} \right]
\]

where \( \varphi_{kl} = \varphi_{kl}^d + \varphi_{kl}^\text{coh} \).

\[
L_{kl}^\text{osc} = \frac{4\pi p}{\Delta m_{kl}^2}, \quad L_{kl}^\text{coh} = \frac{L_{kl}^\text{osc}}{\sqrt{2\pi}\sigma_{\text{rel}}}, \quad L_{kl}^d = \frac{L_{kl}^\text{coh}}{2\sqrt{2}\sigma_{\text{rel}}}, \quad D_{kl}^2 = \frac{1}{2} \left( \Delta m_{kl}^2 \right)^2 \left( \frac{1}{\sigma_{\text{rel}}} \right)^2 = \left( \frac{\sqrt{2\pi}\sigma_x}{L_{kl}^\text{osc}} \right)^2,
\]

where \( L_{kl}^\text{osc} \) is the usual oscillation length of a pair of neutrino states \( |\nu_k\rangle \) and \( |\nu_l\rangle \), \( L_{kl}^\text{coh} \) is interpreted as the neutrino coherence length, i.e. a distance at which the interference of neutrino mass eigenstates vanishes, and finally \( L_{kl}^d \) is the dispersion length, i.e. a distance at which the wave packet is doubled in its spatial dimension due to the dispersion of waves moving with different velocities. On the other hand, the factor \( D_{kl}^2 \) corresponds to the delocalization and suppresses the oscillation if the relative momentum dispersion \( \sigma_{\text{rel}} \) is so small that \( \sigma_x = \frac{1}{2\sigma_p} D_{kl}^2 \).

Moreover, the terms in Eq. (1) which correspond to interference of \( \nu_k \) and \( \nu_l \) states also get suppressed by the denominator factor \( \frac{4\pi}{\sqrt{1 + \left(L/L_{kl}^d\right)^2}} \) and vanish for both limits \( \sigma_p \to 0 \) and \( \sigma_p \to \infty \), so that the oscillation will be destroyed. Detailed discussions of Eq. (1) can be found in Refs. [11, 12].

For illustrative purposes, the left panel of Fig. 1 shows the data points from the far experiment hall (EH3) of Daya Bay [1], along with the oscillation curves corresponding to different values of \( \sigma_{\text{rel}} \) and oscillation parameters\(^2\). It shows that a large (0.5) or extremely small (1 \( \times 10^{-16} \)) \( \sigma_{\text{rel}} \) leads to decoherence effects. Comparing with the plane-wave oscillation curves, the blue and brown curves are more inconsistent with the data. It implies that the Daya Bay data do not suggest significant WP impact.

To perform the analysis we use the GLoBES software [14, 15]. We consider only the statistical errors of the Daya Bay measurement. The right panel of Fig. 1 shows the result of our analysis, where \( \Delta m_{32}^2 \) is marginalized. In a wide range of \( \sigma_p \) the estimates of \( \sin^2 2\theta_{13} \) obtained with the plane-wave and wave-packet models agree with each other. The decoherence effects expected for the Daya Bay baselines tend to suggest a larger value of \( \sin^2 2\theta_{13} \) in the domains \( \sigma_{\text{rel}} \gtrsim O(10^{-1}) \) or \( \sigma_{\text{rel}} \lesssim O(10^{-16}) \).

The results of this simplified analysis agrees with results from the the Daya Bay Collaboration [12] which found the allowed region \( 2.38 \times 10^{-17} < \sigma_{\text{rel}} < 0.23 \) at 95% C.L. The constraints shown in the right panel of Fig. 1 appear to be slightly stronger because the systematic uncertainties of the both data and model were neglected in this work.

3. Conclusion

A wave-packet analysis has been applied to study neutrino oscillations. The wave-packet model leads to decoherence and dispersion effects, which modify the neutrino survival probability formula. An analysis within the WP model shows that in general the estimates of the oscillation parameters obtained with PW and WP models might be different. We show that the wave-packet effects are small for the Daya Bay baselines, and so the neutrino oscillation parameters obtained with the plane-wave analysis are valid.

\(^2\) Since the wave-packet impacts are expected to be more significant at longer baseline, we only show the comparison between the data collected at the Daya Bay far hall and the oscillation curves of different values of \( \sigma_{\text{rel}} \).
Figure 1. Left panel: The data points correspond to the ratio of the observed numbers of $\bar{\nu}_e$ interactions collected in the far hall of the Daya Bay Experiment to the expectation assuming no-oscillation. The x-axis is the effective propagation distance $L_{\text{eff}}$ divided by the average anti-neutrino energy $\langle E \rangle$. $L_{\text{eff}}$ is calculated by equating the actual flux to an effective $\bar{\nu}_e$ flux with a single baseline, and $\langle E \rangle$ is obtained for each bin using the estimated detector response [1]. The vertical lines correspond to the statistical errors. The black solid curve is the plane-wave expectation with $\sin^2 \theta_{13} = 0.095$, $\Delta m_{32}^2 = 2.43 \times 10^{-3}$ eV$^2$. The blue and brown curves are expectations within the wave-packet models assuming $\sigma_{\text{rel}} = 0.5$ (with corresponding best-fit $\sin^2 \theta_{13} = 0.108$ and $\Delta m_{32}^2 = 2.10 \times 10^{-3}$ eV$^2$) and $\sigma_{\text{rel}} = 1 \times 10^{-16}$ (with corresponding best-fit $\sin^2 \theta_{13} = 0.095$, $\Delta m_{32}^2 = 2.2 \times 10^{-3}$ eV$^2$) respectively. Right panel: The constraints of $\sigma_{\text{rel}}$ and $\sin^2 \theta_{13}$ parameters obtained from a fit to Daya Bay data [1] corresponding to 1 $\sigma$ (solid), 2 $\sigma$ (dashed) and 3 $\sigma$ (dot-dashed). Only statistical errors are considered. We profiled over $\Delta m_{32}^2$ to produce this plot. The vertical black line represents our best-fit $\sin^2 \theta_{13}$ based on the plane-wave model.

Acknowledgement
The authors thank David Jaffe, Rupert Leitner, Kam-Biu Luk, Yu Feng Li and Pedro Ochoa-Ricoux for useful discussions and suggestions.

This work is partially supported by the China Postdoctoral Science Foundation funded project, and VC Discretionary Fund VCF2014006 of The Chinese University of Hong Kong.

[1] An F P et al. (Daya Bay) 2015 Phys. Rev. Lett. 115 111802 (Preprint 1505.03456)
[2] Eliezer S and Swift A R 1976 Nucl. Phys. B105 45–51
[3] Fritzsch H and Minkowski P 1976 Phys. Lett. B62 72–76
[4] Bilenky S M and Pontecorvo B 1976 Lett. Nuovo Cim. 17 569
[5] Akhmedov E K and Smirnov A Y 2009 Phys. Atom. Nucl. 72 1363–1381 (Preprint 0905.1903)
[6] Giunti C 2004 Found. Phys. Lett. 17 103–124 (Preprint hep-ph/0302026)
[7] Beuthe M 2003 Phys. Rep. 375 105–218 (Preprint hep-ph/0109119)
[8] Beuthe M 2002 Phys. Rev. D66 013003 (Preprint hep-ph/0202068)
[9] Bernardini A E, Guzzo M M and Torres F R 2006 Eur. Phys. J. C48 613 (Preprint hep-ph/0612001)
[10] Naumov D and Naumov V 2010 J. Phys. G37 105014 (Preprint 1008.0306)
[11] Chan Y L, Chu M C, Tsur K M, Wong C F and Xu J 2016 Eur. Phys. J. C76 310 (Preprint 1507.06421)
[12] An F P et al. (Daya Bay) 2016 (Preprint 1608.01661)
[13] Naumov D 2013 Phys. Part. Nucl. Lett. 10 642–650 (Preprint 1309.1717)
[14] Huber P, Lindner M and Winter W 2005 Comput. Phys. Commun. 167 195 (Preprint hep-ph/0407333)
[15] Huber P, Kopp J, Lindner M, Rolinec M and Winter W 2007 Comput. Phys. Commun. 177 432–438 (Preprint hep-ph/0701187)