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New index of CP phase effect and θ_{13} screening in long baseline neutrino experiments

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Abstract

We introduce a new index of the leptonic CP phase dependence I_{CP} and derive the maximal condition for this index in a simple and general form. $I_{\mathrm{CP}} \simeq 100\%$ may be realized even in the JPARC experiment. In the case that the 1–3 mixing angle can be observed in the next generation reactor experiments, namely $\sin^2 2\theta_{13} > 0.01$, and nevertheless ν_e appearance signal cannot be observed in the JPARC experiment, we conclude that the CP phase δ becomes a value around 135° (45°) for $\Delta m^2_{31} > 0$ ($\Delta m^2_{31} < 0$) without depending the uncertainties of solar and atmospheric parameters.

1. Introduction

In future experiments, the determination of the leptonic CP phase δ is one of the most important aim in elementary particle physics. A lot of effort have been dedicated both from theoretical and experimental point of view in order to attain this aim, see [1–4] and the references therein.

The CP asymmetry, $A_{\mathrm{CP}} = (P_{\mu e} - \bar{P}_{\mu e})/(P_{\mu e} + \bar{P}_{\mu e})$, is widely used as the index of the CP phase dependence. Here, $P_{\mu e}$ and $\bar{P}_{\mu e}$ are the oscillation probabilities for the transition $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, respectively. However, this index has to be improved on the following three points. The first one is that the fake CP violation due to matter effect [5] cannot be separated clearly in A_{CP}. The second one is that only the effect originated from $\sin\delta$ is included in A_{CP}. The third one is that we need to observe the channels both in neutrino and anti-neutrino for calculating A_{CP}.

In this Letter, we introduce a new index of the CP phase dependence improved on the above three points. In arbitrary matter profile, we derive the maximal condition of this index exactly for $\nu_\mu \to \nu_e$ transition. This index can be extended to the case for other channels and other parameters [6]. We can simply find the situation that the CP phase effect becomes large by using this index. As an example, we demonstrate the following interesting phenomena. It is commonly expected that a large ν_e appearance signal is observed in the JPARC experiment [7] if the 1–3 mixing angle θ_{13} is relatively large $\sin^2 2\theta_{13} > 0.01$ and is determined by the next generation reactor experiments like the double CHOOZ experiment [8] and the KASKA experiment [9]. However, there is the possibility that ν_e appearance signal cannot be observed in certain mass squared differences and mixing angles even the case for large θ_{13}. We call this "θ_{13} screening". This occurs due to the almost complete cancellation of the large θ_{13} effect by the CP phase effect. If the background can be estimated precisely, we can obtain the information on the CP phase through the θ_{13} screening. This means that we cannot neglect the CP phase effect, which is actually neglected in many investigations as the first approximation.

2. General formulation for maximal CP phase effect

At first, we write the Hamiltonian in matter [10] as

$$H = O_{23}\Gamma H' \Gamma^\dagger O_{23}^T \tag{1}$$

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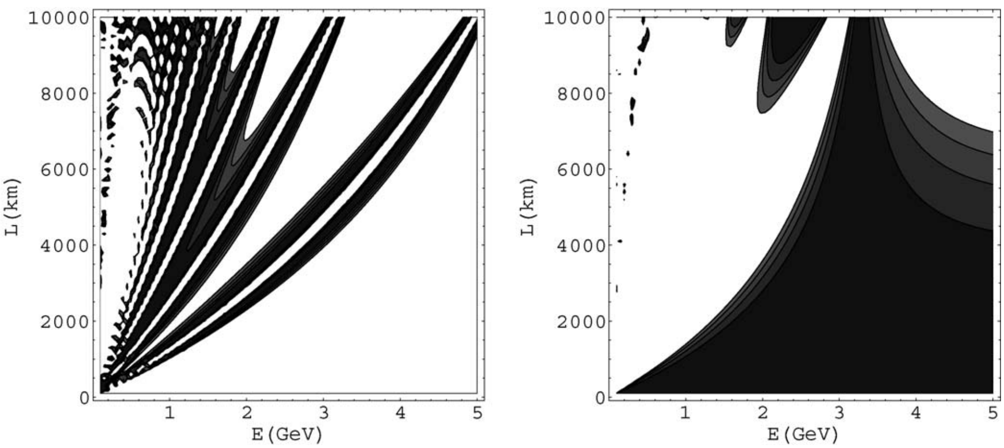

Fig. 1. Region with large I_{CP}. We write the lines for $I_{\mathrm{CP}} = 95\%, 90\%, 85\%, 80\%$. I_{CP} takes the large value in black region. Left and right panels are drawn with two different sets of parameters.

by factoring out the 2–3 mixing angle and the CP phase, where O_{23} is the rotation matrix in the 2–3 generations and Γ is the phase matrix defined by $\Gamma = \mathrm{diag}(1, 1, e^{i\delta})$. The reduced Hamiltonian H' is given by

$$H' = O_{13} O_{12} \,\mathrm{diag}(0, \Delta_{21}, \Delta_{31}) O_{12}^T O_{13}^T + \mathrm{diag}(a, 0, 0), \quad (2)$$

where $\Delta_{ij} = \Delta m_{ij}^2/(2E) = (m_i^2 - m_j^2)/(2E)$, $a = \sqrt{2} G_F N_e$, G_F is the Fermi constant, N_e is the electron number density, E is neutrino energy and m_i is the mass of ν_i. The oscillation probability for $\nu_\mu \to \nu_e$ is proportional to the $\cos\delta$ and $\sin\delta$ in arbitrary matter profile [11] and can be expressed as

$$P_{\mu e} = A\cos\delta + B\sin\delta + C = \sqrt{A^2 + B^2}\sin(\delta + \alpha) + C. \quad (3)$$

Here A, B and C are determined by parameters other than δ and are calculated by

$$A = 2\,\mathrm{Re}\big[S'^*_{\mu e} S'_{\tau e}\big] c_{23} s_{23}, \quad (4)$$

$$B = 2\,\mathrm{Im}\big[S'^*_{\mu e} S'_{\tau e}\big] c_{23} s_{23}, \quad (5)$$

$$C = \big|S'_{\mu e}\big|^2 c_{23}^2 + \big|S'_{\tau e}\big|^2 s_{23}^2, \quad (6)$$

where $S'_{\alpha\beta} = [\exp(-iH'L)]_{\alpha\beta}$, $\tan\alpha = A/B$ and $\sqrt{A^2 + B^2} \times \sin(\delta + \alpha)$ is the CP-dependent term and C is the CP independent term.

Next, let us introduce a new index of the CP phase dependence I_{CP}. Suppose that $P_{\max}$ and $P_{\min}$ as the maximal and minimal values when δ changes from 0° to 360°. Then, we define I_{CP} as

$$I_{\mathrm{CP}} = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}} = \frac{\sqrt{A^2 + B^2}}{C}. \quad (7)$$

Namely, the new index is expressed by the ratio of the coefficient of the CP-dependent term to the CP independent term. I_{CP} is a useful tool to explore where is the most effective region in parameter spaces to extract the CP effect from long baseline experiments although I_{CP} is not an observable. A_{CP} is also similar one and this is an observable. However A_{CP} have to be expressed by δ though δ is still unknown parameter so that A_{CP} seems not to be so good index to make the exploration. On the other hand, I_{CP} is calculated without using δ. This is the main difference between these two indices and it is more effective to use I_{CP}.

In this Letter, we show the region for taking the large value of I_{CP} in the E–L plane. In particular, we investigate how the region changes by the uncertainties of atmospheric and solar parameters if θ_{13} is determined by the future reactor experiment. In Fig. 1 (left), we choose the parameters as $\Delta m_{21}^2 = 7.9 \times 10^{-5}\ \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.31$, $\Delta m_{31}^2 = 2.2 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.50$, which are the best-fit values in the present experiments [12]. We also use $\sin^2 2\theta_{13} = 0.1$, which is near on the upper bound of the CHOOZ experiment [13]. On the other hand, in Fig. 1 (right), we choose $\Delta m_{21}^2 = 8.9 \times 10^{-5}\ \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.40$, $\Delta m_{31}^2 = 1.4 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.34$, $\sin^2 2\theta_{13} = 0.01$, which are within the 3-σ allowed region, respectively [12]. We use the $\rho = 2.8\ \mathrm{g/cm}^3$ as the matter density. Fig. 1 (left) shows that I_{CP} takes a large value along the line $L/E = \mathrm{const}$ in low energy region. In contrary, Fig. 1 (right) shows that there is a wide region with almost $I_{\mathrm{CP}} \simeq 100\%$. The region appears in the baseline shorter than 3000 km and surprisingly it is independent of neutrino energy. So, what is the condition for realizing the maximal I_{CP}? If we notice (4)–(6), we find that the relation between the denominator and the numerator of I_{CP}. Namely, the fact that the average of two positive quantities is in general larger than the square root of their product yields

$$C = \big|S'_{\mu e}\big|^2 c_{23}^2 + \big|S'_{\tau e}\big|^2 s_{23}^2 \geqslant 2\big|S'^*_{\mu e} S'_{\tau e}\big| c_{23} s_{23} = \sqrt{A^2 + B^2}. \quad (8)$$

In relation to this, Burguet et al. have pointed out the fact "the CP-dependent term cannot be larger than the CP independent term" by using the approximate formula [14]. In this Letter, we define I_{CP} without depending on the unknown CP phase and derive the exact inequality in arbitrary matter profile for the first time. Furthermore, we consider the condition that both sides become equal in this inequality. This condition is given by

$$|S'_{\mu e}| c_{23} = |S'_{\tau e}| s_{23} \quad (\text{maximal condition}), \quad (9)$$

and $I_{\mathrm{CP}} = 100\%$ is realized when this condition is satisfied. Below, let us investigate the maximal condition (9) in detail by using the approximate formula including the non-perturbative effect of small parameters θ_{13} and Δm^2_{21}, in constant matter profile [15]. The reduced amplitudes in the maximal condition are approximated by

$$S'_{\mu e} \simeq \lim_{s_{13}\to 0}\big[\exp(-iH'L)\big]_{\mu e}, \tag{10}$$

$$S'_{\tau e} \simeq \lim_{\Delta_{21}\to 0}\big[\exp(-iH'L)\big]_{\tau e}. \tag{11}$$

The maximal condition is rewritten as

$$\frac{\Delta_{21}\sin 2\theta_{12}}{\Delta_\ell}c_{23}\sin\left(\frac{\Delta_\ell L}{2}\right) = \left|\frac{\Delta_{31}\sin 2\theta_{13}}{\Delta_h}s_{23}\sin\left(\frac{\Delta_h L}{2}\right)\right| \tag{12}$$

in this approximation, where $\Delta_h = \Delta m^2_h/(2E)$, $\Delta_\ell = \Delta m^2_\ell/(2E)$ and Δm^2_h (Δm^2_ℓ) stands for the effective mass squared differences corresponding to high (low) energy MSW effect. The concrete expression for Δ_h is given by

$$\Delta_h = \sqrt{(\Delta_{31}\cos 2\theta_{13} - a)^2 + \Delta^2_{31}\sin^2 2\theta_{13}}. \tag{13}$$

We obtain Δ_ℓ by the replacements $\Delta_h \to \Delta_\ell$, $\Delta_{31}\to\Delta_{21}$, $\theta_{13}\to\theta_{12}$. The energy dependence of Δm^2_h and Δm^2_ℓ is mild and roughly speaking we regard these as constant. At this time, (12) becomes the equation for L/E and the region for large $I_{\rm CP}$ appears along the line $L/E = \text{const}$ in Fig. 1 (left). On the other hand, there appears no L/E dependence at short baseline in Fig. 1 (right). This is interpreted as follows. In the case of small x, the approximation $\sin x \simeq x$ becomes good and the E and L dependencies of both sides vanish and the maximal condition can be simplified as

$$\Delta m^2_{21}\sin 2\theta_{12}c_{23} = \left|\Delta m^2_{31}\right|\sin 2\theta_{13}s_{23}. \tag{14}$$

The inequality for L is obtained by $\Delta_\ell L/2 \ll 1$ as

$$L \ll \frac{2}{a} = \frac{2}{\sqrt{2}G_F\rho Y_e} \simeq 3500\ [\text{km}], \tag{15}$$

where we use $\rho = 2.8\ \text{g/cm}^3$ as the matter density and $Y_e = 0.494$ as the electron fraction. The inequality for E is also obtained by $\Delta_h L/2 \ll 1$ as

$$E \gg \frac{\Delta m^2_{31}L}{4} \simeq \frac{L}{500}\ [\text{GeV}], \tag{16}$$

where the baseline length L is measured in the unit of km. The region for satisfying these conditions coincides with that for taking large $I_{\rm CP}$ in Fig. 1 (right).

Next, let us investigate the condition (14). That is rewritten as

$$\sin 2\theta_{13} = 0.036 \times \frac{\Delta m^2_{21}}{8\cdot 10^{-5}}\,\frac{\sin 2\theta_{12}}{0.9}\,\frac{1.0}{\tan\theta_{23}}\,\frac{2\cdot 10^{-3}}{|\Delta m^2_{31}|}. \tag{17}$$

In the case that the parameters except θ_{13} have their best-fit values in the present experiments, the value of θ_{13} satisfying (17) becomes small compared with the bound $\sin 2\theta_{13} > 0.1$ of next generation reactor experiments. However, it is possible to satisfy Eq. (14) if the parameters possess values, which slightly deviate from those of the best-fit. We chose the parameters for satisfying Eq. (14) in Fig. 1 (right). The readers may think that such a situation with large $I_{\rm CP}$ independent of E and L is extraordinary and it is not likely realized. However, if we write the ratio of both sides of (14) as

$$r = \frac{\Delta m^2_{21}c_{23}\sin 2\theta_{12}}{|\Delta m^2_{31}|s_{23}\sin 2\theta_{13}}, \tag{18}$$

$I_{\rm CP}$ is calculated by using r as

$$I_{\rm CP} = \frac{2r}{1+r^2}, \tag{19}$$

and we found that the large CP phase effect is realized as $I_{\rm CP} = 97.5\%$ (88%) with $r = 0.8$ (0.6) for example. Thus, the decrease of $I_{\rm CP}$ according to the difference from Eq. (14) is comparatively mild and the region with large $I_{\rm CP}$ becomes wider than expected. If we describe for the reference, $r = 0.10$ (0.87) and $I_{\rm CP} \simeq 20\%$ (99%) in Fig. 1 (left) (Fig. 1 (right)). The discovery of such a situation, where the maximal condition is satisfied independently of E and L is one of our main results in this Letter. This may be realized in the JPARC experiment under the condition of certain parameter combinations, and is very important to analyze the experimental result.

3. θ_{13} screening in JPARC experiment

We found that the screening condition may be realized in the JPARC experiment. Next, we consider the case such that $I_{\rm CP}$ takes a large value and the CP phase effect contributes to the probability destructively. It is commonly expected that a large ν_e appearance signal is observed in the JPARC experiment, if θ_{13} is large and will be confirmed in next generation reactor experiments. We point out here that the probability can be zero over the entire region in the JPARC experiment due to the cancellation of θ_{13} effect by the CP phase effect. We use the same parameters as in Fig. 1 (right), where Eq. (14) holds. Fig. 2 shows the oscillation probabilities with $\delta = 45°, 135°, 225°, 315°$ in the energy range 0.4–1.2 GeV of the JPARC experiment. In Fig. 2, one can see that the CP-dependent term has the same sign as the CP independent term when $\delta = 315°$. They interfere constructively with each other and generate the large probability. On the other hand, they have opposite sign and almost completely cancel each other when $\delta = 135°$. As a result, the probability for $\nu_\mu \to \nu_e$ transition is

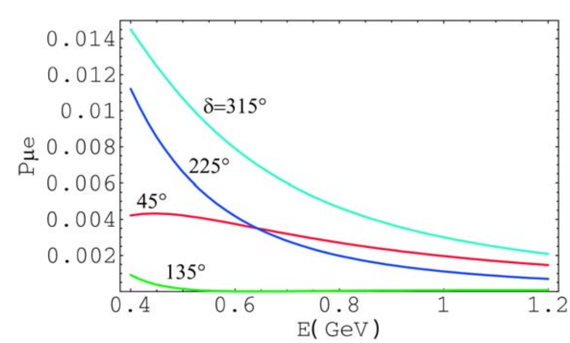

Fig. 2. CP dependence of $P_{\mu e}$ under the maximal condition. Four lines stand for the oscillation probabilities with $\delta = 45°, 135°, 225°$ and $315°$, respectively.

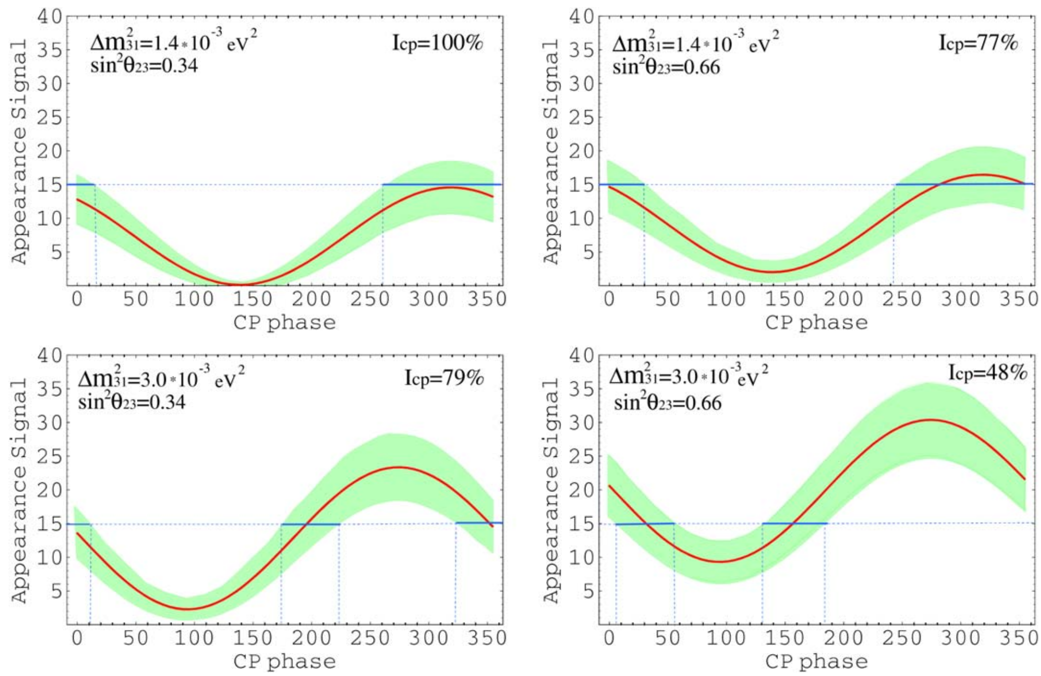

Fig. 3. CP dependence of ν_e appearance signal in the JPARC-SK experiment. We use the parameters as in Fig. 1 (right) except for Δm^2_{31} and $\sin^2\theta_{23}$. The condition (14) is satisfied in the top-left figure, and is not satisfied in other figures. The statistical error is also shown within the 1σ level. We also show the value of $I_{\rm CP}$ calculated at 1 GeV in figures.

strongly suppressed and we call this phenomena "θ_{13} screening".

Let us calculate the value of δ for the θ_{13} screening. At first, the value of α is determined by $\sin\alpha = A/\sqrt{A^2+B^2}$, $\cos\alpha = B/\sqrt{A^2+B^2}$. This leads to

$$\tan\alpha = \frac{A}{B} \simeq \frac{-1}{\tan(\frac{\Delta m^2_{32}L}{4E})} = \tan\left(\frac{\pi}{2} + \frac{\Delta m^2_{32}L}{4E}\right). \tag{20}$$

Substituting $\Delta m^2_{32} = 1.4 \times 10^{-3}$ eV^2, $L = 295$ km and $E = 0.7$ GeV into this relation, we obtain $\alpha \simeq 135°$. If $\delta \simeq 135°$, we obtain $\sin(\delta+\alpha) = \sin 270° = -1$ and as a result C and $\sqrt{A^2+B^2}$ cancel each other from Eq. (3). As seen from (20), the value of δ for the θ_{13} screening changes with E and L in general. However, $\sin(\delta+\alpha)$ takes a local minimum around $\delta + \alpha = 270°$ and the magnitude of the CP-dependent term changes at most 10% even if α changes 30° around this minimum. This is the reason for $P_{\mu e} \simeq 0$ in a wide energy region.

Here, we discuss the relation between the problems of parameter degeneracy and the θ_{13} screening. In this Letter, we investigated the case for large θ_{13}, which will be confirmed by next generation reactor experiments. Namely, we have considered the case of θ_{13}–δ ambiguity free [14]. Next, let us consider the θ_{23} ambiguity [16]. In order for the θ_{13} screening to be realized, the parameters should satisfy the relation (14). Under this condition, only a small θ_{23} near the present lower bound is permitted, namely $\theta_{23} \simeq 35°$, which corresponds to $\sin^2\theta_{23} = 0.34$. Therefore, if the θ_{13} screening is observed, θ_{23} degeneracy is solved. Finally, let us consider the Δm^2_{31} sign ambiguity [17]. In the case for also $\Delta m^2_{31} < 0$, the maximal condition is almost independent of E and L at the baseline of the JPARC experiment $L = 295$ km. The sign of A changes and becomes negative according to the replacement of the sign of Δm^2_{31}. On the other hand, the sign of B does not change and is negative. This leads to $\alpha = 225°$ and the θ_{13} screening occurs around $\delta = 45°$ for $\Delta m^2_{31} < 0$.

Next, in Fig. 3, we numerically estimate ν_e appearance signal, namely the total number of events distinct from the background noise, obtained in the JPARC-SK experiment within the energy range $E = 0.4$–1.2 GeV when the CP phase δ changes from 0° to 360°. In top and down figures, we use $\Delta m^2_{31} = 1.4 \times 10^{-3}$ eV^2 and 3.0×10^{-3} eV^2, respectively. In left and right figures, we use $\sin^2\theta_{23} = 0.34$ and 0.66. Other parameters are taken as in Fig. 1 (right). We assume here only the neutrino beam data as realized in the JPARC-SK for five years. We also give the statistical error within the 1σ level in Fig. 3. We use the globes software to perform the numerical calculation [7,18].

As expected from the oscillation probability in Fig. 2, ν_e appearance signal will become almost zero around $\delta = 135°$ even during the five years data acquisition in the SK experiment in the top-left of Fig. 3. Note that this occurs only when the maximal condition (14) is satisfied, namely $I_{\rm CP} \simeq 100\%$. Other panels in Fig. 3 show that the minimal value of ν_e appearance signal rise and is a little different from zero because (14) is not satisfied so precisely. We obtain the similar results in the case that Δm^2_{21} or $\sin^2\theta_{12}$ changes within the allowed region obtained from solar and the KamLAND experiments. Let us here illustrate how the value of δ is constrained by the experiment. Below, suppose that the atmospheric parameters have some uncertainties as $\Delta m^2_{31} = 1.4$–3.0×10^{-3} eV^2 and $\sin^2\theta_{23} = 0.34$–0.66, while the solar parameters Δm^2_{21} and $\sin^2\theta_{12}$ and $\sin^2\theta_{13}$ are fixed for simplicity. For example, if 15 appearance signals are observed in the experiment, we obtain the allowed region of δ as 0°–50° or 130°–220° or 240°–360° from four figures in Fig. 3. Namely, combined range of all allowed region is totally 260°. Next, we consider the case that no appearance signal is obtained. This gives the allowed region of δ as 110°–160°. Namely, combined range of all allowed region is totally 50°. Thus, we found from above rough estimation that the stronger constraint is obtained in the case of θ_{13} screening even if the uncertainties of parameters except for δ are considered. In other words, we can also obtain the information on the atmospheric and solar parameters. Although the precise estimation of the background is a difficult problem, it is interesting to have strong constraint for not only the value of the CP phase but also other parameters like Δm^2_{31} and $\sin^2\theta_{23}$ when the ν_e appearance signal is not observed and the 1–3 mixing angle has a comparatively large value $\sin^2 2\theta_{13} > 0.01$.

4. Summary and discussion

In summary, we introduced a new index of the CP phase dependence I_{CP} and derived their maximal condition in a simple and general form. In particular, we showed that $I_{\mathrm{CP}} \simeq 100\%$ is realized in a rather wide region in the E–L plane at certain values of parameters. In the case that θ_{13} has a comparatively large value $\sin^2 2\theta_{13} = 0.01$, (namely θ_{13} will be observed in next generation reactor experiments) nevertheless we cannot observe ν_e appearance signal in the JPARC experiment, we obtain the information on the CP phase as $\delta \simeq 135°$ ($\delta \simeq 45°$) for $\Delta m^2_{31} > 0$ ($\Delta m^2_{31} < 0$) without depending on the uncertainties of other parameters. Also for $\sin^2 2\theta_{13} < 0.01$, there is a possibility that the θ_{13} screening will occur. In this case, we need to consider the reason for the absence of ν_e appearance signal in the JPARC experiment more carefully, in order to understand whether θ_{13} is small or the θ_{13} effect is canceled out by the CP phase effect. We also note that the θ_{13} screening may be realized for not only $\nu_\mu \to \nu_e$ oscillation in super-beam experiments but also $\nu_e \to \nu_\tau$ oscillation in neutrino factory experiments. We can also use the zero probability in the θ_{13} screening to explore new physics like non-standard interaction.

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