Instituto de Física
Universidade de São Paulo

CP VIOLATION IN VACUUM NEUTRINO OSCILLATION EXPERIMENTS

Gago, A. M.; Pleitez, V.; Funchal, R. Z.
DEPTO. FÍSICA NUCLEAR

Publicação IF - 1320/98

IFUSP/PRE-PRINT: 1320/98
IFT-P.072/98

CP VIOLATION IN VACUUM NEUTRINO OSCILLATION EXPERIMENTS

A. M. Gago[1] * †, V. Pleitez[2‡], and R. Zukanovich Funchal[1§]
[1] Instituto de Física, Universidade de São Paulo,
C. P. 66.318, 05389-970 São Paulo, Brazil

[2] Instituto de Física Teórica – UNESP
R. Pamplona 145, 01405-900 São Paulo, Brazil.

hep-ph/9810505 28 Oct 1998

Abstract

We discuss the use of the CP asymmetry parameter (A_{CP}) as a possible observable of CP violation in the leptonic sector. In order to do this, we study for a wide range of values of L/E the behavior of this asymmetry for the corresponding maximal value of the CP violation factor allowed by all the present experimental limits on neutrino oscillations in vacuum and the recent Super-Kamiokande atmospheric neutrino result. We work in the three neutrino flavor framework.

PACS numbers: 11.30.Er; 14.60.Pq

Typeset using REVTeX

*Permanent address: Pontificia Universidad Catolica del Perú, AP 1762 Lima, Peru.

†Email: agago@charme.if.usp.br

‡Email: vicente@ift.unesp.br

§Email: zukanov@charme.if.usp.br

We are definitely living in very exciting times in neutrino physics. The recent results from Super-Kamiokande indicating evidence for neutrino oscillations in atmospheric showers [1], the reports of observed neutrino oscillations by the Los Alamos Liquid Scintillator Detector (LSND) [2] in the $\overline{\nu}_\mu \to \overline{\nu}_e$ and $\nu_\mu \to \nu_e$ channels in conjunction with other hints such as the results of solar neutrino experiments [3–6] makes it difficult to believe today that all of these facts are not related to neutrino properties beyond the standard model.

In the past neutrino physics has led to the discovery of neutral currents and provided the first indications in favor of the standard model of electroweak interaction. It may as well, if neutrino oscillations turn out to be confirmed by future experiments, reveal itself as an invaluable tool to cast some light on the origin of CP violation. One can hope this can be achieved in the study of the neutrino oscillation phenomena in some of the future experiments [7–9].

As it is well known [10–13] CP violation in neutrino oscillations can, in principle, be observed in neutrino experiments by looking at the differences of the transition probabilities between CP–conjugate channels, $\Delta P = P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) - P(\nu_\alpha \to \nu_\beta)$. It has been pointed out by many authors that it may be, in practice, very difficult to get a reliable measurement of ΔP due to possible earth matter effects in long baseline neutrino experiments [14,15].

Here we will use the asymmetry parameter, $A_{CP} = \Delta P/[P(\nu_\alpha \to \nu_\beta) + P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)]$, suggested by Cabibbo [10], as an alternative to measure CP violation in the leptonic sector. We will investigate the possible values of this parameter and the corresponding maximal values of ΔP allowed by present experimental data for different L/E situations.

If one tries to explain all the current neutrino data it has been shown that it is necessary to consider at least four different neutrino species due to the fact that the experiments point towards three scales of neutrino mass-squared differences [16]. This bizarre situation may change or be confirmed with more data and one really has to wait before taking it really seriously.

This work will be developed in the three flavor neutrino scheme and for this reason only two mass scale indications can be taken to be right. We will fix them to be:

$$\Delta m^2_{12} \approx 1.3 \text{ eV}^2, \quad \Delta m^2_{23} \approx 3.3 \times 10^{-3} \text{ eV}^2, \tag{1}$$

both within the allowed regions given by terrestrial experiments [2,17,18] and atmospheric neutrino experiments [1] respectively. We will also take into account the probability constraints coming from this two types of experiments.

In the terrestrial case we take the results from two short baseline accelerator experiments LSND [2] and E776 [18] for the channels $\overline{\nu}_\mu \to \overline{\nu}_e$ and $\nu_\mu \to \nu_e$ respectively

LSND:

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = 0.31 \pm 0.10 \pm 0.05\%; \quad L = 30 \text{ m}, \quad E \sim 36 - 60 \text{ MeV}, \tag{2}$$

E776:

$$P(\nu_\mu \to \nu_e) < 3 \times 10^{-3} \text{ at } 90\% \text{ C.L.}; \quad L/E \sim 1. \tag{3}$$

For the oscillation channel $\nu_\mu \to \nu_\tau$ we use the data from CHORUS and NOMAD [19]. These short baseline accelerator experiments give

$$P(\nu_\mu \to \nu_\tau) < 2 \times 10^{-3} \text{ at } 90\% \text{ C.L.}; \quad L/E \sim 0.02. \tag{4}$$

In the search for the disappearance of the $\overline{\nu}_e$ we have from CHOOZ [20], a long baseline reactor experiment,

$$1 - P(\overline{\nu}_e \to \overline{\nu}_e) < 10^{-1} \text{ at } 90\% \text{ C.L.}; \quad L/E \sim 300\,, \tag{5}$$

and from the BUGEY [17] reactor experiment

$$1 - P(\overline{\nu}_e \to \overline{\nu}_e) < 10^{-2} \text{ at } 90\% \text{ C.L.}; \quad L = 15, 40, 95\,\text{m}, \quad E \sim 1 - 6 \text{ MeV}. \tag{6}$$

In the case of atmospheric neutrino experiments we only use the latest Super-Kamiokande [1] result since it is the most precise one. They show that the transition $\nu_\mu \to \nu_\tau$ taking place in vacuum is one of the most probable explanations [21] for the atmospheric neutrino anomaly. Their ranges for the mixing parameters are $5 \times 10^{-4}\text{eV}^2 \leq \Delta m^2_{23} \leq 6 \times 10^{-3}\text{eV}^2$ and $\sin^2 2\theta \geq 0.82$. Using these intervals and replacing them in the two generation oscillation formula we can estimate the maximal and minimal probabilities allowed, that is :

$$0.008 \leq P(\nu_\mu \to \nu_\tau) \leq 0.9095, \quad L/E \sim 13 \times 10^3. \tag{7}$$

Since the probability limits given in Eqs. (2-7) are in fact independent of the number of neutrino generations we are free to use them in the three neutrino flavor framework.

We can get the analytical expressions for ΔP and A_{CP} using the usual form of the CKM matrix parameterization:

$$\mathrm{U} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{13}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}, \tag{8}$$

where c and s denote the cosine and the sine of the respective arguments.

Thus ΔP in vacuum can be written as:

$$\Delta P(\alpha, \beta) = P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) - P(\nu_\alpha \to \nu_\beta) = 4J_{CP}(\sin\Delta_{12} + \sin\Delta_{23} + \sin\Delta_{31}), \tag{9}$$

with $\alpha, \beta = e, \mu, \tau$ and

$$\Delta_{ij} = 2.54 \left(\frac{\Delta m^2_{ij}}{1\text{eV}^2}\right)\left(\frac{L}{\text{km}}\right)\left(\frac{1\text{GeV}}{E}\right), \; i, j = 1, 2, 3; \tag{10}$$

where $\Delta m^2_{ij} = m^2_j - m^2_i$ and the well known Jarlskog invariant

$$J_{CP} = c^2_{13}s_{13}c_{12}s_{12}c_{23}s_{23}\sin\delta. \tag{11}$$

We can see from Eqs. (9-11) that $\Delta P(\mu, e) = \Delta P(\mu, \tau) = \Delta P(e, \tau)$ so they are all simply referred to as ΔP.

On the other hand $\mathrm{A}(\alpha, \beta)_{CP}$, which depends on the specific channel (α, β), is given by :

$$\mathrm{A}(\alpha, \beta)_{CP} = \frac{P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) - P(\nu_\alpha \to \nu_\beta)}{P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) + P(\nu_\alpha \to \nu_\beta)}. \tag{12}$$

In order to determine the maximum permitted values of ΔP and $\mathrm{A}(\mu, e)_{CP}$ we proceed in the following way. We choose randomly different values of the mixing parameters s_{12}^2, s_{23}^2 and s_{13}^2 taken in the interval 0 to 1. Once we have defined these parameters we evaluate the probabilities according to the experimental channels and values of L/E appearing in the Eqs. (2-7), these probabilities are obtained using the complete expression for the oscillations in three generations without any approximation. We check if they pass simultaneously all the experimental constraints also given in these equations. In the positive case we compute the CP violation factor J_{CP} for fixed values of the phase angle δ. We select among them the maximal value of J_{CP}, $J_{CP}^{\max}$, for each δ and calculate the corresponding values of $\Delta P^{\max}$ and $\mathrm{A}(\mu, e)_{CP}$ for L/E varying from 1 to 200.

In the Table I we show that $J_{CP}^{\max}$ increases with $\sin\delta$ in a non linear way, differently from what is naively expected from Eq. (11). This is because the value of $c_{13}^2 s_{13} c_{12} s_{12} c_{23} s_{23}$ which maximizes J_{CP} for different $\sin\delta$ is not a constant. This is not strange since the probabilities are functions of mixing angles as well as of δ and we impose that the mixing parameters used in the maximization must satisfy the probability limits given by Eqs. (2-7). In addition the values obtained are in fact much smaller than the constraint $J_{CP}^{\max} \approx 0.096$ [22] , resulting from the unitarity of the mixing matrix.

In Figs. 1 we show $\Delta P^{\max}$ as a function of L/E for $\sin\delta = 1$ and $\sin\delta = 0.5$, Figs. 1(a) and 1(b) respectively. One can get other curves for different values of $\sin\delta$ which will have exactly the same form as these ones, only the oscillation amplitudes will decrease in proportion to the corresponding $J_{CP}^{\max}$. In Fig. 1(a) we see that the maximum attained, around $\mathcal{O}(0.008)$, in agreement with other estimation of this value [15], occurs in the region $L/E \approx 185 - 200$. We observe that, after maximization, $\Delta P^{\max}$ as a function of L/E depends on the mass hierarchy that we have adopted through a sum of sine functions which can be directly seen in Eq. (9). It essentially means that if one adopts another hierarchy the maxima of $\Delta P^{\max}$ will have other values and will occur in a different L/E region than in Figs. 1(a) and (b).

In Figs. 2(a) and (b) we show the behavior of $\mathrm{A}(\mu, e)_{CP}$ as a function of L/E for $\sin\delta$=1. In Figs. 2(c) and (d) we show the same for $\sin\delta$=0.5. We can observe the growing of A_{CP} with L/E. In the interval $150 \leq L/E \leq 200$, A_{CP} is near to the maximum possible value [10]. Moreover we can note the difference in the shape of oscillation for the different values of $\sin\delta$, also we have that in average the values of A_{CP} for $\sin\delta$=1 are higher than in the case of $\sin\delta$=0.5, as expected.

We have found the maximal allowed values for $\Delta P^{\max}$ with their respective A_{CP}, as a function of L/E and $\sin\delta$. This was done in the three neutrino flavor framework using constraints from recent experimental data and admitting the two mass squared differences $\Delta m_{12}^2 \approx 1.3$ eV^2 and $\Delta m_{23}^2 \approx 3.3 \times 10^{-3}$ eV^2.

We have seen that in general the values of A_{CP} are much more sizable than the corresponding $\Delta P^{\max}$. In addition since in the asymmetry the systematic errors cancel out, even if the absolute flux of the neutrino beam is determined with an accuracy of 10 % it may be possible to measure CP violation at 1 % level. This is particularly interesting since in long baseline experiment there are expected matter effects that fake genuine CP violation [15]. We hope that the matter effects will be less important in the asymmetry.

ACKNOWLEDGMENTS

This work was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), and by Programa de Apoio a Núcleos de Excelência (PRONEX).

REFERENCES

[1] The Super-Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Lett. B 433 (1998) 9; hep-ex/9807003.

[2] LSND Collaboration, C. Athanassopoulos *et al.*, Phys. Rev. Lett. 75 (1995) 2650; *ibid.* 77 (1996) 3082; Phys. Rev. C 54 (1996) 2685; Phys. Rev. Lett. 81 (1998) 1774.

[3] B. T. Cleveland *et al.*, Nucl. Phys. B (Proc. Suppl.) 38 (1995) 47; R. Davis, Prog. Part. Nucl. Phys. 32 (1994) 13.

[4] GALLEX Collaboration, W. Hampel *et al.*, Phys. Lett. B 388 (1996) 384.

[5] D. N. Abdurashitov *et al.*, Nucl. Phys. Proc. Suppl. 48 (1996) 299.

[6] Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Rev. Lett. 77 (1996) 1683; Super-Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Rev. Lett. 81 (1998) 1158.

[7] Y. Oyama, talk given at the YITP Workshop on Flavor Physics, Kyoto, Japan, 28-30 Jan. 1998 (hep-ex/9803014).

[8] MINOS Collaboration, Fermilab report NuMI-L-337 Technical Design Report, Aug. 1998.

[9] ICARUS Collaboration, P. Cennini *et al.*, LNGS-94/99, May 1994.

[10] N. Cabibbo, Phys. Lett. B 72 (1978) 333.

[11] V. Barger, K. Whisnant, and R. J. N. Phillips, Phys. Rev. Lett. 45 (1980) 2084.

[12] S. M. Bilenky, J. Hosek, and S. T. Petcov, Phys. Lett. B 94 (1980) 495.

[13] S. Pakvasa, in: Proceedings of the XXth International Conference of High Energy Physics, Eds. L. Durand and L. G. Pondrom, AIP Conf. Proc. No. 68 (AIP, New York, 1981), Vol. 2, p. 1164.

[14] M. Tanimoto, Phys. Rev. D 55 (1997) 322; J. Arafune and J. Sato, Phys. Rev. D 55 (1997) 1653.

[15] H. Minakata and H. Nunokawa, Phys. Lett. B 413 (1997) 369; Phys. Rev. D 57 (1998) 4403.

[16] A. Yu Smirnov, in: Proceeding of the XXVIIIth International Conference on High Energy Physics, Warsaw 1996, ICHEP'96, Vol. 1, p. 288 (hep-ph/9611465).

[17] Bugey Collaboration, B. Achkar *et al.*, Nucl. Phys. B 434 (1995) 503.

[18] E776 Collaboration, L. Borodovsky *et al.*, Phys. Rev. Lett. 68 (1992) 274.

[19] CHORUS Collaboration, E. Eskut *et al.*, Nucl. Instrum. Meth. A 401 (1997) 7; NOMAD Collaboration, J. Altegoer *et al.*, *ibid* 404 (1998) 96.

[20] CHOOZ Collaboration, M. Apolonio *et al.*, Phys. Lett. B 420 (1998) 397.

[21] However for an alternative solution to atmospheric neutrino anomaly see M. C. Gonzalez-Garcia *et al.* hep-ph/9809531.

[22] C. Jarlskog, Phys. Rev. Lett. 55 (1985) 1039.

TABLES

$J_{CP}^{\max}$	$c_{13}^2 s_{13} c_{12} s_{12} c_{23} s_{23}$	$\sin\delta$
0.00017	0.00066	0.2588
0.00034	0.00068	0.5000
0.00053	0.00076	0.7071
0.00068	0.00078	0.8660
0.00072	0.00074	0.9659
0.00083	0.00083	1.0000

TABLE I. Maximal values of the Jarlskog factor obtained for different values of $\sin\delta$.

FIGURES

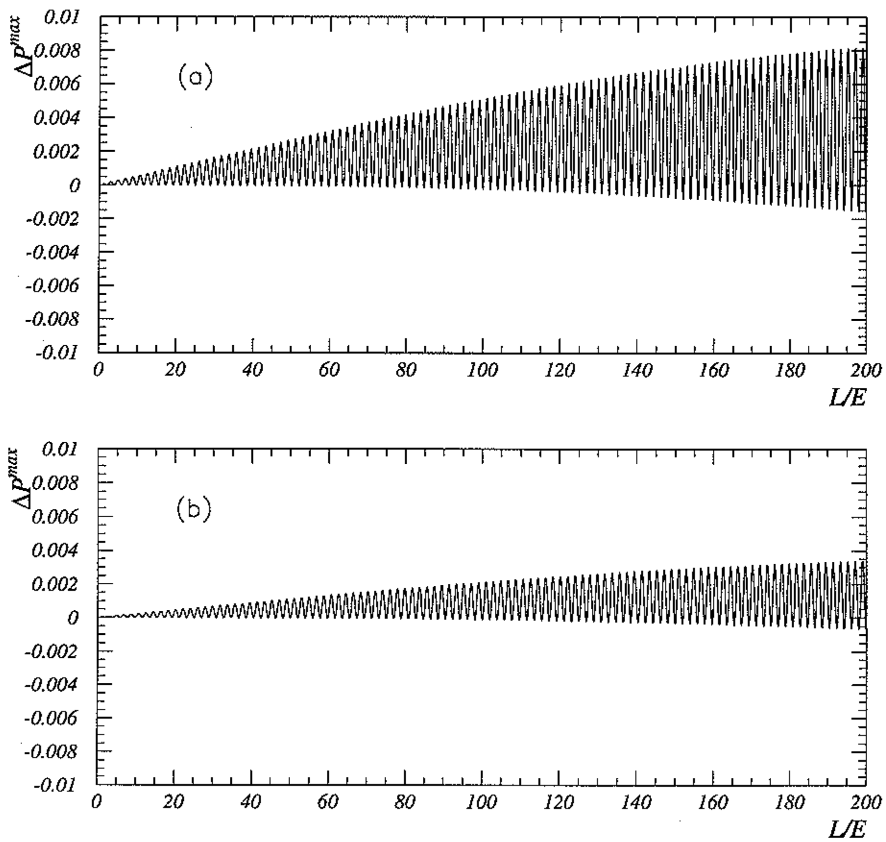

FIG. 1. Values of $\Delta P^{\,\mathrm{max}}$ as a function of L/E for (a) $\sin\delta = 1$ and (b) $\sin\delta = 0.5$.

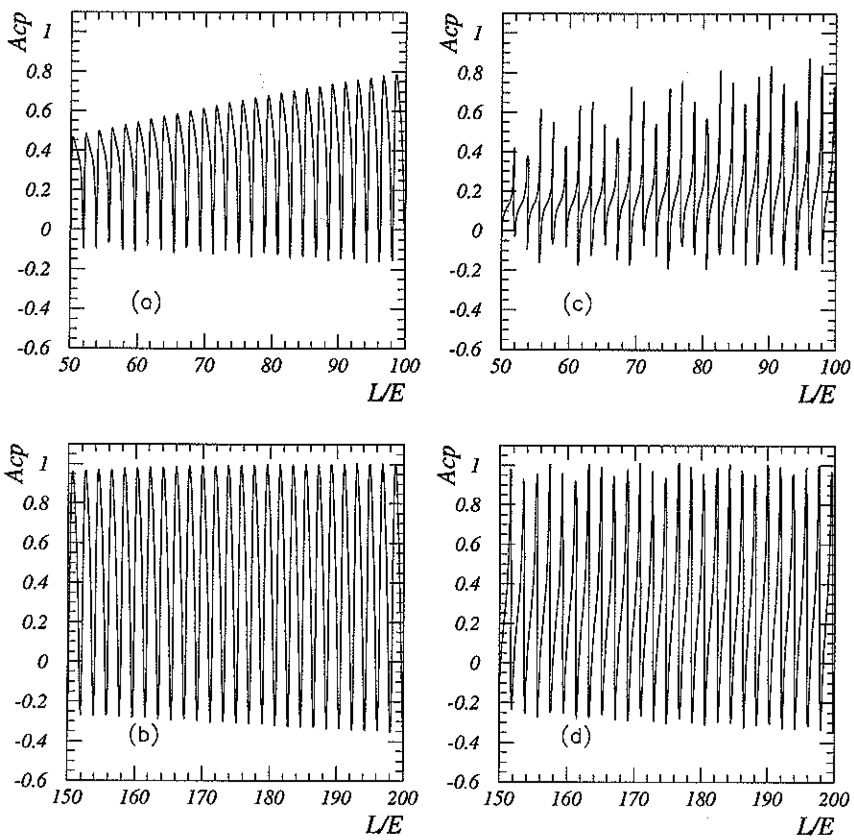

FIG. 2. Values of $A(\mu, e)_{CP}$ as a function of L/E for $\sin\delta = 1$ (a-b) and $\sin\delta = 0.5$ (c-d)