DO NEUTRINOS VIOLATE CP?  

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ABSTRACT  
In trying to answer the question in the title of my talk, I have argued on ground of naturalness that leptonic CP violation is very likely to exist both in the form of the Kobayashi-Maskawa type and the Majorana type phases. The latter part of the argument has to be backed up by a general argument by Yanagida which states that neutrinos must be Majorana particles because our universe is asymmetric with respect to baryon number. The argument is reviewed. Since the naturalness argument raises the possibility of naturally small \( \theta_{13} \) and \( \theta_{23} - \pi/4 \), I discuss possible experimental methods for probing into these two small quantities. They include recent proposal of the resonant \( \bar{\nu}_e \) absorption reaction enhanced by the Mössbauer effect which may allow extremely high sensitivity for not only \( \theta_{13} \) but also \( \Delta m^2_{31} \). The issue of how to resolve the \( \theta_{23} \) octant degeneracy is briefly discussed with emphasis on the atmospheric neutrino observation and the reactor-accelerator combined methods.  

1. It is a tough question, isn’t it?  
I am happy to be here again, the unique “aqua city”, under the kind invitation by Milla, who was also so kind to give me such a tough question as in the title of my talk! But, since it is my duty to give an answer to her question, let me start my lecture from a trial of answering it. I don’t know how far I can go, but it is nice if you find some of the comments below enjoyable to you.  
Clearly, observing leptonic CP violation is one of the prime targets of the future neutrino experiments. It is so because CP violation is one of the unresolved mystery in particle physics, and people feel something deep in that. Furthermore, since we now have the successful description of CP violation in the quark sector, the Kobayashi-Maskawa mechanism\(^{11} \), understanding of leptonic CP violation will shed light to the lepton-quark correspondence\(^{2} \). Even more interestingly, the lepton sector might have another source of CP violation thanks to the possible Majorana nature of neutrinos. It is likely that this question is related to another intriguing question of baryon number asymmetry in the universe\(^{3} \), as we will see below.  

2. Do neutrinos violate CP?; Kobayashi-Maskawa type CP violation  
Let us start by asking if there is any CP violation in the lepton sector due to the
Kobayashi-Maskawa type phase $\delta$ in the lepton flavor mixing matrix, the MNS matrix. Since it is a complete analogue of the CKM matrix in the quark sector, we can consult to many particle theory textbooks on how it is defined. They say,

$$U_{\text{MNS}} = S^\dagger(l)S(\nu)$$

(1)

where $S(\nu)$ and $S(l)$ denote unitary matrices which diagonalize the mass matrices of neutrinos and the charged leptons, respectively. The phase which is responsible for leptonic CP violation comes from physics of neutrino or charged lepton masses, or from both. Let us assume for definiteness that the neutrinos are Dirac particles. Then, the each unitary matrix $S(\nu)$ and $S(l)$ has two phases even after their left phases absorbed into the wave functions.

The question is: Is there any chance that these phases all cancel out when we take combination $S^\dagger(l)S(\nu)$? We argue that it is highly unlikely. If you actually compute $S^\dagger(l)S(\nu)$ by assuming for each of $S(l)$ and $S(\nu)$ the standard form of the CKM matrix with extra right phases, you will be convinced of how unlikely is the cancellation. The values of phases of two matrices $S(\nu)$ and $S(l)$ have to be arranged so that they precisely cancel with each other when they meet after experiencing shifts due to non-Abelian nature of the building block of the MNS matrix.

I have another argument against the possible cancellation of CP violating phases in the MNS matrix. To indicate the point, I propose to compare the two things, accidentally small $\theta_{13}$ and accidentally small $\delta$. Can they be equally natural?

I answer the question in the negative for symmetry reasons. People invented some symmetries, most of whose may have rooted in more phenomenological $\mu \leftrightarrow \tau$ exchange symmetries motivated by the nearly maximal atmospheric angle $\theta_{23}$. (I have no idea if the lists in and are complete, because of so many references; Apology to any omission of relevant ones.) The symmetries imply $\theta_{23} = \pi/4$ and $\theta_{13} = 0$ in the symmetry limit. Therefore, the small $\theta_{13}$ is natural according to the definition of naturalness à la ’t Hooft. On the other hand, no symmetry is known for naturally small $\delta$. Therefore, absence of CP violation in the lepton sector due to the Kobayashi-Maskawa type phase highly unlikely.

3. Do neutrinos violate CP?; Majorana-type CP violation

Most likely, the neutrinos are Majorana particles as preferred by a variety of models, most notably by the see-saw mechanism. If it is the case, we will have CP violation due to extra Majorana phases in the lepton flavor mixing matrix. Since there are two Majorana phases in three-generation neutrinos, the possibility of accidentally small CP violation is even more unlikely in the case of Majorana-type CP violation.

Therefore, the real question is; Are the neutrinos Majorana particles? There is a strong argument given by Yanagida, which answers in the positive to this question.
So let me introduce it for you, assuming that it is not familiar to the audience. His argument starts from the well known facts on which everybody would agree:

- We know that our universe is asymmetric with respect to baryon number.

- We know that above $\sim 1 \text{ TeV}$ the only meaningful quantum number is $B - L$, not the baryon number $B$ or the lepton number $L$ separately, because of the anomaly in the Standard Model \cite{12}, or more precisely speaking, the gsphaleronh effect \cite{13}.

- Therefore, we must have $B + L$ generation in some stages of the cosmological evolution to have nonzero baryon number to date.

I hope that all of them above are agreeable by everybody. (I asked the audience in the lecture room if someone disagrees with any of the statements above, but no one did.) If so, here is the second step in the Yanagida argument:

- Let us assume the Standard Model of particle physics. Then, there is no renormalizable operator which violates $B - L$, and hence there is no chance of generating baryon number asymmetry (unless it is so carefully designed as to evade the sphaleron extinction). Therefore, we must go beyond the Standard Model to have nonzero baryon number in the universe.

- The model independent way of searching for the possible $B - L$ violating operator is to look for suitable higher dimensional operators \cite{17}. The unique lowest dimension operator which violates $B - L$ is

$$\frac{1}{M^2} \phi^4 \nu$$

which must exists so that baryon number asymmetry (and we ourselves) exists. Therefore, the Majorana mass term must exist for neutrinos.

\textsuperscript{b}Here is some comments on the gsphaleronh for those who are not familiar to it. Everybody knows that because of the instanton configuration the gauge theory vacuum is enriched by the periodic vacua which differ by the topological winding number and are separated by a barrier whose hight is given by $\sim M_W/\alpha$. (Consult, e.g., to Coleman’s lectures \cite{14} for more about it.) The sphaleron is nothing but the field configuration at the top of the barrier \cite{15}. One can show that by tunneling to the adjacent vacuum the fermion number (baryon or lepton number) changes by one unit due to the anomaly in chiral gauge theories. The transition conserves $B - L$ because it is anomaly free. Now at zero temperature the transition is severely suppressed by the penetration factor \cite{12}. But, Kuzmin, Rubakov, and Shaposhnikov \cite{13} pointed out that the transition can proceed at high temperature $T$, and have shown that the rate at temperature around the electroweak phase transition can be calculable by using sphaleron configuration. It is natural because $M_{\text{sphaleron}}/T$ characterize the difficulty or easiness of transition taking place due to thermal effects. A fair computation exists to support the conclusion \cite{16}. Thus, all the nonvanishing $B - L$ generated in earlier cosmological evolution is expected to be wiped out at the time of electroweak transition.
Two immediate comments are in order:

1. The formula in (2) is nothing but the seesaw formula for neutrino masses. In the present discussion, however, it is derived in a “model-independent” way.

2. I note that most likely the operator in (2) is responsible for the neutrino mass observed by Super-Kamiokande and KamLAND experiments. The former atmospheric oscillation was confirmed by K2K, and the latter solar oscillation has been hinted by the long-term extensive efforts by various solar neutrino observation which was initiated by the pioneering Davis experiment and has been concluded by SNO.

4. Naturally small \( \theta_{13} \) and/or \( \theta_{23} - \pi/4 \) ?

I argued above, on ground of naturalness, that the Kobayashi-Maskawa type CP violating phase \( \delta \) is unlikely to be canceled between the two unitary matrices which diagonalize the neutrino and the charged lepton mass matrices. The argument raises the possibility that \( \theta_{13} \) could be tuned to be very small and at the same time \( \theta_{23} \) be close to the maximal. Therefore, I would like to address these issues in the rest of my talk.

Since \( \mu \leftrightarrow \tau \) exchange symmetry is badly broken (note that \( m_\tau \simeq 20 m_\mu \)), the predictions \( \theta_{13} = 0 \) and \( \theta_{23} = \pi/4 \) cannot be exact. It is important to try to compute deviations of the results obtained in the symmetry limit. Only by finding correlation between these two small quantities one can establish the symmetry, if any, by distinguishing it from some other possibilities such as the quark-lepton complementarity extended to 2-3 sector which also suggests that \( \theta_{23} \) is close to \( \pi/4 \). At the moment, however, we do not have a reliable theoretical machinery to compute them.

I focus here on the possible experimental methods for determining the small corrections to the symmetry limit. However, you may ask the question; The method for measurement of \( \theta_{13} \) has been extensively discussed by using varying experimental means; accelerator, reactor, and astrophysical neutrinos. Are there any other possibilities to explore? Amazingly, the answer seems Yes.

5. Mössbauer enhanced resonant absorption of monochromatic antineutrino beam

Recently, it was proposed that the the resonant absorption reaction

\[ \bar{\nu}_e + ^3\text{He} + \text{orbital e}^- \rightarrow ^3\text{H} \]  

with simultaneous capture of an atomic orbital electron can be dramatically enhanced

\[ ^3\text{He} \]

\[ \rightarrow ^3\text{H} \]
by using the inverse reaction $^3\text{H} \rightarrow \bar{\nu}_e + ^3\text{He} + \text{orbital } \text{e}^-$, by which the resonance condition is automatically satisfied. (See \cite{35,36} for earlier suggestions.) Furthermore, by embedding both the source $^3\text{H}$ and the target $^3\text{H}$ atoms into solid the overlap between the line widths of the emission and the absorption can be dramatically improved, which may lead to the enhancement of the reaction cross section of (3) by a factor of $\sim 10^{11}$ \cite{33}. To realize the enhancement it is important to secure that both the source and the target atoms are placed in a metal so that they can enjoy the same environment.\footnote{If the line shift occurs between the source and the target atoms it may be cancelled by gravitational effect by placing them in a different elevation. But, since we want to remain in a suitable underground site, the height difference between the source and the target would practically be less than $\sim 100 \text{ m}$ ($\sim 10 \text{ m}$ for the $\theta_{13}$ experiment). This places a limit on absolute value of the relative line shift manageable by this method to the order of $< 2 \times 10^{-10}$ ($2 \times 10^{-11}$) eV.}

One might naively think that the probability of having beta decay with simultaneous capture of electrons into the atomic orbit is tiny. But, the author of \cite{37} argues that the process occurs not by capturing an emitted electron to the orbit but by creating an electron into the orbit. In fact, the calculated branching fraction of the bound state beta decay to the conventional electron emitting decay is not so small, $4.7 \times 10^{-3}$. Therefore, it appears that the possibility deserves further attention which, I hope, would trigger closer examinations of its experimental feasibility.

5.1. 10 m baseline $\theta_{13}$ experiments

Why the new proposal interesting in the context of measurement of small $\theta_{13}$? First of all, the ultra-low neutrino energy of 18.6 keV of (3) makes it possible, with the first oscillation maximum of $L_{OM} = 9.2 \left( \Delta m_{31}^2 / 2.5 \times 10^{-3} \text{eV}^2 \right)^{-1} \text{ m}$, to design a 10 m baseline $\theta_{13}$ experiment. Furthermore, the Mössbauer enhancement of the reaction cross section of (3) to $\sigma_{res} \simeq 5 \times 10^{-32} \text{cm}^2$ enables us an enormous statistics

$$R_{\text{enhanced}} = 1.2 \times 10^6 \left( \frac{SM_T}{1 \text{MCi} \cdot 100 \text{ g}} \right) \left( \frac{L}{10 \text{ m}} \right)^{-2} \text{ day}^{-1},$$

a million events a day by using 100 g (not 100 kiloton!) of $^3\text{He}$ target, assuming 1 MCi source.

We have argued in \cite{38} that if the direct counting of produced $^3\text{H}$ atom works, the relative systematic error can be as low as 0.2% by a movable detector setting, and if not it may be of the order of $\simeq 1\%$. For concreteness, we restrict ourselves here to a particular setting described as Run IIB in \cite{38}:

Run IIB: Measurement at 10 different detector locations; $L = L_i \left( i = 1, \ldots, 10 \right)$ where $L_{i+1} = L_i + \frac{2}{5} L_{OM}$ and $L_1 = \frac{1}{5} L_{OM}$ so that the entire period, $\Delta = 0$ to $2\pi$, is covered. At each location an equal number of $10^6$ events is to be collected.

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The huge statistics and the controlled uncorrelated systematic error to 0.2% (1%) level should allow precision measurement of $\theta_{13}$ up to $\sin^2 2\theta_{13} = 0.002$ (0.008) or so at 1$\sigma$ CL.

5.2. Possible extreme accuracy in $\Delta m^2_{31}$ measurement

Though slightly off line from the present discussion, it is worth to mention the additional physics potential of 10 m $\theta_{13}$ experiment. The $\bar{\nu}_e$ beam from the tritium decay is monochromatic for practically all purposes even before the Mössbauer enhancement. Then, it is natural to think about precision measurement of $\Delta m^2_{31}$ by using the recoilless resonant absorption. This expectation was confirmed in which the accuracy of $\Delta m^2_{31}$ determination is shown to reach sub percent level.

For an exposure of Run IIB defined above, the allowed regions at 1$\sigma$-3$\sigma$ CL are given in Fig. 1. The figures are for the uncorrelated systematic error of 0.2%.

By optimizing on $\theta_{13}$, we have obtained for 1 DOF the following sensitivity to $\Delta m^2_{31}$ with Run IIB; If the uncorrelated systematic error of 0.2% is realized, the accuracy of measurement of $\Delta m^2_{31}$ is $\simeq 0.3 \left( \sin^2 2\theta_{13}/0.1 \right)^{-1}\%$ at 1$\sigma$ CL. For the pessimistic systematic error of 1% the sensitivity is worsen by about a factor of four. For details of the analysis procedure and results for various settings, see.

The obvious possible application of the extreme sensitivity to $\Delta m^2_{31}$ is the method...
for determining the neutrino mass hierarchy by comparing two kind of disappearance measurement $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$, as proposed in [39,40].

6. Which octant does $\theta_{23}$ live?

Determining which octant $\theta_{23}$ lives and how far it is from the maximal angle $\pi/4$ is not an easy question to answer. Nevertheless, it is important to find ways to solve it because the $\theta_{23}$ octant degeneracy is one of the major obstacle in precision determination of $\theta_{23}$.

Principle of resolving the $\theta_{23}$ degeneracy is simple; Look for oscillation channels which depend upon $\theta_{23}$ not through the combination $s_{23}^2 \sin^2 2\theta_{13}$. However, it can be shown in mostly by analytic manner that it is very difficult to resolve the $\theta_{23}$ degeneracy only by accelerator experiments with modest baseline of $L < 1000$ km.

Thus, at the moment there are two ways, to my knowledge, to resolve the $\theta_{23}$ degeneracy. Let us discuss them briefly one by one.

6.1. High statistics atmospheric neutrino observation

The atmospheric method for resolving the $\theta_{23}$ degeneracy utilizes the solar oscillation term which is proportional to $c_{23}^2$ and independent of $\theta_{13}$ in a good approximation. Therefore, its sensitivity to the $\theta_{23}$ degeneracy essentially relies on detection capability of the solar term. Since the term is independent of $\theta_{13}$ the method works even for vanishingly small $\theta_{13}$. See Fig. 2 which is taken from [46]. On the other hand, it requires enormous statistics which requires the current Super-Kamiokande to run $\sim 80$ years. Clearly, construction of much larger detector such as Hyper-Kamiokande is the necessity.

6.2. Reactor-accelerator combined method

The other possibility of resolving the $\theta_{23}$ degeneracy is to combine reactor measurement of $\theta_{13}$ to accelerator $\nu_\mu$ disappearance and $\nu_e$ appearance experiments. (See [41] for earlier suggestion.) The principle is very simple; The accelerator disappearance and appearance measurement determine $\sin^2 2\theta_{23}$ and $s_{23}^2 \sin^2 2\theta_{13}$, respectively, leaving a degenerate solution if $\theta_{23}$ is not maximal. The reactor measurement of $\theta_{13}$, which is largely independent of other mixing angles, picks up one of the solutions.

Quite recently, we have revisited the idea to examine quantitatively the limit of resolving power of the $\theta_{23}$ degeneracy by this method. We have assumed for accelerator experiment the phase II of the T2K experiment with 2 (6) years running of

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*If it would be possible to create a very long baseline experiment with e.g., $L = 6000$ km, there could be ways to circumvent the argument. But, it is hard to create intense enough beam or build huge detectors which can compensate the flux depletion proportional to $L^{-2}$, and to prepare beam line pointing toward them well below the horizon.
Figure 2: The discrimination between the first and the second octant of $\theta_{23}$ by 1.8 Mton-year (3.3 years of HK) exposure of atmospheric neutrinos. The CP phase is taken as $\delta = \pi/4$. Discrimination can be done for relatively large deviation of $\theta_{23}$ from the maximal down to a vanishingly small $\theta_{13}$ (left figure). On the other hand, it is getting very hard for a smaller deviation, $\sin^2 2\theta_{23} = 0.99$ (right figure). Courtesy by Takaaki Kajita, also presented at Next Generation of Nucleon Decay and Neutrino Detectors (NNN05).  

neutrino (anti-neutrino) modes with 4MW beam power with the Hyper-Kamiokande detector whose fiducial volume is 0.54 Mt. For the reactor experiment, the exposure of 10 GW-kt-yr is assumed. For the T2K II experiment the systematic errors are assumed to be 2%. Since the accuracy of the reactor measurement of $\theta_{13}$ is of crucial importance for the sensitivity of resolving the degeneracy we have examined two sets of the systematic errors: Pessimistic errors; detector correlated errors of 2% and uncorrelated errors of 0.5%. Optimistic errors; detector correlated errors of 1% and uncorrelated errors of 0.2%. (See 43 for details of the systematic errors.)

The resultant sensitivity regions obtained by assuming the pessimistic and the optimistic systematic errors are given in Figs. 3 and Figs. 4 respectively. At relatively large $\theta_{13}$ the method is shown to be powerful in resolving the $\theta_{23}$ degeneracy. At small $\theta_{13}$, however, resolving power of the degeneracy is limited even for the case of optimistic systematic errors. It is notable that resolving power of the degeneracy is not symmetric with respect to $\theta_{23} = \pi/4$; It is easier to resolve the degeneracy for $\theta_{23}$ in the first (second) octant for relatively large (small) $\theta_{13}$. It appears that it is the result of intricate interplay of the various factors 43.

I note that at large $\theta_{13}$ in particular in the first octant the reactor-accelerator method has better sensitivities, while the atmospheric method wins at small $\theta_{13}$. To improve the resolving power of the former we need a better accuracy in $\theta_{13}$ deter-
Figure 3: The region in $\sin^2 2\theta_{13} - \sin^2 \theta_{23}$ space where the $\theta_{23}$ octant degeneracy can be resolved at 90% (thin green) and 99% (thick red) CL. The solid (dashed) curve is for the case taking the normal (inverted) hierarchy while performing the fit, assuming the normal hierarchy as an input. The conservative systematic errors, as indicated in the figure, are considered here.

Minimization. Naturally, the 10 m baseline experiment using the Mössbauer enhanced resonant absorption of monochromatic antineutrino beam discussed in the previous section might be of help.

7. Miscellaneous remarks

My presentation in the workshop included remarks on miscellaneous topics including (1) introducing the bi-probability plot for intuitive understanding of the CP phase-matter effect interplay, (2) importance of use of two-detector setup to detect CP violation, (3) some comments on how to solve parameter degeneracies. In particular, I emphasized the role of spectrum analysis in resolving the so called intrinsic degeneracy. It was my prejudice that the intrinsic degeneracy is hard to resolve because the differences between the two degenerate solutions, $\theta_{13}$ and $\sin \delta$, are so tiny. However, we have learned in exploration of the idea of the Kamioka-Korea two identical detector complex (T2KK) that it is the easiest degeneracy to lift. (For T2KK itself see and .) In Fig. which is just one of thousand figures behind the paper, it is illustrated that the spectrum analysis by HK placed in
Kamioka only (without a Korean detector) is powerful enough to (almost) resolve the intrinsic degeneracy despite a rather small value of $\theta_{13}$, $\sin^2 2\theta_{13} = 0.01$.

Notice, however, that this setting does not resolve the degeneracy caused by the unknown mass hierarchy at all. To resolve both of the degeneracy simultaneously we need T2KK. It is also notable that the degenerate solutions have “X-shaped” structure which can be understood as a consequence of cooperation of a symmetry behind the sign-$\Delta m^2$ degeneracy and the property of the intrinsic degeneracy.

8. Conclusion

I have concluded my talk with several short remarks:

- Leptonic CP violation, due to both the Kobayashi-Maskawa type and the Majorana-type phases is very likely to exist.

- There are still rooms (referring to T2KK and other ideas) to make progress along the line of conventional superbeam to explore leptonic CP violation.

- New opportunities seem exist in physics to be done with the Mössbauer enhanced resonant absorption of monochromatic neutrino beam.
Figure 5: The region allowed in $\delta - \sin^2 2\theta_{13}$ space by 2 years of neutrino and 6 years of antineutrino running in the T2K II experiment. Taken from supplementary figures behind the reference [51]. The true solutions are assumed to be located at $(\sin^2 2\theta_{13} \text{ and } \delta) = (0.01, \pi/4)$ with positive sign of $\Delta m^2_{31}$, as indicated as the green star. Three contours in each figure correspond to the 68% (blue line), 90% (black line) and 99% (red line) C.L. sensitivities, which are defined as the difference of the $\chi^2$ being 2.30, 4.61 and 9.21, respectively.

- Among the parameter degeneracies the $\theta_{23}$ octant degeneracy may be the hardest one to solve. New ideas and/or gigantic detectors are called for.

9. Acknowledgements

I thank Tsutomu Yanagida for useful correspondences. I am grateful to all the collaborators of the works [51][8][38] for enjoyable collaborations through which my recognitions to the topics discussed in this manuscript have been deepened. I thank Departamento de Física, Pontifícia Universidade Católica (PUC) do Rio de Janeiro for hospitality where this manuscript was written. My visit is supported by Bilateral Programs, Scientist Exchanges based on Japan Society of Promotion of Science and
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