"PRACTICAL CONFUSION THEOREMS"

PROPERTIES OF DIRAC AND MAJORANA NEUTRINOS

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BORIS KAYSER FEST
"NEUTRINOS: DATA, COSMOS AND THE PLANCK SCALE"
KITP UCSB

2002 WAS EXCEPTIONAL FOR THE STUDIES OF ν'S:

- SNO : NC DATA $\Rightarrow$ $\overset{(-)}{\nu}_{\mu,\tau}$ IN $\Phi(\nu_\odot)$
- KAMLAND:
  - FIRST EVIDENCE FOR ν-OSCILLATIONS IN AN EXPERIMENT WITH "TERRESTRIAL" ν'S
  - EVIDENCE FOR ν-MIXING IN VACUUM
  - $\nu_\odot$: LMA SOLUTION (CPT)
  - KAMLAND "MASSACRE": SMA, LOW, QVO, VO, RSFP, FCNC, ...
  - DETERMINES THE PRIORITIES OF THE FUTURE RESEARCH
- SK IS OPERATIONAL AGAIN
- MINIBOONE STARTED
- THE ACHIEVEMENTS IN THE FIELD ($\nu_\odot$ - ASTRONOMY, SN ν'S DETECTION) AND THE FUNDAMENTAL CONTRIBUTIONS MADE BY

R. DAVIS AND M. KOSHIBA

HONORED BY THE NOBEL PRIZE FOR PHYSICS.

EVIDENCES FOR ν-OSCILLATIONS:

- ν_{ATM} : SK UP-DOWN ASYMMETRY (ZENITH ANGLE DEPENDENCE) MULTI-GEV μ-LIKE SAMPLE

  DOMINANT $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\tau$

  K2K; MINOS, CNGS.

- $\nu_\odot$: HOMESTAKE, KAMIOKANDE, SAGE, GALLEX/GNO, SUPER-KAMIOKANDE, SNO

  DOMINANT $\nu_e \rightarrow \nu_{\mu,\tau}$

  KAMLAND; BOREXINO, ...

- LSND

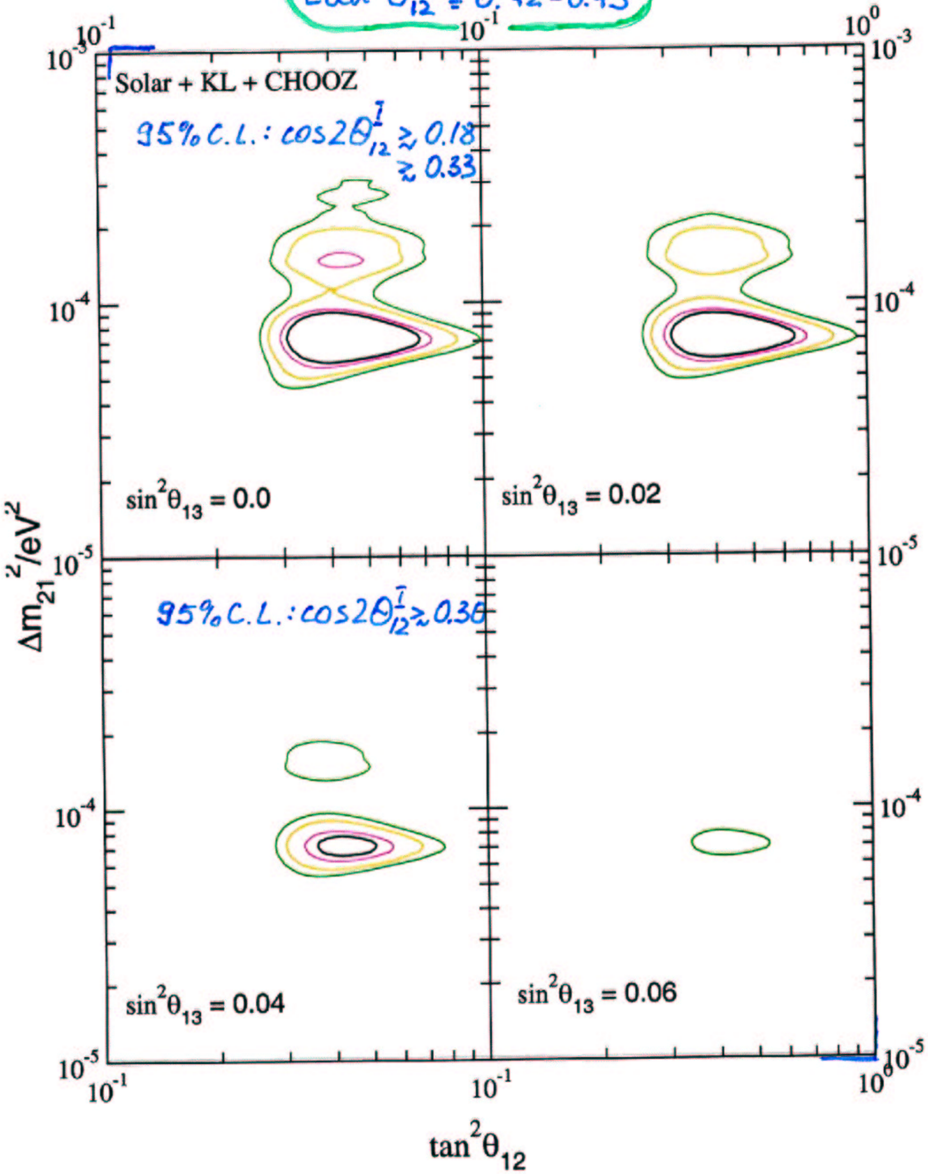
  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ MINIBOONE

$$\nu_{lL} = \sum_{j=1} U_{lj}\, \nu_{jL}, \quad l = e, \mu, \tau$$

ν- FACTORIES : 3-ν MIXING, LMA MSW

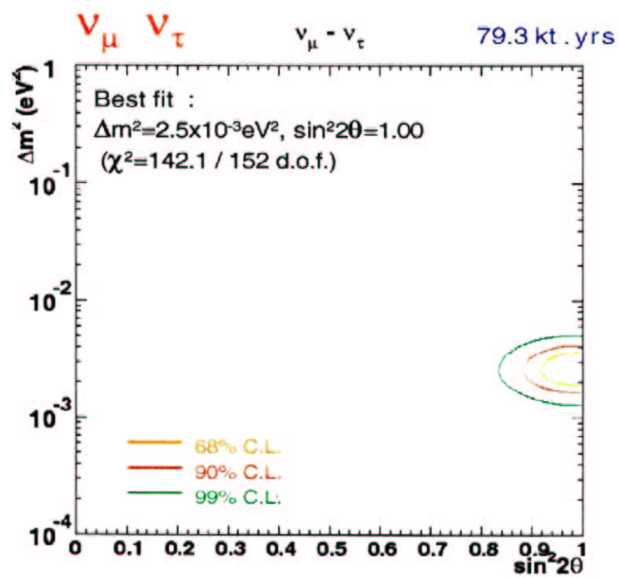
$L \sim (3000 - 7000)$ km.

BEST FIT: $\Delta m^2_{21} \simeq 7 \cdot 10^{-5}\, eV^2$, $\tan^2\theta_{12} \simeq 0.42 - 0.45$ S. CHOUBEY ET AL.



Allowed region

(FC + PC + UP-thru + UP-stop)



SK combined result

$\Delta m^2 = (1.7 \sim 4) \times 10^{-3} eV^2$

$\sin^2 2\theta > 0.89$ (90% C.L.)

SIGN(Δm^2) - UNDETERMINED

$3\text{-}\nu$ MIXING : $m_1 < m_2 < m_3$ - NH

CHOOZ : $\bar{\nu}_e \to \bar{\nu}_e$

~ 1 km
$E_{\bar{\nu}}$ ~ 2 MeV

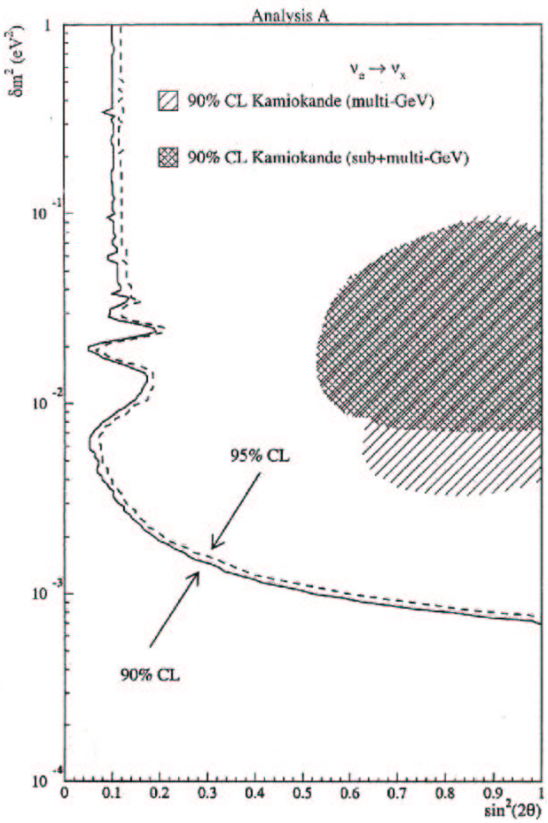


Figure 9: Exclusion plot for the oscillation parameters based on the absolute comparison of measured vs. expected positron yields.

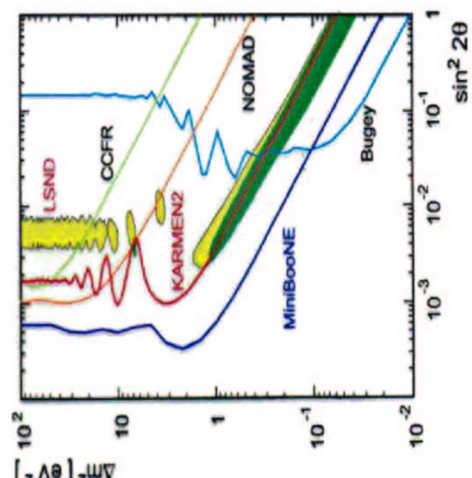
16

Index .pdf-file << Prev Next >>

G. Drexlin: LSND and Karmen (31/38)

Conclusions

final oscillation results from LSND and KARMEN2 published and compatibility analysis submitted for publication



LSND (1993-98)

combined DAR & DIF analysis (new reconstr.)
87.9 ± 22.4 ± 6.0 *beam excess* events
P = (0.264 ± 0.067 ± 0.045)%

KARMEN2 (1997-01)

final DAR oscillation analysis 4y of data
15 evts. ↔ (15.8 ± 0.5) bg expect. *no excess*
$\sin^2 2\theta < 1.7 \times 10^{-3}$, most stringent limit so far

LSND & KARMEN2

detailed statistical analysis using full inform.
incompatibility at individual 60% Confid. Levels
areas of stat. compatibility only at $\Delta m^2 < 1$ eV^2
L-number violating μ-decays excluded

MAJORANA VERSUS DIRAC ν's ($d=4$, CPT)

TWO POSSIBLE WAYS OF DEFINING A MAJORANA SPIN $1/2$ PARTICLE IN QFT: USING FIELDS OR STATES

FIELDS: $\chi_k(x)$ - 4 COMPONENT COMPLEX, SPIN $\frac{1}{2}$, m_k

MAJORANA CONDITION:

$$C\,\overline{\chi}_k^{\,T}(x) = \xi_k\,\chi_k(x),\quad |\xi_k|^2 = 1$$

- INVARIANT UNDER THE PROPER LORENTZ TRANSF.
- REDUCES THE NUMBER OF INDEPENDENT COMPONENTS IN $\chi_k(x)$ BY A FACTOR OF 2
- PURELY ALGEBRAIC CONDITION; HAS NOTHING TO DO WITH C-CONJ. SYMMETRY

$\nu_{\ell L}(x)$ - $SU(2)_L$ DOUBLET $\left\{ \nu_L,\ \tilde{\nu}_R \right.$
$\ell = e, \mu, \tau$

$\nu_{\ell' R}(x)$ - $SU(2)_L$ SINGLET $\left\{ \nu_R,\ \tilde{\nu}_L \right.$

"STERILE", "INERT" PONTECORVO '67

$$\nu^c_{\ell R}(x) \equiv C\,\overline{\nu}_{\ell L}^{\,T}(x) = \left(\nu_{\ell L}(x)\right)^c$$

$$\nu^c_{\ell L}(x) \equiv C\,\overline{\nu}_{\ell R}^{\,T}(x) = \left(\nu_{\ell R}(x)\right)^c$$

SOMETIMES $\left(\nu_{\ell L}(x)\right)^c$ CALLED "CHARGE CONJUGATED (OF $\nu_{\ell L}(x)$)"

HOWEVER,

$$U_C\,\nu_{\ell L}(x)\,U_C^{-1} = \eta_C\,C\,\overline{\nu}_{\ell R}^{\,T}(x)$$

$$U_C\,\nu_{\ell R}(x)\,U_C^{-1} = \eta_C^*\,C\,\overline{\nu}_{\ell L}^{\,T}(x)$$

IF NO $\nu_{\ell R}$ ARE PRESENT, U_C CANNOT BE DEFINED FOR $\nu_{\ell L}$.

$$\nu_L \xrightarrow{C} \tilde{\nu}_L$$

$\Psi(x),\ m:\ \Psi(x)$ – 4 COMPONENT COMPLEX

$C\,\overline{\Psi}^{T}(x) \neq \xi'\,\Psi(x)$, $\Psi(x)$ – DIRAC

IMPLICATIONS:

$\chi(x)$: 2 SPIN STATES OF A SPIN $\frac{1}{2}$ ABSOLUTELY NEUTRAL PARTICLE

$Q_{U(1)} = 0$: $Q_{el} = 0,\ L_{l} = 0,\ L = 0, \dots$

$\chi \equiv \tilde{\chi}$ PARTICLE ≡ ANTIPARTICLE

$U(1):\ \chi(x) \not\rightarrow e^{i\alpha}\chi(x)$ – CANNOT ABSORB PHASES; MAJORANA COND. IS NOT INVARIANT WITH RESPECT TO $U(1)$

$$\chi(x) = \frac{1}{(2\pi)^{3/2}} \int \frac{d\vec{p}}{\sqrt{N}} \sum_{r=-1,1} \left\{ u^{r}(p)\,a_{r}(p)\,e^{ipx} + \xi^{*}\,C\,\overline{u}^{r\,T}(p)\,a_{r}^{\dagger}(p)\,e^{-ipx} \right\}$$

$$\overbrace{\Psi_\alpha(x)\,\overline{\Psi}_\beta(y)} = S_{F\alpha\beta}(x-y;\, m_\Psi) \neq 0$$

$$\overbrace{\Psi_\alpha(x)\,\Psi_\beta(y)} = 0, \qquad \overbrace{\overline{\Psi}_\alpha(x)\,\overline{\Psi}_\beta(y)} = 0$$

$$\overbrace{\chi_\alpha(x)\,\overline{\chi}_\beta(y)} = S_{F\alpha\beta}(x-y;\, m_\chi)$$

$$\overbrace{\chi_\alpha(x)\,\chi_\beta(y)} = -\,\xi^{*}\,S_{F\alpha\kappa}(x-y;\, m_\chi)\,C_{\kappa\beta}$$

PHYSICAL REVIEW D VOLUME 26, NUMBER 7 1 OCTOBER 1982

Majorana neutrinos and their electromagnetic properties

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(Received 29 January 1982)

To help develop a picture of Majorana neutrinos, we study their electromagnetic properties. We show that *CPT* invariance forbids a Majorana neutrino from having a magnetic or electric dipole moment. Then, by considering the process $\gamma\rightarrow\nu\bar{\nu}$, we find the most general expression for the matrix element of the electromagnetic current of a Majorana neutrino. The result is verified in a way which leads us to explore the behavior under parity of such a particle. Next, we see how electromagnetic properties which follow from one-loop diagrams conform to our general results. Finally, we show how the striking electromagnetic differences between Majorana and Dirac neutrinos can become invisible as the neutrino mass goes to zero.

I. INTRODUCTION

A number of widely discussed recent theoretical models[1] suggest that neutrinos are massive Majorana particles, identical to their antiparticles. Thus, it is of interest to develop a picture of the characteristics of a Majorana neutrino. Here we study its electromagnetic properties, and contrast them with those of a Dirac neutrino, which is distinct from its antiparticle. We begin by showing that *CPT* invariance forbids a Majorana neutrino from having either a magnetic or an electric dipole moment. Next, we question whether a physical Majorana neutrino state is indeed an eigenstate of charge conjugation *C*. Without assuming that it is, we derive in two ways the most general form for the matrix element

$$\langle \nu^{M}(p_f,s_f)\,|\,J_{\mu}^{\mathrm{EM}}\,|\,\nu^{M}(p_i,s_i)\rangle\ ,$$

where J_{μ}^{EM} is the electromagnetic current operator, and $\nu^{M}(p,s)$ is a Majorana neutrino of momentum p and spin projection s. This matrix element contains only one form factor. We show that this fact follows very simply from the requirement that the final state in the crossed-channel process $\gamma\rightarrow\nu^{M}\nu^{M}$ be antisymmetric. The derivations of the electromagnetic matrix element reveal that a Majorana neutrino has very interesting parity properties, which we discuss. Next, noting that a Dirac neutrino has three more form factors than a Majorana neutrino, we examine how the extra form factors manage to vanish when the electromagnetic properties of a Majorana neutrino are calculated in $SU(2)_L\times U(1)$ to one-loop order. Lastly, we compare the electromagnetic interactions of a Majorana and a Dirac neutrino in the massless limit. We find that they conform to what seems to be a general rule: If all weak currents are left-handed, then the difference between a Majorana and a Dirac neutrino becomes invisible as the mass goes to zero. This occurs in spite of gross differences between these particles when the mass is not negligible.

II. STATIC ELECTROMAGNETIC PROPERTIES

It has been argued on various grounds, both in ancient papers and recent ones,[2] that a Majorana neutrino cannot have a magnetic or electric dipole moment. It seems not to have been noticed, however, that this conclusion already follows trivially from the relatively weak assumption of *CPT* invariance. Suppose a Majorana neutrino has a magnetic dipole moment μ and electric dipole moment d. Then, when it is at rest, its interaction energy in a combination of static, uniform magnetic and electric fields is of the form $-\mu\langle\vec{s}\cdot\vec{B}\rangle - d\langle\vec{s}\cdot\vec{E}\rangle$. Here $\vec{s}$ is, of course, the neutrino spin operator. Now, in the *CPT*-reflected state, the fields $\vec{B}$ and $\vec{E}$ are unchanged. However, the effect of *CPT* on a Majorana neutrino at rest is simply to reverse its spin (apart from a phase factor). Thus, the dipole interaction energy changes sign when we go to the *CPT*-reflected state, so if *CPT* invariance holds, μ and d must vanish.[3]

RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 28, NUMBER 9 1 NOVEMBER 1983

CPT and *CP* properties of Majorana particles, and the consequences

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Since a Majorana neutrino is its own antiparticle under *CPT*, rather than *C*, an analysis of the *CPT* and *CP* characteristics of a Majorana particle is performed. The *CPT* transformation properties of a Majorana particle of arbitrary spin are obtained in a very simple way. Implications of these properties for the electromagnetic matrix elements of Majorana particles of spin $\frac{1}{2}$ are derived. Finally, the question of when different Majorana neutrinos will make opposing contributions to neutrinoless double-β decay is answered.

Majorana particles are predicted both by grand unified theories, in which these particles are neutrinos, and by supersymmetric theories, in which they are photinos, gluinos, and other states. Until recently, a Majorana particle has been pictured as one which is its own antiparticle under charge conjugation *C*. However, a *physical* Majorana *neutrino*, dressed as it is by maximally *C*-violating weak interactions, cannot be an eigenstate of *C*.[1] Instead, it is an eigenstate of *CPT*, which presumably is not violated at all. It may also be an approximate eigenstate of *CP*. To explore the physics of this situation, an analysis of the *CPT* and *CP* properties of an arbitrary Majorana particle, and of the consequences of these properties, has been carried out. Here we report the main results; further discussion and details will be presented elsewhere.[2]

The effect of *CPT* ($\equiv\zeta$) on the state of any *CPT*-self-conjugate particle f of momentum $\vec{p}$, spin J, and $J_z=s$ is given by

$$\zeta|f(\vec{p},J,s)\rangle=\eta^s|f(\vec{p},J,-s)\rangle\ . \tag{1}$$

Here, η^s is a phase factor, and we are allowing for the possibility that, for given J, it may depend on s. What can one say about this phase factor, and what are its consequences? To find out, let us go to the rest frame and define the operator

$$b=e^{-i\pi J_y}\zeta\ . \tag{2}$$

The effect of b on f is obviously

$$b|f(J,s)\rangle=\mu^s|f(J,s)\rangle\ , \tag{3}$$

where μ^s is some new phase factor. Bearing in mind that ζ, hence b, is antiunitary, one can show trivially that $b^2=1$ when acting on the states $|f(J,s)\rangle$. Since *CPT* commutes with rotations, the definition of b then implies that

$$\zeta^2 e^{-2i\pi J_y}=1\ . \tag{4}$$

Now, independent of conventions, a rotation through 2π reproduces the original state times $(-1)^{2J}$. Thus, ζ^2, applied to any Majorana (i.e., *CPT*-self-conjugate) particle of spin J, does exactly the same thing[3]:

$$\zeta^2=(-1)^{2J}\ . \tag{5}$$

From Eq. (1), and the antiunitarity of ζ,

$$\zeta^2|f(J,s)\rangle=(\eta^s)^*\eta^{-s}|f(J,s)\rangle\ . \tag{6}$$

Thus, Eq. (5) implies that

$$\eta^{-s}=(-1)^{2J}\eta^s\ . \tag{7}$$

Apart from this constraint, the individual phase factors η^s are arbitrary, since the states $|f(J,s)\rangle$ can always be redefined according to

$$|f(J,s)\rangle\to|f(J,s)\rangle'=e^{i\phi_s}|f(J,s)\rangle\ ,$$

with ϕ_s an arbitrary phase. Under this redefinition

$$\eta^s=\langle f(J,-s)|\zeta|f(J,s)\rangle\to(\eta^s)'=e^{-i(\phi_{-s}+\phi_s)}\eta^s\ ,$$

but Eq. (7) is still obeyed.[4]

With the *CPT* transformation properties of the Majorana states known, one can now derive *CPT* constraints on matrix elements of the form $\langle f|Q|f\rangle$, where Q is any Hermitian operator whose *CPT* properties are also known. Consider, for example, the electromagnetic current $J_\mu^{\rm EM}$.[5] The photon field $A_\mu(x=0)$ is *CPT*-odd, so if the electromagnetic interaction $J_\mu^{\rm EM}A_\mu$ is to conserve *CPT*, $J_\mu^{\rm EM}(x=0)$ must be *CPT*-odd also. Thus,

$$\begin{aligned}\langle f(\vec{p}_f,J,s_f)|J_\mu^{\rm EM}(0)|f(\vec{p}_i,J,s_i)\rangle&=-\langle\zeta[f(\vec{p}_i,J,s_i)]|J_\mu^{\rm EM}(0)|\zeta[f(\vec{p}_f,J,s_f)]\rangle\\&=-(\eta^{s_i})^*\eta^{s_f}\langle f(\vec{p}_i,J,-s_i)|J_\mu^{\rm EM}(0)|f(\vec{p}_f,J,-s_f)\rangle\ .\end{aligned} \tag{8}$$

For the case of greatest interest, $J=\frac{1}{2}$,[6] Lorentz invariance and current conservation imply that

$$\langle f(\vec{p}_f,\tfrac{1}{2},s_f)|J_\mu^{\rm EM}(0)|f(\vec{p}_i,\tfrac{1}{2},s_i)\rangle=i\bar{u}(\vec{p}_f,s_f)[F\gamma_\mu+G(q^2\gamma_\mu-\not{q}q_\mu)\gamma_5+M\sigma_{\mu\nu}q_\nu+Ei\sigma_{\mu\nu}q_\nu\gamma_5]u(\vec{p}_i,s_i)\ . \tag{9}$$

Here u is a Dirac spinor, $q=p_f-p_i$, and F, G, M, and E are form factors depending on q^2. Writing the analogous expres-

PHYSICAL REVIEW D VOLUME 30, NUMBER 5 1 SEPTEMBER 1984

CPT, *CP*, and *C* phases, and their effects, in Majorana-particle processes

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(Received 3 April 1984)

In neutrinoless double-β decay, the contributions of two virtual Majorana neutrinos with opposite *CP* parity will interfere destructively. This makes it evident that the amplitudes for reactions involving Majorana particles contain significant new phase factors, reflecting the special discrete-symmetry properties of these particles. To study this phenomenon, we derive and examine the *CPT*, *CP*, and *C* properties of Majorana particles. We then apply these properties, especially to the study of neutrinoless double-β decay, and to the neutral weak and electromagnetic interactions of Majorana particles. We show how the new phase factors in the Feynman amplitudes for Majorana-particle processes arise, and see that their precise form and location within these amplitudes depends on one's choice of formalism.

I. INTRODUCTION

Majorana particles, being their own antiparticles, have special *CPT*, *CP*, and *C* properties, with significant physical consequences. Since these particles occur commonly both in grand unified and supersymmetric theories, one would like to know what these consequences are. In a recent paper,[1] the *CPT* properties of an arbitrary Majorana particle were found and then used to learn about the electromagnetic interactions of such a particle. In addition, it was shown that in neutrinoless double-β decay [$(\beta\beta)_{0\nu}$], the contributions of different virtual Majorana neutrinos of definite mass can oppose each other, even if *CP* is conserved.[2] Thus, $(\beta\beta)_{0\nu}$ whose observation would signal that neutrinos are of Majorana character, may have an invisibly small or vanishing rate even if they *are* of this character. The possibility of opposing contributions from different neutrinos was demonstrated in Ref. 1 without relying on field theory (i.e., without using Feynman's rules), and without requiring any knowledge of the phases of the leptonic mixing matrix U. However, practical calculations of the amplitudes for $(\beta\beta)_{0\nu}$ or for other processes involving Majorana particles would, of course, use Feynman's rules and would demand a knowledge of any special phase factors which may occur in field-theoretic amplitudes when Majorana particles are present. Therefore, in this paper we focus on these new phase factors. We uncover their presence in reaction amplitudes, show how they can appear in different, alternative places in the amplitudes depending on one's choice of formalism, and show how they affect Majorana-particle processes, especially $(\beta\beta)_{0\nu}$.

In Sec. II we present a very plausible argument, based on a Feynman diagram, for the *false* conclusion that different Majorana-neutrino contributions always add in $(\beta\beta)_{0\nu}$ so long as *CP* is conserved. This falacious argument illustrates the traps into which one can fall through neglect of the new phase factors which appear as a result of the special *C*, *CP*, and *CPT* properties of Majorana particles. We proceed to discuss the true situation in $(\beta\beta)_{0\nu}$ as deduced without reliance on field theory or Feynman's rules. In Sec. III we then begin the *proper* field-theoretic treatment of Majorana particles by examining the *C*, *CP*, and *CPT* properties (derived in the Appendix) of Majorana fields and states. Special attention is given to the phase factors which appear, and to the restrictions on their possible values. The physical consequences of these restrictions are illustrated by a simple example. In Sec. IV we find the further constraints on phases which result from *CPT* and *CP* invariance of the interaction of special interest in $(\beta\beta)_{0\nu}$: the charged-current weak interaction with neutrino mixing. Section V discusses two especially convenient field-theoretic formalisms, or "languages" as we shall call them, which deal in alternative ways with the phases encountered in Majorana-neutrino physics when *CP* is conserved. For each of these languages, we see how the physically significant phases are contained in the $(\beta\beta)_{0\nu}$ amplitude given by Feynman's rules. The generalization of the conclusions drawn from this analysis to other problems involving Majorana particles is discussed. In Sec. VI we use the *CPT* properties of Majorana particles to infer the general structure of their neutral weak currents and to gain information on electromagnetic transitions among them. We also discuss consequences of *CP* invariance, and see how electromagnetic transition form factors acquire some of their traits when they are calculated in terms of loop diagrams. Section VII summarizes our results.

II. CANCELLATIONS IN $(\beta\beta)_{0\nu}$

Are neutrinos Majorana particles? The only known practical way to study this question is to search for neutrinoless double-β decay. In this process, a pair of virtual W bosons, generated by two neutrons in a nucleus, produces a pair of outgoing electrons by virtual neutrino exchange (Fig. 1). As Fig. 1 shows, the amplitude for the process is the sum of the contributions from all the neutrino mass eigenstates ν_m which couple to an electron. This coupling is described by the general charged-current weak interaction with neutrino mixing,

[17]We thank Alfred S. Goldhaber for the conversation in which this argument was constructed.

[18]We thank R. Mohapatra for asking us this question.

[19]Note from Table I that $\eta_c^* \Psi^c$, and not $\Psi^c \equiv \gamma_2 \Psi^*$, is the charge-conjugate field $C\Psi C^{-1}$. In the Majorana case, it is dangerous to call Ψ^c the "charge-conjugate field" because, as Eq. (5.8) indicates, the phase factor relating Ψ^c to Ψ is the arbitrary creation phase factor, rather than the C parity of the Majorana particle. Indeed, in language L2, for example, $\nu_m^c = [\bar{\eta}_{CP}(\nu_m)/i]\nu_m$. Furthermore, the field Ψ^c is a useful concept even when, as here, C is not conserved. When it is conserved, $\eta_c^* \Psi^c = \bar{\eta}_c \Psi$ bears the proper relation of a charge-conjugate field to Ψ.

[20]It is trivial to check that the propagator $\nu_m \bar{\nu}_m$ contains no unconventional phases, even though a creation phase factor is in general present in the ν_m field.

[21]If one follows the approach used in Ref. 1 to obtain Eq. (2.2), but invokes only CPT invariance, rather than CP invariance, one finds that

$$A[(\beta\beta)_{0\nu}] \propto \sum_m \bar{\eta}_\xi^{\,\xi-+1/2}(\nu_m) U_{em}{}^2 M_m .$$

From Table I and the equality of the $\eta_\xi(\nu_m)$,

$$\bar{\eta}_\xi^{\,\xi-+1/2}(\nu_m) \propto \lambda(\nu_m) .$$

Thus, one confirms Eq. (5.10).

[22]In Ref. 2, Wolfenstein was implicitly using the language we are calling L2.

[22(a)]*Note added in proof.* After submission of this work for publication, we received a Joint Institute for Nuclear Research (Dubna) report by S. Bilenky, N. Nedelcheva, and S. Petcov (unpublished), which, in a spirit very similar to that of the present paper, stresses the arbitrariness of the factors $\lambda(\nu_m)$ appearing in Eq. (5.8), but shows that $A[(\beta\beta)_{0\nu}]$ has the form of Eq. (2.2) independently of these factors. Bilenky *et al.* favor a formalism which we might call language L3 in which the elements of the CP-conserving U matrix have phases of $\pm(\pi/4)$.

[23]After this work was essentially completed, we received an interesting paper by A. Barroso and J. Maalampi [Phys. Lett. **132B**, 355 (1983)] which discusses the possibility of locating significant phases in alternative places in the *CP-violating*, two-generation case.

[24]C. Prescott *et al.*, Phys. Lett. **77B**, 347 (1978).

[25]That $\langle \tilde{\gamma} | N_\mu | \tilde{\gamma} \rangle$ must involve only three form factors can be seen very easily by considering the cross-channel process $Z^0(q^2) \to \tilde{\gamma}\tilde{\gamma}$, where the Z^0 is allowed to be off shell and so can have either $J=1$ or $J=0$. Supposing for simplicity that the photinos are nonrelativistic, there are then three allowed antisymmetric $\tilde{\gamma}\tilde{\gamma}$ final states: ${}^3P_1$, ${}^3P_0$, and ${}^1S_0$.

[26]The use of CPT constraints to determine the electromagnetic matrix element of a Majorana fermion was first attempted by J. Nieves [Phys. Rev. D **26**, 3152 (1982)], and by B. McKellar [Los Alamos National Laboratory Report No. LA-UR-82-1197 (unpublished)]. However, their calculations needed revision to take into account the nontrivial CPT phase factors $\bar{\eta}_\xi^{\,\xi}$.

[27]Equation (6.6) agrees with the result obtained by other means by Kayser (Ref. 14), by Nieves (Ref. 26), and by R. Shrock [Nucl. Phys. **B206**, 359 (1982)]. See also J. Schechter and J. Valle, Phys. Rev. D **24**, 1883 (1981).

[28]Note that for a Majorana particle f of well-defined C and P, the electromagnetic coupling $\gamma \to ff$ is C and P violating, since $C(ff) = \bar{\eta}_c^{\,2}(f) = 1$ and $P(ff; {}^3P_1) = -\bar{\eta}_P^{\,2}(f) = 1$.

[29]In a Comment on Ref. 1 [Phys. Rev. D **29**, 1542 (1984)], A. Khare and J. Oliensis have just used these same CPT techniques to constrain the *gravitational* interaction of a spin-$\frac{1}{2}$ Majorana particle.

[30]For the special case $\xi = 1$, the relations (6.8) were obtained earlier from CPT by McKellar (Ref. 26), and through another method by Nieves (Ref. 26). These earlier treatments did not uncover the fact that ξ, which in general is not unity, is present in these relations.

[31]Nieves (Ref. 26) and McKellar (Ref. 26).

[32]P. Pal and L. Wolfenstein, Phys. Rev. D **25**, 766 (1982).

[33]See Kayser (Ref. 14) and McKellar (Ref. 26).

[34]For language L2, essentially this analysis is given in Ref. 32.

[35]For $\xi = 1$, the requirements of Eq. (6.8) are verified for the form factors resulting from loop diagrams by Nieves (Ref. 26).

[36]A. Zee, Phys. Lett. **93B**, 389 (1980).

[37]D. Chang and P. Pal, Phys. Rev. D **26**, 3113 (1982).

[38]We thank P. Pal for showing explicitly that these relations are representation-independent.

[39]Carruthers (in *Spin and Isospin in Particle Physics*, Ref. 15) has carried out the reverse analysis in which the discrete-symmetry transformations are defined in terms of their effects on states, and the implied effects on fields are then found and required to be simple. The conclusions of his analysis and the one given here are mostly in agreement. See, in addition, S. Weinberg, Phys. Rev. **133**, B1318 (1964). Also, after this work was essentially completed, we received a paper by M. Doi *et al.* [Prog. Theor. Phys. **70**, 1331 (1983)], which treats the case $\lambda = 1$ and follows a third approach; namely, the discrete-symmetry transformations are required to leave the free Lagrangian, expressed in terms of two-component Majorana fields, invariant, and the consequences of this requirement are found.

CP:

$$U_{CP}\, \chi(x)\, U_{CP}^{-1} = \eta_{CP}(\chi)\, \gamma_4\, \chi(x_p) \quad (= \tilde{\eta}_{CP} \gamma_4 C \bar{\chi}^T(x_p))$$

$$\eta_{CP}(\chi) = \pm i \qquad (= \tilde{\eta}_{CP} \xi)$$

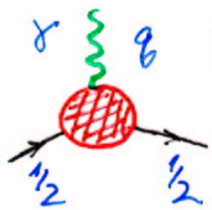
$$U_{CP}\, \Psi(x)\, U_{CP}^{-1} = \underbrace{\eta_{CP}(\Psi)}_{\text{UNPHYSICAL}}\, \gamma_4\, C \bar{\Psi}^T(x_p)$$

COUPLINGS AND INTRINSIC PROPERTIES:

$$\bar{\chi}(x) \gamma_\mu \chi(x) = 0 \qquad Q_{el} = 0 \quad (Q_{U(1)} = 0)$$

$$\bar{\chi}(x) \sigma_{\mu\nu} \chi(x) = 0 \qquad \mu_\chi = 0$$

$$\bar{\chi}(x) \sigma_{\mu\nu} \gamma_5 \chi(x) = 0 \qquad d_\chi = 0$$



LORENTZ INVARIANCE + $\partial_\mu J_\mu^{em} = 0$:

$$\Gamma_\mu(q) = \mu\, \sigma_{\mu\nu} q_\nu + i d\, \sigma_{\mu\nu} \gamma_5 q_\nu + G^V (\delta_{\mu\nu} q^2 - q_\mu q_\nu) \gamma_\nu + G^A (\delta_{\mu\nu} q^2 - q_\mu q_\nu) \gamma_\nu \gamma_5$$

Ψ : $\mu \neq 0$, $d \neq 0$ (CP-INV.: $d = 0$), $G^V \neq 0$, $G^A \neq 0$

χ : $\mu = 0$, $d = 0$, $G^V = 0$, $G^A \neq 0$

REAL PHOTON: $q^2 = 0$, $q_\mu \varepsilon_\mu^\lambda(q) = 0$

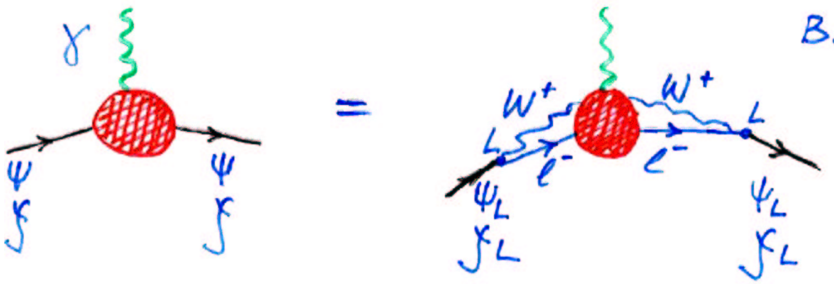
ST, $\nu_{eL}(x)$ ONLY, $m_\nu = 0$:

$\nu_L \equiv \Psi_L$, LH ν, RH $\tilde{\nu}$

$\nu_L \equiv \chi_L$, LH ν, RH ν

UNDISTINGUISHABLE ("CONFUSION THEOREM")

B. KAYSER



Ψ: $\Gamma_\mu(q) \longrightarrow \Gamma_\mu^{\Psi_L}(q) = \frac{1}{2}(1+\gamma_5)\Gamma_\mu(q)\frac{1}{2}(1+\gamma_5)$

$$= (G_\Psi^V + G_\Psi^A)(\delta_{\mu\nu} q^2 - q_\mu q_\nu)\gamma_\nu \tfrac{1}{2}(1+\gamma_5)$$

$G_\Psi^V = G_\Psi^A$ (NO RH COUPLINGS: $P_R \Gamma_\mu P_R = 0$)

χ: $\Gamma_\mu(q) \rightarrow \Gamma_\mu^{\chi_L}(q) = \frac{1}{2}(1+\gamma_5)[\Gamma_\mu(\gamma_5) - \Gamma_\mu(-\gamma_5)] \times \frac{1}{2}(1+\gamma_5)$

$$= 2G_\chi^A(\delta_{\mu\nu} q^2 - q_\mu q_\nu)\gamma_\nu \tfrac{1}{2}(1+\gamma_5)$$

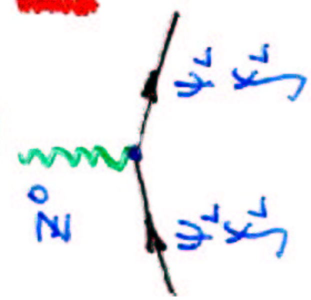
B. KAYSER

SIMILARLY.

Ψ: $\frac{1}{2}(1+\gamma_5)\gamma_\mu(g_V^2 + g_A^2\gamma_5)\frac{1}{2}(1+\gamma_5) = (g_V^2 + g_A^2)\gamma_\mu \frac{1}{2}(1+\gamma_5)$

ST: $g_V^2 = g_A^2 = 1$

χ: $\frac{1}{2}(1+\gamma_5)\gamma_\mu(2g_A^2\gamma_5)\frac{1}{2}(1+\gamma_5) = 2g_A^2\gamma_\mu \frac{1}{2}(1+\gamma_5)$



Comment on Recent Argument That Neutrinos Are Not Majorana Particles*

Boris Kayser

National Science Foundation
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Arlington, VA 22230 USA

February 1997

Abstract

Existing data on neutrino-electron scattering do not imply that neutrinos are not Majorana particles. The question of whether neutrinos are of Majorana or of Dirac character remains completely open.

Recently, it has been argued[1] that existing data imply that neutrinos are not Majorana particles. The argument is as follows:

1. If some neutrino is a Majorana particle, then its vector neutral current (NC) vanishes.
2. The CHARM II experiment has found that, at least at the 2σ level, the product of the vector NC couplings of a ν_μ and an electron is nonzero.[2]
3. If, as suggested by the CHARM II experiment, the ν_μ vector NC coupling is really nonzero, then the ν_μ cannot be a Majorana neutrino. In that case, the other neutrinos are probably not Majorana particles either.

This argument is not correct. In particular, the assertion in step (2) is not right. The CHARM II experiment studied the NC reactions $\overset{(-)}{\nu}_\mu e \to \overset{(-)}{\nu}_\mu e$. As explained below, experiments on NC interactions between a ν_μ (and $\bar{\nu}_\mu$) and some target cannot determine the ν_μ NC vector coupling.

*National Science Foundation preprint NSF-PT-97-1. The statements in this paper are not official views of the National Science Foundation.

1

$$\left.\begin{array}{l}\bar{\chi}(x)\gamma_\mu\chi(x) = 0\\ \bar{\chi}(x)\gamma_\mu\gamma_5\chi(x) \neq 0\end{array}\right\}\ \chi + \chi \to f + \bar{f}$$ – P-WAVE SUPPRESSION

IMPLICATIONS: ABUNDANCE OF RELIC χ
LIGHTEST NEUTRALINOS IN
SUSY (MSSM) – CDM

H. GOLDBERG

MORE GENERALLY,

B. KAYSER,
R. SHROCK,
...

$$\bar{\chi}_j(x)\,\sigma_{\mu\nu}\,(F^V_{ji} + F^A_{ji}\gamma_5)\,\chi_i$$

$$\chi_i \to \chi_j + \gamma$$

$$\bar{\chi}_j(x)\,\gamma_\mu\,(V_{ji} + A_{ji}\gamma_5)\,\chi_i(x)$$

CP-INVARIANCE:

$$\eta_{CP}(\chi_i)\,\eta_{CP}(\chi_j) = -1,\ F^V_{ji} = V_{ji} = 0 \quad (E1)$$

$$\eta_{CP}(\chi_i)\,\eta_{CP}(\chi_j) = +1,\ F^A_{ji} = A_{ji} = 0 \quad (M1)$$

$\cancel{CP}$: BOTH $F^V \neq 0$, $F^A \neq 0$

$V \neq 0$, $A \neq 0$

MSSM (SUSY):

$$e^+ + e^- \to \chi_i + \chi_j$$

THRESHOLD BEHAVIOR OF σ:

CP-INV.: S-WAVE OR P-WAVE

ALL THE ABOVE RESULTS CAN BE DERIVED USING THE CPT-INVARIANCE, CPT-TRANSFORMATION PROPERTIES AND WORKING WITH AMPLITUDES OF THE PROCESSES:

CPT:

B. KAYSER;

B. KAYSER, A. GOLDHABER, ...

$$U_{CPT}\,|\chi(\vec{k},\rho)\rangle = \eta_{CPT}(\chi)\,|\chi(-\vec{k},\rho)\rangle .$$

$$U_{CPT}\,|\psi(\vec{k},\rho)\rangle = \eta_{CPT}(\psi)\,|\tilde{\psi}(-\vec{k},\rho)\rangle$$

UNPHYSICAL

3-ν MIXING:

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

U_{PMNS}

PARAMETERS: U_{PMNS} – $n \times n$

		n	2	3	4
ANGLES		$\frac{n(n-1)}{2}$	1	3	6
CP-VIOLATING PHASES:	ν_j – DIRAC	$\frac{(n-1)(n-2)}{2}$	0	1	3
	ν_j – MAJORANA	$\frac{n(n-1)}{2}$	1	3	6

BILENKY, HOSEK, PETCOV '80; DOI ET AL., '81.

KAYSER, PETCOV, ROSEN
$(\beta\beta)_{0\nu}$ - DECAY... (UNPUBLISHED)

- $|<m>| \neq 0$: $m_j \geq |<m>|$
- LR - CONTRIBUTION:

$$\sum_j U^L_{ej} U^{R*}_{ej} \frac{\hat{q}}{q^2 + m_j^2} \cong$$

$$\cong \sum_j U^L_{ej} U^{R*}_{ej} \frac{\hat{q}}{q^2} \left(- \frac{m_j^2}{q^2} \right)$$

- THE PAPER WHICH TOOK THE LONGEST TIME NOT TO WRITE ('84 - '98)
- AMONG THE MOST QUOTED UNPUBLISHED WORK

STANDARD PARAMETRIZATION:

$$U_{PMNS} = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} e^{i\alpha_{21}/2} & U_{e3} e^{i(\frac{\alpha_{31}}{2}+\delta)} \\ -s_{12} c_{23} - c_{12} s_{23} U^*_{e3} & (c_{12} c_{23} - s_{12} s_{23} U^*_{e3}) e^{i\frac{\alpha_{21}}{2}} & s_{23} c_{13} e^{i(\alpha_{31}/2+\delta)} \\ s_{12} s_{23} - c_{12} c_{23} U^*_{e3} & (-c_{12} s_{23} - s_{12} c_{23} U^*_{e3}) e^{i\frac{\alpha_{21}}{2}} & c_{23} c_{13} e^{i(\alpha_{31}/2+\delta)} \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, $0 \leq \theta_{12}, \theta_{13}, \theta_{23} \leq \pi/2$

$U_{e3} = s_{13} e^{-i\delta}$, $\delta \in [0, 2\pi]$ - DIRAC CP-VIOLATING PHASE

α_{21}, α_{31} - MAJORANA CP-VIOLATING PHASES

IF ν_j ARE MAJORANA PARTICLES, CP - SYMMETRY CAN BE VIOLATED EVEN IN THE CASE OF $n = 2$ FAMILIES OF LEPTONS: S.M. BILENKY, J. HOSEK, S.T.P. '80

$$n^M_{CP} = \frac{n(n+1)}{2} - n = \frac{n(n-1)}{2}$$

α_{21}, α_{31}: DO NOT APPEAR IN $P(\overset{(-)}{\nu}_l \to \overset{(-)}{\nu}_{l'})$

- AFFECT THE $(\beta\beta)_{0\nu}$ - DECAY RATE
- IN SUSY SEE - SAW MODELS, THE RATES OF THE LFV DECAYS.

"PARAMETERS":

$\theta_{12}, \theta_{13}, \theta_{23}$

ν_j DIRAC — MAJORANA

δ — $\delta, \alpha_{21}, \alpha_{31}$

m_1, m_2, m_3

$m_{1,2,3}$: MEASURED IN ν-OSCILLATION EXPERIMENTS

$$\Delta m^2_{\odot} = \Delta m^2_{21} > 0, \quad |\Delta m^2_{ATM}| = |\Delta m^2_{31}|$$

(A) $m_1 < m_2 < m_3$ OR $m_3 < m_1 < m_2$

(B) $m_1 < m_2 < m_3$:

$$m_1, m_2, m_3 \Rightarrow m_1, \ \Delta m^2_{21} > 0, \ \Delta m^2_{32} > 0$$

$$m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$$

$$m_3 = \sqrt{m_1^2 + \Delta m^2_{21} + \Delta m^2_{32}}$$

$$\Delta m^2_{ATM} = \Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$$

TWO POSSIBILITIES:

$\Delta m^2_{\odot} = \Delta m^2_{21}$ - NH

$\Delta m^2_{\odot} = \Delta m^2_{32}$ - IH

] - "DISCRETE" PARAMETER

THE MAIN PROBLEMS IN THE STUDIES OF ν-MIXING:

- DETERMINATION OF $\Delta m^2_{\odot}$, $\theta_{\odot}$, Δm^2_{atm}, θ_{atm} WITH A HIGH PRECISION
- MEASURE, OR IMPROVE BY AT LEAST A FACTOR OF ~ 10 THE EXISTING LIMITS ON, $|U_{e3}|^2 = \sin^2\theta_{13}$
- DETERMINE THE TYPE OF ν-MASS SPECTRUM,
  - $m_1 \ll m_2 \ll m_3$, NH
  - $m_1 \ll m_2 \cong m_3$, IH
  - $m_1 \cong m_2 \cong m_3$, $m_j^2 \gg \Delta m^2_{atm}$, QD
- DETERMINE, OR OBTAIN CONSTRAINTS ON, THE ABSOLUTE ν-MASS SCALE (LIGHTEST ν MASS)
- DETERMINE THE NATURE OF ν_j (DIRAC VS MAJORANA)
- ESTABLISH WHETHER CP-SYMMETRY IS VIOLATED IN THE LEPTON SECTOR
  1. DUE TO THE DIRAC PHASE, δ,
  2. DUE TO THE MAJORANA PHASES α_{21}, α_{31}, IF ν_j - MAJORANA
- FIND A THEORY WHICH EXPLAINS THE DATA (THE THEORY)

$(\beta\beta)_{0\nu}$ - DECAY EXPERIMENTS:

- MAJORANA NATURE OF ν_j
- TYPE OF SPECTRUM (NH, IH, QD)
- ABSOLUTE ν-MASS SCALE

^3H β-DECAY, COSMOLOGY...

- CP-VIOLATION DUE TO THE MAJORANA CP-VIOLATING PHASES

July 26, 1987.

Dear Boris, Peter,

Enclosed is my contribution to our paper. I had some problem writting it without having the preceding part at hand. (It came out rather long (and certainly can be reduced somewhat. I did not write the Introduction. I thought I cannot write it better than Peter who has been in the subject of $(\beta\beta)_{0\nu}$-decay since the time I was a small child.

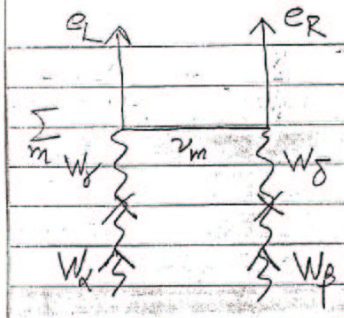
I would be happy to see the final version before it will be ~~sent~~ published (as a preprint or otherwise).

Finally, let me add that it was nice to meet you both and discuss physics with you. I hope this will happen again before too long. Meanwhile, let us keep in touch.

All the best,
Sergey Petcov.

257

The High-E Argument (cont'd)



This may be dangerous when W_γ and W_δ have LH coupling, and W_β an W_γ RH coupling, because it adds a diagram for each ν_m.

Serguey says at high E we should be able to neglect the W mass matrix. Yes, but in

$$W_\alpha = W_1 \cos\zeta + W_2 \sin\zeta$$

$$W_\beta = -W_1 \sin\zeta + W_2 \cos\zeta,$$

$\zeta \sim \left(\frac{M_1}{M_2}\right)^{\frac{1}{2} \text{ or } 1 \text{ or } 2}$, so the mixing does not disappear as $E \to \infty$.

Let us then consider

$$A \equiv \langle \underbrace{e_L e_R}_{\text{neglect masses}} | T | W_\lambda W_\rho \rangle$$

where $W_\lambda, W_\mu, \ldots$ have LH coupling, and $W_\rho, W_\sigma, \ldots$ have RH coupling.

For the fields, let

$$\underset{\text{gauge ES}}{W_\alpha} = \sum_i X_{\alpha i} \underset{\text{mass ES}}{W_i}; \qquad X^\dagger X = X X^\dagger = 1.$$

Ref. SISSA ???/98/EP
September 1998

Neutrinoless Double Beta Decay, Right-Handed Currents and the Evidences for Oscillations of Solar and Atmospheric Neutrinos ???

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c) Istituto Nazionale di Fizica Nucleare, Sezione di Trieste, I-34013 Trieste, Italy

d) Department of Energy, Washington D.C.

Abstract

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UWThPh-1999-41
DFTT 36/99
SISSA 89/99/EP
hep-ph/9907234
July 1999

Constraints from Neutrino Oscillation Experiments on the Effective Majorana Mass in Neutrinoless Double β-Decay

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Abstract

We determine the possible values of the effective Majorana neutrino mass $|\langle m\rangle| = |\sum_j U_{ej}^2 m_j|$ in the different phenomenologically viable three and

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FERMILAB-Pub-02/298-T
UMD-PP-03-027

Manifest CP Violation from Majorana Phases

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We hunt for and discuss manifestly CP-violating effects which are mediated by Majorana phases. These phases are present if the Standard Model neutrinos are Majorana particles. We argue that while Majorana phases do affect the strength of neutrinoless double beta decay (a well known fact), they do so in a way that involves no manifest violation of CP. The conditions for manifestly CP-violating phenomena – differences between the rates for CP-mirror-image processes – are presented, and three examples are discussed: (i) neutrino $\leftrightarrow$ antineutrino oscillation; (ii) rare decays of K and B mesons and their antiparticles and (iii) the lepton asymmetry generated by the decay of hypothetical very heavy right-handed "see-saw" neutrinos. We also find that, for the case of degenerate light neutrinos, manifestly CP-violating effects in neutrino $\leftrightarrow$ antineutrino oscillation vanish, although flavor-changing transitions do not. Finally, we comment on leptogenesis with degenerate right-handed neutrinos, and contrast it to the neutrino $\leftrightarrow$ antineutrino oscillation case.

I. INTRODUCTION

If neutrinos are Majorana particles, then the leptonic mixing matrix U can contain more CP-violating phases than its quark counterpart (for the same number of generations) [1]. The additional phases, known as Majorana phases, have no effect on neutrino oscillation. Indeed, the only current or proposed neutrino experiment that could in principle provide evidence of Majorana phases is the search for neutrinoless double beta decay, $0\nu\beta\beta$ [2]. The rate for this process depends not only on the neutrino masses and mixing angles, but also on CP-violating phases, notably including the Majorana phases. However, even if experimental and theoretical uncertainties should permit us to obtain evidence for a non-vanishing Majorana phase from the rate of $0\nu\beta\beta$ [3], the effect of CP-violating phases on this reaction is not a manifestly CP-violating phenomenon. By the latter, we mean a CP-odd effect – a difference between the rate for some physical process and that for its CP-mirror image. While CP-odd phases in the leptonic mixing matrix do affect the rate Γ for $0\nu\beta\beta$, they do so in a CP-even way; that is, their effect on the rate Γ for some particular nuclear double beta decay is the same as on the rate $\bar{\Gamma}$ for the CP-mirror-image decay (the decay of an antinucleus), so that $\Gamma = \bar{\Gamma}$. Therefore, even if we could study the neutrinoless double beta decay of antinuclei (an impossibility in practice, to say the least), we would be unable to observe a "smoking gun" signal of CP-violation due to Majorana phases.

In this paper, we ask whether Majorana phases, like the more familiar CP-violating "Dirac" phase in the quark mixing matrix, can lead to CP-odd effects. If so, where and under what conditions can these effects occur, and what are they? Are they observable in practice?

An increasingly appealing explanation of the present baryon asymmetry in the Universe rests on early-universe "leptogenesis," resulting from CP violation in the decays of so-far hypothetical, very heavy Majorana neutral leptons [4]. The required CP violation in this process can come from Majorana phases. Furthermore, it is a CP-odd effect – a difference between two CP-mirror-image decays, one of which yields a lepton, the other an antilepton. Thus, Majorana phases can, in principle, yield CP-odd effects. However, the Majorana phases that act in the early Universe are not those in the mixing matrix U that governs light neutrino mixing [5]. Moreover, the role of these "early-universe phases" depends on the existence of hypothetical heavy Majorana leptons.* We therefore ask whether the Majorana phases in the light-neutrino mixing matrix U can lead to CP-odd effects that depend only on the (assumed) Majorana nature of the light neutrinos, and not on the existence of any additional Majorana particles.

We find that the answer is yes – Majorana phases in U can induce CP-odd effects. In particular, they do so in the process of "neutrino $\leftrightarrow$ antineutrino oscillations" [7]. By that we mean a process in which, for example, a neutrino "beam" is created by incoming positively-charged leptons, but is measured in a detector via the production of negatively-charged leptons. If Majorana phases are present, the rates for this process and for its CP-mirror image (where the charges of the charged leptons are reversed) will, in general, differ. We explicitly point out why CP-odd effects can occur in neutrino $\leftrightarrow$ antineutrino oscillations but not in $0\nu\beta\beta$. We further discuss under what conditions

* The existence of heavy "right-handed neutrinos" is strongly motivated by the see-saw mechanism for generating light neutrino masses [6]. Unfortunately, even if this beautiful theoretical idea is correct, we may never be able to observe direct evidence for the existence of heavy right-handed neutrinos if their masses are indeed many orders of magnitude above the weak-scale, as naively indicated by the experimental evidence for neutrino masses.

arXiv:hep-ph/0203261 v1 27 Mar 2002

CPT Violation and the Nature of Neutrinos

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Abstract

In order to accommodate the neutrino oscillation signals from the solar, atmospheric, and LSND data, a sterile fourth neutrino is generally invoked, though the fits to the data are becoming more and more constrained. However, it has recently been shown that the data can be explained with only three neutrinos, if one invokes CPT violation to allow different masses and mixing angles for neutrinos and antineutrinos. We explore the nature of neutrinos in such CPT-violating scenarios. Majorana neutrino masses are allowed, but in general, there are no longer Majorana neutrinos in the conventional sense. However, CPT-violating models still have interesting consequences for neutrinoless double beta decay. Compared to the usual case, while the larger mass scale (from LSND) may appear, a greater degree of suppression can also occur.

Key words: Neutrino mass and mixing, double beta decay
PACS: 14.60.Pq, 23.40.-s

FERMILAB-Pub-02/014-T, FERMILAB-Pub-02/014-A

1 Introduction

In recent years, stronger and stronger experimental evidence for neutrino oscillations has been accumulating. As is well-known, this evidence would extend the Standard Model by requiring neutrino masses and mixings. While knowing the values of the mass and mixing parameters may be an important clue to physics beyond the Standard Model, more information is needed. For example,

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Preprint submitted to Elsevier Science 24 February 2002

HAPPY BIRTHDAY, BORIS!

THANK YOU FOR BEING AROUND!