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KITP
NEUTRINOS ET AL.

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FERMILAB - TH

MANIFEST CP-VIOLATION FROM MAJORANA PHASES*

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- SM w/ MAJORANA MASSIVE NEUTRINOS AND MAJORANA PHASES
  - DEFINING MAJORANA PHASES (AND DIRAC PHASES)
  - WHEN CAN WE "SEE" MAJORANA PHASES?
- MANIFEST $\not{CP}$ - WHAT IS IT?
  - $O_{\nu\beta\beta}$ VERSUS ANTI-$O_{\nu\beta\beta}$
  - NECESSARY CONDITIONS FOR $\not{CP}$
- $\not{CP}$ AND OSCILLATIONS
  - $\nu_\alpha \to \nu_\beta$ OSCILLATIONS
  - $\nu_\alpha \to \bar{\nu}_\beta$ OSCILLATIONS
- $\not{CP}$ AND "RESCATTERING"
  - $K^\pm \to \mu^\mp \mu^\mp \pi^\pm$ ET AL
  - LEPTO GENESIS
- CONCLUSIONS

SM + MASSIVE MAJORANA NEUTRINOS

$$\mathcal{L}_{INT} = -\frac{g}{\sqrt{2}}\left[\bar{\ell}_\alpha \not{W}^- U_{\alpha i}\, \nu_i + \bar{\nu}_i \not{W}^+ U^*_{\alpha i}\, \ell_\alpha\right]$$

"LEFT-HANDED" CHARGED LEPTONS

"LEFT-HANDED" NEUTRINOS

$$\mathcal{L}_{MASS} = -\left[\ell_\alpha\, m_\ell^{\alpha\beta}\, e^c_\beta + H.C.\right] \rightarrow$$

CHARGED LEPTON MASS

e^c = "LEFT-HANDED" SINGLET CHARGED ANTI-LEPTON

$$-\frac{1}{2}\left[\nu_i\, m_\nu^{ij}\, \nu_j + H.C.\right] \rightarrow$$

NEUTRINO MAJORANA MASS.

BASIS CHOICE

- m_ℓ, m_ν DIAGONAL, REAL, POSITIVE
- $U_{\alpha i}$ = LEPTONIC MIXING MATRIX (UNITARY MATRIX)

PARAMETRIZING $U_{\alpha i}$

$$\boxed{U = E^{i\phi_\alpha/2}\, U'\, E^{i\xi_i/2}}$$

$$E^{i\alpha_j} \equiv \begin{pmatrix} e^{i\alpha_1} & & 0 \\ & e^{i\alpha_2} & \\ 0 & & \ddots \end{pmatrix}$$

ϕ_α ARE UNPHYSICAL $\rightarrow$ ABSORBED BY e^c FIELDS

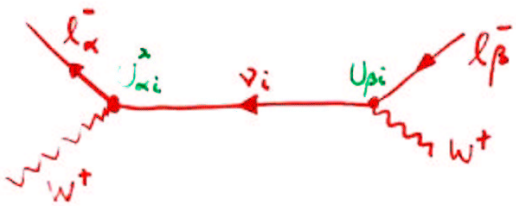
ξ_i ARE POTENTIALLY PHYSICAL ! MAJORANA PHASES

e.g. $$U(2) \rightarrow \underset{\text{GLOBAL}}{e^{i\eta}} \underset{\sigma_3\text{-ROTATION}}{\begin{pmatrix} e^{i\phi/2} & \\ & e^{-i\phi/2} \end{pmatrix}} \underset{\sigma_2\text{-ROTATION}}{\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}} \underset{\sigma_3\text{-ROTATION}}{\begin{pmatrix} e^{i\xi/2} & \\ & e^{-i\xi/2} \end{pmatrix}}$$

ANY "LEFT-OVER PHASES" IN U' ARE DEFINED TO BE DIRAC PHASES

IN WORDS

"A MAJORANA PHASE IS CHARACTERIZED AS A PHASE WHICH IS COMMON TO ALL ELEMENTS OF A GIVEN COLUMN OF THE MIXING MATRIX"



(LEADING ORDER FOR $\ell_\alpha^- \to \ell_\beta^-$)

$$A_L \propto \sum_i U_{\beta i} U^*_{\alpha i} f_i$$

↳ NO EFFECT OF PHASES THAT MULTIPLY A COLUMN OF THE MIXING MATRIX ($e^{-i\xi_i/2} \times e^{i\xi_i/2} \equiv 1$)

WE EXPLORE, THEREFORE,

"NEUTRINO-ANTINEUTRINO" OSCILLATIONS

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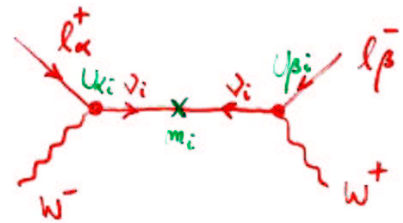
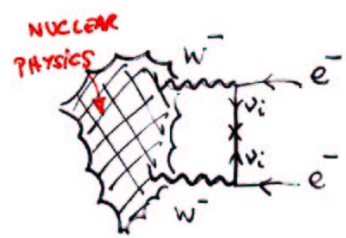


$\ell_\alpha^+ \to \ell_\beta^-$ "OSCILLATION"

$$A_\chi \propto \sum_i U_{\alpha i} U_{\beta i}\, m_i\, g_i$$

↳ $e^{i\xi_i}\, U'_{\alpha i} U'_{\beta i}$

"BEST" EXAMPLE: NEUTRINOLESS DOUBLE BETA DECAY ($0\nu\beta\beta$)



$$A_{\beta\beta} = \sum_i U_{ei}^2\, m_i\, K$$

↓ KINETIATICS + NUCLEAR PHYSICS

"OBSERVABLE"

$$m_{\beta\beta} \equiv \left| \sum_i U_{ei}^2\, m_i \right| \overset{U_{e3}\to 0}{=} \left| m_1 \cos\theta_\odot\, e^{i\xi_1} + m_2 \sin\theta_\odot\, e^{i\xi_2} \right|$$

DEPENDENCY ON MAJORANA PHASE!

MANIFEST $\not{CP}$: RATE(PROCESS) $\neq$ RATE(ANTI-PROCESS)

ASSUME ANTI-$0\nu\beta\beta$ $\left(\bar{Z} \to \overline{Z+2} + e^+ + e^+ \right)$:

$$\bar{A}_{\beta\beta} = \sum_i (U_{ei}^*)^2 m_i \bar{K} \qquad \left(A_{\beta\beta} = \sum_i U_{ei}^2 m_i K \right)$$

$$|\bar{A}_{\beta\beta}|^2 = |A_{\beta\beta}|^2 \Rightarrow \text{RATES ARE THE SAME!}$$

EVEN THOUGH MAJORANA PHASES AFFECT THE RATE FOR NEUTRINOLESS DOUBLE-BETA DECAY, THEY DO SO IN A CP-EVEN WAY (AT LEAST AT LEADING ORDER...).

WHAT DO WE REQUIRE IN ORDER TO OBSERVE MANIFEST $\not{CP}$?

$\not{CP}$-101: CONDITIONS FOR CP-INVARIANCE VIOLATION

ASSUMING THAT CP-VIOLATION COMES FROM PHASES, IT IS TRIVIAL TO STATE NECESSARY CONDITIONS FOR $\not{CP}$ TO BE OBSERVABLE:

- THE AMPLITUDE FOR A PROCESS P MUST CONTAIN AT LEAST 2 DISTINCT CONTRIBUTIONS

$$A = \underbrace{a_1}_{\text{REAL}} \underbrace{e^{i\delta_1}}_{\text{CP-EVEN}} \underbrace{e^{i\phi_1}}_{\text{CP-ODD}} + a_2 e^{i\delta_2} e^{i\phi_2}$$

$$\bar{A} = a_1 e^{i\delta_1} e^{-i\phi_1} + a_2 e^{i\delta_2} e^{-i\phi_2}$$

$$\Delta_{CP} = |\bar{A}|^2 - |A|^2 = 4 a_1 a_2 \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)$$

- THE DISTINCT CONTRIBUTIONS MUST BE PROPORTIONAL TO DISTINCT CP-ODD PHASES ("WEAK PHASES") $(\phi_1 - \phi_2 \neq 0 \bmod \pi)$

- THE DISTINCT CONTRIBUTIONS MUST BE PROPORTIONAL TO DISTINCT CP-EVEN PHASES ("STRONG PHASES") $(\delta_1 - \delta_2 \neq 0 \bmod \pi)$

WHAT GOES WRONG WITH $U_{\nu\beta\beta}$?

- NO DISTINCT CP-EVEN PHASES!

NEUTRINO OSCILLATIONS: IF THERE 3 OR MORE NEUTRINO FLAVORS, IT IS WELL KNOWN THAT, IN GENERAL $P_{\alpha\beta} \neq P_{\bar{\alpha}\bar{\beta}}$ (MANIFEST CP)

$$A_L^{\alpha\beta} = \sum_i U_{\alpha i}^* U_{\beta i} \, e^{-i \frac{m_i^2 L}{2E}}$$

$$\bar{A}_L^{\alpha\beta} = \sum_i \underbrace{U_{\alpha i} U_{\beta i}^*}_{\text{CP-ODD PHASE}} \, \underbrace{e^{-i \frac{m_i^2 L}{2E}}}_{\text{CP-EVEN PHASE!}}$$

$$P_{\alpha\beta} - P_{\bar{\alpha}\bar{\beta}} \propto J \sin\left(\frac{\Delta m_{12}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{13}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

$\hookrightarrow$ JARLSKOG INVARIANT $\supset \sin\delta \Rightarrow$ "DIRAC PHASE"

- WHEN CP RESTORED?
  - $\delta = 0 \bmod \pi$
  - ALL m_i^2 THE SAME
  - ONE $\theta = 0$ OR 2 MASSES ARE THE SAME

NEUTRINO $\leftrightarrow$ ANTINEUTRINO OSCILLATIONS

- VIOLATES $L \Rightarrow$ MAJORANA PHASES ENTER
- CP-EVEN PHASE FROM THE "OSCILLATORY TERM".

$$A_\mu = \sum_i (U_{\alpha i} U_{\beta i}) \frac{m_i}{E} e^{-i m_i^2 L/2E} \underset{\sim}{S}$$

$$\bar{A}_\mu = \sum_i (U_{\alpha i}^* U_{\beta i}^*) \frac{m_i}{E} e^{-i m_i^2 L/2E} \underset{\sim}{\bar{S}}$$

$\hookrightarrow$ KINEMATICAL, PHASE-SPACE FACTORS (INDEPENDENT ON i)

2-FLAVOR $\nu \leftrightarrow \bar{\nu}$ OSCILLATIONS: [e.g. $e,\mu \leftrightarrow 1,2$]

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e^{i\xi_1/2} & 0 \\ 0 & e^{i\xi_2/2} \end{pmatrix} \qquad \xi = \xi_2 - \xi_1$$

$$A_\mu^{e\mu} = \frac{\sin 2\theta}{2} S \left[-e^{i\xi_1} e^{-i m_1^2 \frac{L}{2E}} \frac{m_1}{E} + e^{i\xi_2} e^{-i m_2^2 \frac{L}{2E}} \frac{m_2}{E} \right]$$

$$\bar{A}_\mu^{e\mu} = \frac{\sin 2\theta}{2} \bar{S} \left[\xi_1 \leftrightarrow -\xi_1 \quad \oplus \quad \xi_2 \leftrightarrow -\xi_2 \right]$$

$$|A_K^{e\mu}|^2 = \frac{\sin^2 2\theta}{4E^2}|S|^2\left[m_1^2+m_2^2-2m_1m_2\cos\left(\frac{\Delta m^2 L}{2E}-\xi\right)\right]$$

$$|\bar{A}_K^{e\mu}|^2 = \frac{\sin^2 2\theta}{4E^2}|S|^2\left[m_1^2+m_2^2-2m_1m_2\cos\left(\frac{\Delta m^2 L}{2E}+\xi\right)\right]$$

$\Delta m^2 \equiv m_2^2 - m_1^2$

$$\boxed{\Delta_{CP} = \frac{\sin^2 2\theta}{E^2}|S|^2 m_1 m_2 \sin\left(\frac{\Delta m^2 L}{4E}\right)\sin\xi}$$

$$\frac{\Gamma_K^{e\mu}+\bar{\Gamma}_K^{e\mu}}{2} = \frac{\sin^2 2\theta}{4E^2}|S|^2\left[m_1^2+m_2^2-2m_1m_2\cos\left(\frac{\Delta m^2 L}{2E}\right)\cos\xi\right]$$

AS EXPECTED

- $\Delta_{CP} \propto \sin\xi$ [CP-ODD PHASE]
- $\Delta_{CP} \propto \sin\left(\frac{\Delta m^2 L}{4E}\right)$ [CP-EVEN PHASE]
- $\Delta_{CP} \propto \sin^2 2\theta$ [2 CONTRIBUTIONS]

RESTORING $\not{CP}$:

$\xi = 0 \mod \pi$ [NO CP-ODD PHASES] (OR $m_1=0$ OR $m_2=0$)

$L=0$ ZERO BASELINE "OSCILLATIONS"
$\Delta m^2 = 0$ DEGENERATE NEUTRINOS
} [NO CP-EVEN PHASES]

"NON-INTUITIVE COMMENTS"

ZERO BASELINE OSCILLATIONS:

$$\bar{\Gamma}_K^{e\mu} = \Gamma_K^{e\mu} = \frac{\sin^2 2\theta}{4E^2}|S|^2\left[m_1^2+m_2^2-2m_1m_2\cos\xi\right]$$

$\Rightarrow$ THE "WRONG" HELICITY COMPONENT OF THE "$|\nu_e\rangle$" STATE ALREADY CONTAINS A "$|\nu_\mu\rangle$" COMPONENT TO IT

DEGENERATE MASS OSCILLATIONS: $\Delta m^2 = 0$

$$\bar{\Gamma}_K^{e\mu} = \Gamma_K^{e\mu} = \frac{m^2 \sin^2 2\theta}{E^2}|S|^2 \sin^2\left(\frac{\xi}{2}\right)$$

$\neq 0$ AS LONG AS $\xi \in 0, 2\pi$. THIS SEEMS VERY WEIRD... (HOW CAN ONE DEFINE THE MIXING ANGLE?)

IN THE QUARK SECTOR, IF ALL UP-TYPE OR DOWN-TYPE QUARKS WERE DEGENERATE, THERE WOULD BE NO CKM MATRIX TO SPEAK OF...

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} V^{ij}_{CKM} \bar{u}^i_L \not{W} d^j_L - m \mathbb{1}^{ij} \bar{d}^i_L d^{c\,j}_L + H.C.$$

$$d'^i_L = V^{ij}_{CKM} d^j_L \qquad m\, d'^i_L \mathbb{1}^{ij} d^{c'\,j}_L \Rightarrow V_{CKM} \text{ ABSORBED!}$$

WHAT ABOUT THE NEUTRINO SECTOR ?

$$-\frac{M}{2} \nu_i \nu_i \Rightarrow -\frac{M}{2} \nu_\alpha \left[U'^* E^{-i\xi_i/2} E^{-i\xi_i/2} U'^\dagger \right]_{\alpha\beta} \nu_\beta$$

NO SIMPLIFICATION!

EVEN WHEN ALL CP-ODD PHASES ARE, THERE IS STILL THE POSSIBILITY THAT MIXING ANGLES CAN BE DEFINED.

$$\text{EG. } E^{-i\xi_i} = \begin{pmatrix} 1 & & \\ & -1 & \\ & & \ddots \end{pmatrix}$$

CP-PARITIES.

MORE GENERICALLY, IN THE BASIS WHERE THE CHARGED LEPTON MASSES + THE CHARGED CURRENT INTERACTIONS IS DIAGONAL

$$M_{\alpha\beta} = \left(U'^* E^{-i\xi_i/2} M^D_\nu E^{-i\xi_i/2} U'^\dagger \right)_{\alpha\beta}$$

DIRAC PHASES — DIAGONAL — MAJORANA PHASES

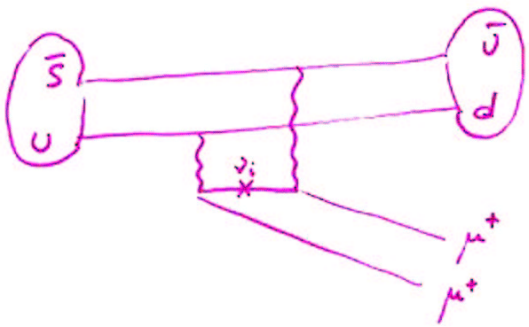
ONE CAN, THEREFORE, "ABSORB" THE MAJORANA PHASES INTO THE MASSES $\Rightarrow$ $M^{D\,\prime}_\nu = E^{-i\xi_i} M^D_\nu$

IN THIS SENSE, IT IS EASY TO SEE WHY THERE ARE STILL MIXING ANGLES IN THE "DEGENERATE MASS CASE" $\rightarrow$ THE MASSES WERE ONLY DEGENERATE IN ABSOLUTE VALUE!

INCIDENTLY, IF ALL CHARGED LEPTON MASSES WERE DEGENERATE, ONE COULD STILL "ROTATE AWAY" THE LEPTONIC MIXING MATRIX, MAJORANA MASSES AND ALL...

CP-VIOLATION WITH "RESCATTERING" PHASES.

- LEPTON NUMBER VIOLATING MESON DECAYS.

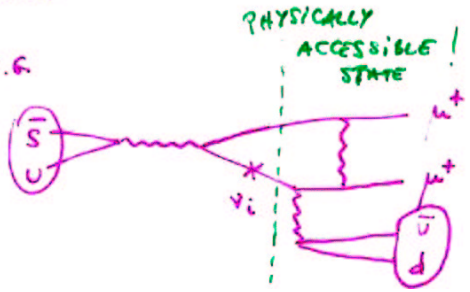


$K^+ \to \mu^+\mu^+\pi^-$

$$A^{LO}_{\mu\mu} = \left[\sum_i U^2_{\mu i}\, m_i\right] K \equiv F e^{i\phi}$$ $\Rightarrow$ NO $\not{CP}$ [LIKE $0\nu\beta\beta$]

HOWEVER, NLO

E.G.



$K^+ \to \mu^+\nu$
$\hookrightarrow \mu^+\mu^+\pi^-$

$$A(K^+ \to \pi^-\mu^+\mu^+) = F e^{i\phi} + G e^{i\psi} e^{i\gamma}$$
$$A(K^- \to \pi^+\mu^-\mu^-) = F e^{-i\phi} + G e^{-i\psi} e^{i\gamma}$$

FROM THE ABSORPTIVE PART, THERE IS A $\to$ SCATTERING PHASE, CP-EVEN (LIKE "STRONG PHASES")

UNFORTUNATELY $\phi = \psi$ [SAME WEAK PHASE], SUCH THAT $\Gamma(K^+ \to \pi^-\mu^+\mu^+) = \Gamma(K^- \to \pi^+\mu^-\mu^-)$.

HOWEVER, "NEW PHYSICS" CAN EASILY ADD EXTRA CP-ODD PHASES (E.G. SUSY + $\not{R}_P$)

OF COURSE, BY LOOKING AT HIGHER ORDER EFFECTS, EVEN $0\nu\beta\beta$ CAN LEAD TO $\not{CP}$ EFFECTS.

e.g. $Z \to (Z+2)\, \underbrace{e^-e^-\nu_e\nu_e}_{\text{REAL STATE}} \to e^-e^-$ $\ominus$ NEW CP-ODD PHASES

- "LEPTOGENESIS"

$$\mathcal{L} = -\frac{M^{ij}}{2} N_i N_j - y_{\alpha i}\left[\bar{\nu}_\alpha \bar{\varphi}^0 - \bar{\ell}_\alpha \varphi^-\right] N + H.c.$$

$L_\alpha = \begin{pmatrix} \nu_\alpha \\ \ell_\alpha \end{pmatrix} \rightarrow$ LEPTON DOUBLET

$H = \phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \rightarrow$ HIGGS-SCALAR DOUBLET

INTEGRATING OUT THE N_i-FIELDS (ASSUMING $M \gg M_{WEAK}$) ONE OBTAINS VERY SMALL MAJORANA NEUTRINO MASSES

$$\mathcal{L}^{EFF} = y \frac{1}{M} y \, (LH)(LH) \quad \text{[SEESAW MECHANISM]}$$

WE ARE INTERESTED IN THE DECAY OF THE N'S.

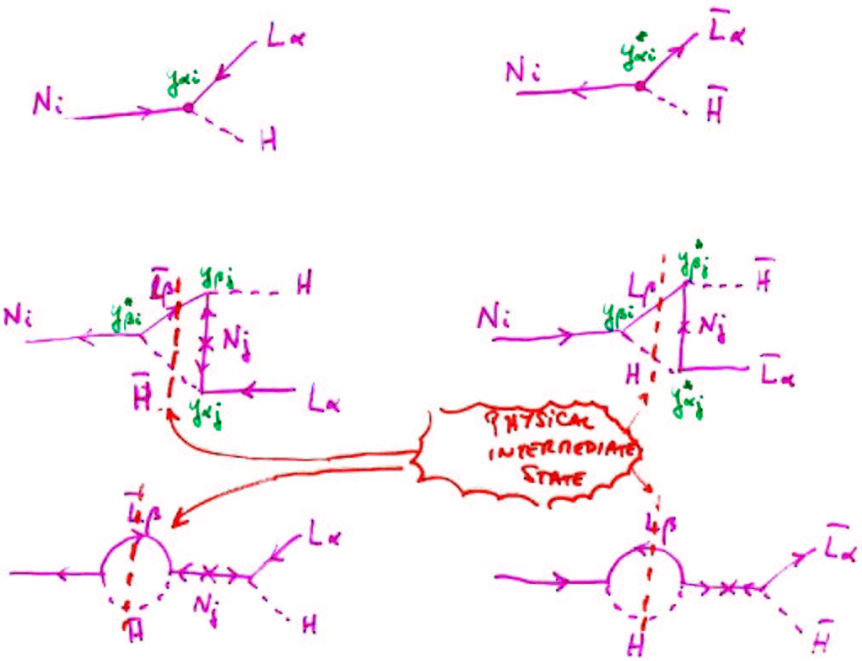
IN PARTICULAR

$$\Gamma(N \rightarrow LH) - \Gamma(N \rightarrow \bar{L}\bar{H})$$

IF THIS HAPPENS OUT OF EQUILIBRIUM IN THE EARLY UNIVERSE, WE CAN GENERATE A NET LEPTON NUMBER (LATER BARYON NUMBER) FOR THE OBSERVABLE UNIVERSE.

WE STUDY THE GEDANKEN EXPERIMENT OF PLACING SOME N_i IN A BOX, WAITING FOR ALL OF THEM TO DECAY, AND ASKING WHETHER THERE ARE MORE LEPTONS THAN ANTI LEPTONS.

- ASSUME $SU(2) \times U(1)$ NO BROKEN
- HIGGS MASSLESS
- CHOOSE BASIS WHERE M^{ij} IS DIAGONAL



THE INTERFERING PROCESSES, THAT ACQUIRE A RELATIVE CP-EVEN PHASE ARE

$N \to LH$ $\quad\times\quad$ $N \to \bar{L}\bar{H}$

$N \to \bar{L}\bar{H} \to LH$ $\quad\quad$ $N \to LH \to \bar{L}\bar{H}$

$$A_{\alpha i} = \left[y_{\alpha i} + \sum_{j,\beta} f(i,j)\, y^*_{\beta i}\, y_{\beta j}\, y_{\alpha j} \right] K_i$$

$$\bar{A}_{\alpha i} = \left[y^*_{\alpha i} + \sum_{j,\beta} f(i,j)\, y_{\beta i}\, y^*_{\beta j}\, y^*_{\alpha j} \right] K_i$$

$$\Delta_i = \sum_\alpha \left(|\bar{A}_{\alpha i}|^2 - |A_{\alpha i}|^2 \right) \Big/ \sum_\alpha \left(|\bar{A}_{\alpha i}|^2 + |A_{\alpha i}|^2 \right)$$

$$\propto \frac{2}{(y^\dagger y)_{ii}} \sum_j \underbrace{\mathrm{Im}\{(y^\dagger y)^2_{ij}\}}_{\text{CP-ODD PHASE.}} \times \underbrace{\mathrm{Im}\{f(i,j)\}}_{\text{CP-EVEN PHASE. FROM ABSORPTIVE PART OF LOOP.}}$$

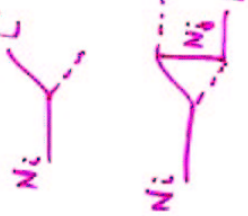
COMPARISON TO $\nu \leftrightarrow \bar{\nu}$ OSCILLATIONS

CP-ODD $\nu \leftrightarrow \bar{\nu}$

$\mathrm{Im}\left((U^*_{\alpha i} U_{\beta i})(U_{\alpha j} U^*_{\beta j}) \right)$

$N \to LH$

$\mathrm{Im}\left(y^*_{\alpha i}\, y_{\beta i}\, y^*_{\alpha j}\, y_{\beta j} \right)$



"SAME" DEPENDENCY ON CP-ODD PHASES δ.

RESTORING CP

$\sum_j \mathrm{Im}\{(y^\dagger y)^2_{ij}\}$ IN THE BASIS WHERE M^{ij} IS REAL, POSITIVE, DIAGONAL

THERE IS NO $\not{CP}$ IF:

- THERE IS ONLY ONE RIGHT-HANDED NEUTRINO $(y^\dagger y)^2_{ii} \in \mathbb{R}$
- $y^\dagger y$ IS DIAGONAL WHEN M^{ij} IS DIAGONAL (NO MIXING)
  - ↳ MIXING COMES FROM A MIS-MATCH BETWEEN THE BASIS WHERE M^{ij} IS DIAGONAL (MASS BASIS) AND WHERE $(y^\dagger y)_{ij}$ IS DIAGONAL ("DECAY BASIS")
- $y^\dagger y$ IS DIAGONAL IF ALL EIGENVALUES OF y ARE THE SAME IN MAGNITUDE

$$y = V^\dagger \begin{pmatrix} x & & 0 \\ & x & \\ 0 & & \ddots \end{pmatrix} U$$

$$y^\dagger y = U^\dagger \begin{pmatrix} |x|^2 & & 0 \\ & |x|^2 & \\ 0 & & \ddots \end{pmatrix} U = \begin{pmatrix} |x|^2 & & 0 \\ & \ddots & \\ 0 & & \ddots \end{pmatrix}$$

↓

"SAME" AS THE CASE WHERE ALL CHARGED LEPTON MASSES ARE DEGENERATE...

- WHAT IF ALL RIGHT-HANDED NEUTRINO MASSES ARE DEGENERATE? →

DEGENERATE N_i'S:

$$\Delta_i \sim \sum_j \frac{\mathrm{Im}(f)\ \mathrm{Im}\{(y^\dagger y)^2_{ij}\}}{(y^\dagger y)_{ii}}$$

NOT ZERO!

ONE CANNOT DO AWAY WITH THE MIXING, AS IN THE $\nu \leftrightarrow \bar{\nu}$ OSCILLATION, UNLESS THERE ARE NO CP-ODD PHASES...

HOW ABOUT THIS? $\sum_i \Delta_i \sim \sum_{i,j} \frac{\mathrm{Im}(y^\dagger y)^2_{ij}}{(y^\dagger y)_{ii}} \neq 0$ (IN GENERAL)

UNLESS, SAY, $(y^\dagger y)_{ii}$ ARE ALL THE SAME...

NOTE ($\sum_{i,j} \mathrm{Im}(y^\dagger y)^2_{ij} = 0$)

WE DON'T REALLY KNOW WHAT THIS IMPLIES, OR WHETHER IT IS RELEVANT, BUT IT IS CERTAINLY CURIOUS...

CONCLUDING REMARKS

- MAJORANA PHASES CAN LEAD TO LOW-ENERGY, MANIFESTLY CP-ODD PHYSICAL PHENOMENA
  E.G. $\nu \leftrightarrow \bar{\nu}$ OSC.

- THE MIXING OF MAJORANA FERMIONS IS "PECULIAR". LOTS OF "INTUITIVELY OBVIOUS" RESULTS NEED NOT APPLY!

- UNFORTUNATELY, ALL PHENOMENA DISCUSSED HERE ARE SEVERAL ORDERS OF MAGNITUDE TOO SMALL TO BE OBSERVED IN PRINCIPLE... ☹

WHY? ⇒ MAJORANA PHASES ⇔ L-NUMBER VIOLATION

$$A \propto \frac{m}{E}$$

m → L-PARAMETER, BY ASSUMPTION