On the asymptotic nature of neutrinos: the proton testimony

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Literature

- M. Blasone, G. Lambiase and **G. L.**, Phys. Rev. D **96**, 025023 (2017)
- M.Blasone, G.Lambiase, **G. L.** and L.Petruzziello, Phys. Rev. D **97**, 105008 (2018)
- M. Blasone, G. Lambiase, **G. L.** and L. Petruzziello, Phys. Lett. B **800**, 135083 (2020)
- M. Blasone, G. Lambiase, **G. L.** and L. Petruzziello, Eur. Phys. J. C **80**, 130 (2020)

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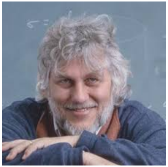
The Unruh effect

"*. . . the behavior of particle detectors under acceleration a is investigated where it is shown that an accelerated detector even in flat spacetime will detect particles in the vacuum. . .*

. . . This result is exactly what one would expect of a detector immersed in a thermal bath of temperature [*Unruh (1976)*]

$$T_{\mathrm{U}} = a/2\pi \quad "$$

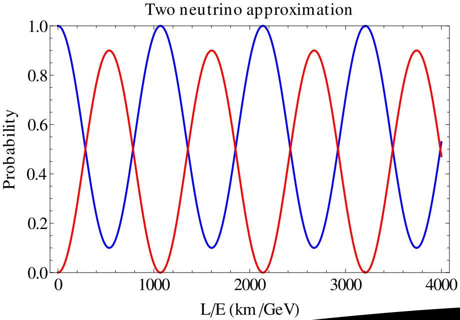


Quantum Mechanics [*Pontecorvo et al. (1978)*]

$$|\nu_e\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta$$

$$|\nu_\mu\rangle = -|\nu_1\rangle \sin\theta + |\nu_2\rangle \cos\theta$$

Flavor and mass representations are **unitarily equivalent**.



The "magic" of neutrinos

- **Quantum Field Theory** [*Blasone and Vitiello (1995)*]

$$\nu_e(x) \,=\, \nu_1(x)\,\cos\theta \,+\, \nu_2(x)\,\sin\theta$$

$$\nu_\mu(x) \,=\, -\nu_1(x)\,\sin\theta \,+\, \nu_2(x)\,\cos\theta$$

- **Mass** and **flavor** field expansions

$$\nu_i(x) = \sum_{\mathbf{k},\sigma}\left[\alpha^\sigma_{\mathbf{k},i}\, u^\sigma_{\mathbf{k},i}\, e^{-ik\cdot x} \,+\, \beta^{\sigma\,\dagger}_{\mathbf{k},i}\, v^\sigma_{\mathbf{k},i}\, e^{+ik\cdot x}\right], \quad i = 1,2$$

$$\nu_\chi(x) = \sum_{\mathbf{k},\sigma}\left[\alpha^\sigma_{\mathbf{k},\chi}(t)\, u^\sigma_{\mathbf{k},j}\, e^{-ik\cdot x} \,+\, \beta^{\sigma\,\dagger}_{\mathbf{k},\chi}(t)\, v^\sigma_{\mathbf{k},j}\, e^{+ik\cdot x}\right], \quad (\chi, j) = (e,1), (\mu,2)$$

- Flavor vacuum annihilator

$$\alpha^{\sigma}_{\mathbf{k},e}(t) = \underbrace{\cos\theta\;\alpha^{\sigma}_{\mathbf{k},1} \;+\; \sin\theta}_{\textit{Pontecorvo rotation}}\;\underbrace{\left(\rho^{\mathbf{k}\,*}_{12}(t)\;\alpha^{\sigma}_{\mathbf{k},2} \;+\; \varepsilon^{\sigma}\;\lambda^{\mathbf{k}}_{12}(t)\;\beta^{\sigma\dagger}_{-\mathbf{k},2}\right)}_{\textbf{Bogoliubov transformation}}$$

- Bogoliubov coefficients

$$\rho^{\mathbf{k}}_{12}(t) \;\equiv\; u^{\sigma\dagger}_{\mathbf{k},2}(t)\,u^{\sigma}_{\mathbf{k},1}(t) \;=\; v^{\sigma\dagger}_{-\mathbf{k},1}(t)\,v^{\sigma}_{-\mathbf{k},2}(t)$$

$$\lambda^{\mathbf{k}}_{12}(t) \;\equiv\; \varepsilon^{\sigma}\;u^{\sigma\dagger}_{\mathbf{k},1}(t)\,v^{\sigma}_{-\mathbf{k},2}(t) \;=\; -\varepsilon^{\sigma}\;u^{\sigma\dagger}_{\mathbf{k},2}(t)\,v^{\sigma}_{-\mathbf{k},1}(t)$$

- **Inequivalent** Fock spaces $\Longrightarrow$ **Inequivalent** representations

$$\lim_{V\to\infty}\;{}_{1,2}\langle 0|0(\theta,t)\rangle_{e,\mu} = 0$$

QM vs QFT

The Standard Model is based on QFT. . .

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

. . . so the QFT viewpoint is more fundamental than the QM one.

Under the magnifying glass

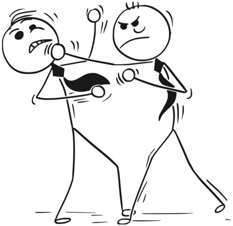
Asymptotic neutrino states: flavor or mass?

$$\mathcal{A} \simeq {}_{\mathrm{out}}\langle \bar{\ell}, \nu, \ldots \, | \, \hat{S}_I \, | \, \ldots \rangle_{\mathrm{in}}$$

$$\searrow$$

$|\nu_{e,\mu}\rangle$ or $|\nu_{1,2}\rangle$?

Flavor states		**Mass states**
M. Blasone, G. Vitiello (1995)		*R. E. Shrock (1980)*
C. Ji et al. (2002)		*C. Giunti (2005)*
C. Lee (2017)		*C. Kim et al. (2007)*
⋮		⋮



Neutrinos as **virtual states**? $\Longrightarrow$ Divergent decay rates [*Cardall (1999)*]

Flavor or mass states?

Flavor states

M. Blasone, G. Vitiello (1995)

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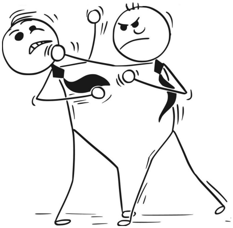
⋮



Mass states

R. E. Shrock (1980)

C. Giunti (2005)

C. Kim et al. (2007)

⋮

~~Neutrinos as **virtual states**? ⟶ Divergent decay rates [*Cardall (1999)*]~~

A mathematical curiosity? NO

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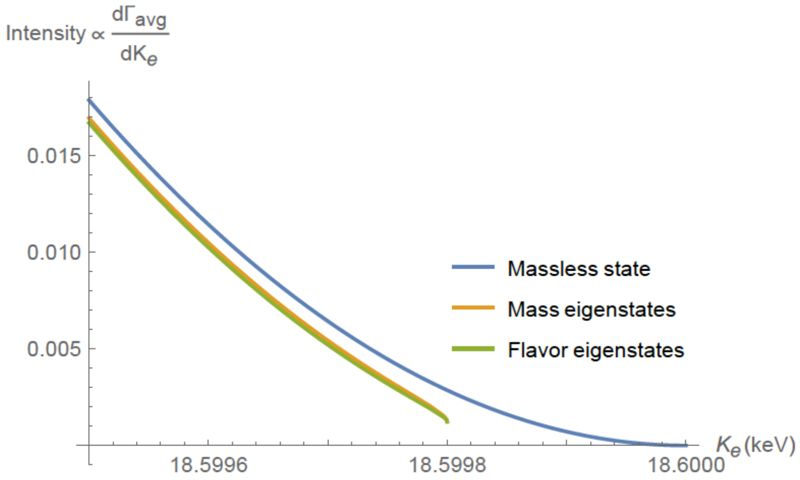

Fig.: Intensity of Tritium β-decay spectrum versus the electron kinetic energy near the end point energy (from arXiv:1709.06306 [hep-ph])

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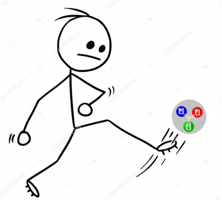
Decay of accelerated particles

Decay properties are not universal [*Ginzburg (1965)*, *Muller (1997)*]

$$\tau_{proton} \gg \tau_{universe} \sim 10^{10}\ \mathrm{yr} \implies \text{protons are } \textbf{stable}!$$

However, if we "kick" the proton...



$$\mathbf{p} \to \mathbf{n} + \mathbf{e}^{+} + \nu_{\mathbf{e}}$$

acceleration	lifetime
a_{LHC}	$\tau_p \sim 10^{3\times10^{8}}\,\mathrm{yr}$
a_{pulsar}	$\tau_p \sim 10^{-1}\,\mathrm{s}$

Laboratory frame

$$p \to n + e^+ + \nu_e$$

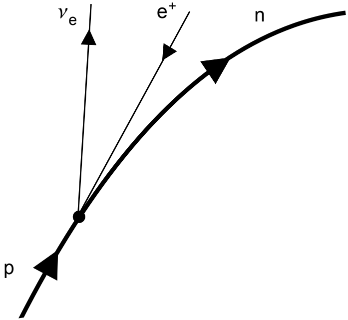


Fig.: The accelerating field provides the proton with the missing energy to decay

Comoving frame

$$p + e \to n + \nu_e \qquad p + \bar{\nu}_e \to n + e^+ \qquad p + e + \bar{\nu}_e \to n$$

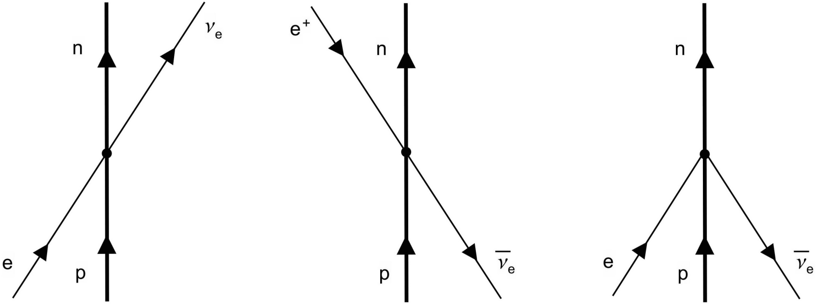


Fig.: The decay is allowed to occur due to the Unruh effect

Setting the stage

Basic assumptions [*Matsas et al. (1999)*]:

- Massless neutrino
- $|\mathbf{k}_e| \sim |\mathbf{k}_{\nu_e}| \ll M_{p,n}$ (*no-recoil approximation*)
- Current-current Fermi theory (*semiclassical description*)

$$\widehat{S}_I = \int d^4x \sqrt{-g}\, \widehat{j}_\mu \left(\widehat{\overline{\Psi}}_\nu \gamma^\mu \widehat{\Psi}_e + \widehat{\overline{\Psi}}_e \gamma^\mu \widehat{\Psi}_\nu \right)$$

$$\widehat{j}^\mu = \widehat{q}(\tau)\, u^\mu\, \delta\left(u - a^{-1}\right), \quad \widehat{q}(\tau) = e^{i\widehat{H}\tau}\, \widehat{q}_0\, e^{-i\widehat{H}\tau}$$

$$\widehat{H}\,|n\rangle = m_n\,|n\rangle\,, \quad \widehat{H}\,|p\rangle = m_p\,|p\rangle\,, \quad G_F = |\langle p|\,\hat{q}_0\,|n\rangle|$$

Laboratory frame

- Tree-level transition amplitude

$$\mathcal{A}^{p\to n} = \langle n| \otimes \langle e^{+}_{k_e\,\sigma_e}, \nu_{k_\nu\,\sigma_\nu}| \widehat{S}_I \,|0\rangle \otimes |p\rangle$$

- Differential transition rate

$$\frac{d^2\mathcal{P}^{p\to n}_{in}}{dk_e dk_\nu} = \frac{1}{2}\sum_{\sigma_e=\pm}\sum_{\sigma_\nu=\pm} |\mathcal{A}^{p\to n}|^2$$

- **Scalar decay rate**

$$\Gamma^{p\to n}_{in} \equiv \frac{\mathcal{P}^{p\to n}_{in}}{T} = \frac{4G_F^2 a}{\pi^2 e^{\pi\Delta m/a}} \int_0^\infty d\tilde{k}_e \int_0^\infty d\tilde{k}_\nu K_{2i\Delta m/a}\left[2\left(\tilde{\omega}_e + \tilde{\omega}_\nu\right)\right]$$

Comoving frame

$$\Gamma^{p\to n}_{com} = \frac{G_F^2\, m_e}{a\,\pi^2\, e^{\pi \Delta m/a}} \int_{-\infty}^{+\infty} d\omega\, \frac{K_{i\omega/a+1/2}(m_e/a) K_{i\omega/a-1/2}(m_e/a)}{\cosh\left[\pi\left(\omega - \Delta m\right)/a\right]}$$

Result

$$\Gamma^{p\to n}_{in} = \Gamma^{p\to n}_{com}$$

Remark

The Unruh effect is **mandatory** for the General Covariance of QFT

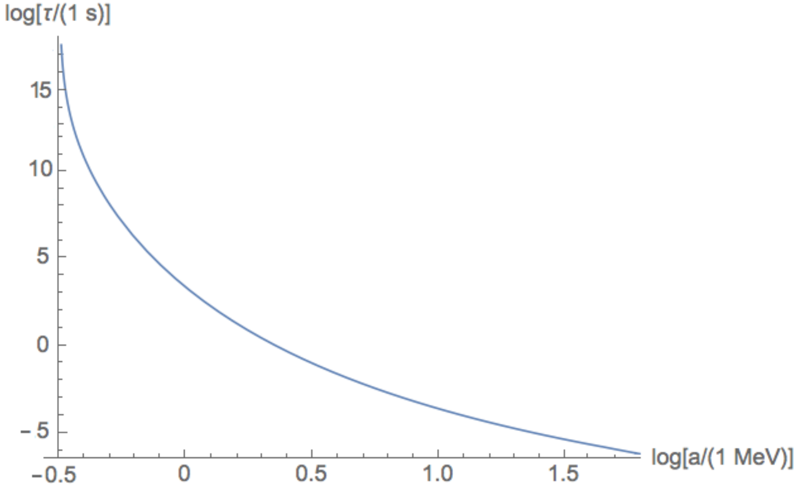


Fig.: The mean proper lifetime τ of the proton versus its proper acceleration a.

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Neutrino mixing in the inverse β-decay [*Ahluwalia et al. (2016)*]

"*In the **laboratory frame**, the interaction is the electroweak vertex, hence neutrinos are **flavor eigenstates**.
In the **comoving frame**, the proton interacts with neutrinos in Rindler states, which display a thermal weight and are **mass eigenstates***".

"*...if flavor eigenstates were the asymptotic states also in the accelerating frame, the **thermality** of the Unruh effect would be **violated***".

"*...we conclude that the rates in the two frames **disagree** when taking into account neutrino mixings*".

The "paladins" of General Covariance of QFT

Non-thermal Unruh effect

Unruh spectrum for **mixed neutrinos** [**G.L.** (2017)]

$$ {}_{\mathrm{M}}\langle 0|\mathcal{N}(\theta,\omega)|0\rangle_{\mathrm{M}} = \underbrace{\frac{1}{e^{a\,\omega/T_{\mathrm{U}}}+1}}_{Thermal\ spectrum} + \underbrace{\sin^2\theta\left\{\mathcal{O}\left(\frac{\delta m}{m}\right)^2\right\}}_{Non-thermal\ corrections} $$

Remark

The Unruh effect for mixed fields is **non-thermal**

Inverse β-decay and neutrino mixing

Neutrino mixing in the inverse β-decay [*Ahluwalia et al. (2016)*]

"*In the laboratory frame, the interaction is the electroweak vertex, hence neutrinos are in **flavor eigenstates**.*
~~*In the comoving frame, the proton interacts with neutrinos in Rindler states, which display an effective thermal weight and are **mass eigenstates***"~~.

$$\mathcal{A}^{p\to n} = \langle n| \otimes \langle e^{+}_{k_e\, \sigma_e}, \nu_{k_\nu\, \sigma_\nu}| \widehat{S}_I\, |0\rangle \otimes |p\rangle$$

$$\boxed{\begin{aligned} |\nu_e\rangle &= |\nu_1\rangle \cos\theta \,+\, |\nu_2\rangle \sin\theta \\ |\nu_\mu\rangle &= -|\nu_1\rangle \sin\theta \,+\, |\nu_2\rangle \cos\theta \end{aligned}}$$

Using asymptotic **flavor neutrinos**, we get in the *laboratory frame*

$$\Gamma^{p\to n}_{in} \;=\; \cos^4\theta\, \Gamma^{p\to n}_{1} \,+\, \sin^4\theta\, \Gamma^{p\to n}_{2} \,+\, \cos^2\theta \sin^2\theta\, \Gamma^{p\to n}_{12}$$

$$\Gamma^{p\to n}_{i} \;\equiv\; \frac{1}{T} \sum_{\sigma_\nu, \sigma_e} {G_F}^2 \int d^3 k_\nu \int d^3 k_e \left|\mathcal{I}_{\sigma_\nu \sigma_e}(\omega_{\nu_i}, \omega_e)\right|^2, \quad i = 1, 2,$$

$$\Gamma^{p\to n}_{12} \;\equiv\; \frac{1}{T} \sum_{\sigma_\nu, \sigma_e} {G_F}^2 \int d^3 k_\nu \int d^3 k_e \left[\mathcal{I}_{\sigma_\nu \sigma_e}(\omega_{\nu_{\mathbf{1}}}, \omega_e)\, \mathcal{I}^*_{\sigma_\nu \sigma_e}(\omega_{\nu_{\mathbf{2}}}, \omega_e) + \mathrm{c.c.}\right]$$

...and in the *comoving frame*

$$\Gamma^{p\to n}_{com} = \cos^4\theta\,\widetilde{\Gamma}^{p\to n}_1 + \sin^4\theta\,\widetilde{\Gamma}^{p\to n}_2 + \cos^2\theta\sin^2\theta\,\widetilde{\Gamma}^{p\to n}_{12}$$

$$\begin{aligned}
\widetilde{\Gamma}^{p\to n}_{12} \quad = \quad & \frac{2\,G_F^2}{a^2\,\pi^7\,\sqrt{l_{\nu_1}l_{\nu_2}}\,e^{\pi\Delta m/a}}\int_{-\infty}^{+\infty} d\omega \left\{\int d^2k_e\, l_e\left|K_{i\omega/a+1/2}\left(\frac{l_e}{a}\right)\right|^2\right.\\
& \times \int d^2k_\nu\left(\kappa_\nu^2 + m_{\nu_1}m_{\nu_2} + l_{\nu_1}l_{\nu_2}\right)\\
& \times \mathrm{Re}\left\{K_{i(\omega-\Delta m)/a+1/2}\left(\frac{l_{\nu_1}}{a}\right)K_{i(\omega-\Delta m)/a-1/2}\left(\frac{l_{\nu_2}}{a}\right)\right\}\\
& + m_e\int d^2k_e\int d^2k_\nu\left(l_{\nu_1}m_{\nu_2} + l_{\nu_2}m_{\nu_1}\right)\\
& \times \mathrm{Re}\left\{K^2_{i\omega/a+1/2}\left(\frac{l_e}{a}\right)K_{i(\omega-\Delta m)/a-1/2}\left(\frac{l_{\nu_1}}{a}\right)\right.\\
& \left.\left.\times\, K_{i(\omega-\Delta m)/a-1/2}\left(\frac{l_{\nu_2}}{a}\right)\right\}\right\}, \qquad \kappa_\nu \equiv (k_\nu^x, k_\nu^y)
\end{aligned}$$

Laboratory vs comoving decay rates

$$\Gamma_{in}^{p\to n} = \cos^4\theta\,\Gamma_1^{p\to n} + \sin^4\theta\,\Gamma_2^{p\to n} + \cos^2\theta\sin^2\theta\,\Gamma_{12}^{p\to n},$$

$$\Gamma_{com}^{p\to n} = \cos^4\theta\,\widetilde{\Gamma}_1^{p\to n} + \sin^4\theta\,\widetilde{\Gamma}_2^{p\to n} + \cos^2\theta\sin^2\theta\,\widetilde{\Gamma}_{12}^{p\to n}$$

$$\Gamma_i^{p\to n} = \widetilde{\Gamma}_i^{p\to n}, \qquad i = 1, 2$$

What about the “off-diagonal” terms?

$$\Gamma_{12}^{p\to n} \stackrel{?}{=} \widetilde{\Gamma}_{12}^{p\to n}$$

Comparing the decay rates

Laboratory vs comoving decay rates

$$\Gamma^{p\to n}_{in} = \cos^4\theta\,\Gamma^{p\to n}_1 + \sin^4\theta\,\Gamma^{p\to n}_2 + \cos^2\theta\sin^2\theta\,\Gamma^{p\to n}_{12},$$

$$\Gamma^{p\to n}_{com} = \cos^4\theta\,\widetilde{\Gamma}^{p\to n}_1 + \sin^4\theta\,\widetilde{\Gamma}^{p\to n}_2 + \cos^2\theta\sin^2\theta\,\widetilde{\Gamma}^{p\to n}_{12}$$

$$\Gamma^{p\to n}_i = \widetilde{\Gamma}^{p\to n}_i, \qquad i = 1, 2$$

What about the "off-diagonal" terms?

$$\Gamma^{p\to n}_{12} \stackrel{?}{=} \widetilde{\Gamma}^{p\to n}_{12}$$

Comparing the decay rates

Non-trivial analytic calculations...

...but, for $\frac{\delta m}{m} \ll 1$

$$\Gamma_{12}^{p\to n} = \widetilde{\Gamma}_{12}^{p\to n} \quad \text{up to } \mathcal{O}\left(\frac{\delta m}{m}\right)$$

Result

$$\Gamma_{in}^{p\to n} = \Gamma_{com}^{p\to n} \quad \text{up to } \mathcal{O}\left(\frac{\delta m}{m}\right)$$

Comparing the decay rates

Non-trivial analytic calculations…

…but, for $\frac{\delta m}{m} \ll 1$

$$\Gamma_{12}^{p\to n} = \widetilde{\Gamma}_{12}^{p\to n} \quad \text{up to } \mathcal{O}\left(\frac{\delta m}{m}\right)$$

Result

$$\Gamma_{in}^{p\to n} = \Gamma_{com}^{p\to n} \quad \text{up to } \mathcal{O}\left(\frac{\delta m}{m}\right)$$

Solving the controversy with **mass eigenstates** [*Matsas et al. (2018)*] ?

" [...] *a physical Fock space for flavor neutrinos cannot be constructed.* ***Flavor states are only phenomenological*** *since their definition depends on the specific process.*"

" *We should view the* ***neutrino states with well defined mass as the fundamental ones****.* [...] *The decay rates calculated in this way are perfectly in agreement*".

Why not mass states?

- A physical Fock space for flavor neutrinos can be rigorously defined [*Blasone and Vitiello (1995)*]

- Mass eigenstates *wipe mixing out* of calculations

$$\Gamma^{p\to n+\bar{\ell}_\alpha+\nu_i} = |U_{\alpha,i}|^2\Gamma_i, \qquad i=1,2$$

- They are inconsistent with the description of *neutrino oscillations*

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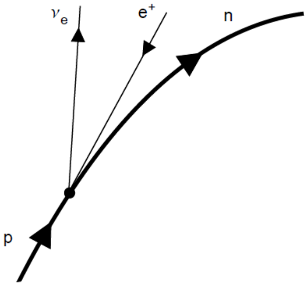
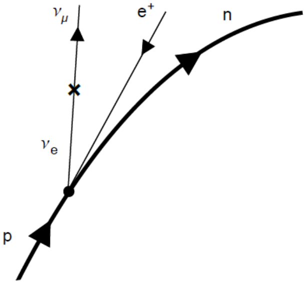
Neutrino oscillations (inertial frame)



a) Without oscillations

$$\Gamma_{in}^{(\nu_e)} = c_\theta^4\,\Gamma_1^{p\to n} + s_\theta^4\,\Gamma_2^{p\to n} + c_\theta^2\,s_\theta^2\,\Gamma_{12}^{p\to n}$$

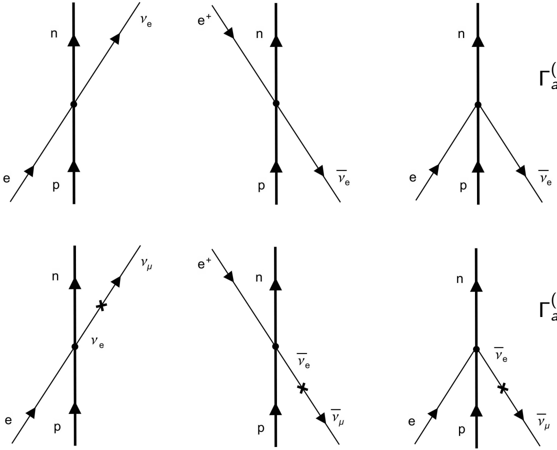


b) With oscillations

$$\Gamma_{in}^{(\nu_\mu)} = c_\theta^2\,s_\theta^2\left(\Gamma_1^{p\to n} + \Gamma_2^{p\to n} - \Gamma_{12}^{p\to n}\right)$$

Total decay rate

$$\Gamma_{in}^{tot} \equiv \Gamma_{in}^{(\nu_e)} + \Gamma_{in}^{(\nu_\mu)} = \cos^2\theta\,\Gamma_1^{p\to n} + \sin^2\theta\,\Gamma_2^{p\to n}$$



a) Without oscillations

$$\Gamma^{(\nu_e)}_{acc} = c^4_\theta\,\widetilde{\Gamma}^{p\to n}_1 + s^4_\theta\,\widetilde{\Gamma}^{p\to n}_2 + c^2_\theta\,s^2_\theta\,\widetilde{\Gamma}^{p\to n}_{12}$$

b) With oscillations

$$\Gamma^{(\nu_\mu)}_{acc} = c^2_\theta\,s^2_\theta\left(\widetilde{\Gamma}^{p\to n}_1 + \widetilde{\Gamma}^{p\to n}_2 - \widetilde{\Gamma}^{p\to n}_{12}\right)$$

Total decay rate

$$\Gamma^{tot}_{acc} = \cos^2\theta\,\widetilde{\Gamma}^{p\to n}_1 + \sin^2\theta\,\widetilde{\Gamma}^{p\to n}_2 = \Gamma^{tot}_{in}$$

- PMNS matrix

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

- Jarlskog invariant (phase-independent parameter)

$$\mathrm{Im}\left[U_{\delta i}\, U^*_{\gamma_i}\, U^*_{\delta j}\, U_{\gamma j}\right] \equiv J \sum_{\lambda, k} \varepsilon_{\delta\gamma\lambda}\, \varepsilon_{ijk}$$

$$\delta, \gamma, \lambda = \{e, \mu, \tau\}, \quad i, j, k = \{1, 2, 3\}$$

- Physics cannot depend on the PMNS matrix parameterization
$\Longrightarrow$ **CP-violation observables** must depend on J solely

- **Mass states** are inconsistent with CP-violation in neutrino oscillations

$$A_{CP}^{(e,j)} = \Gamma_{\nu_e,\nu_j} - \Gamma_{\bar{\nu}_e,\bar{\nu}_j} = |U_{ej}|^2|\mathcal{A}_j|^2 - |U_{ej}^*|^2|\mathcal{A}_j|^2 = 0\,, \quad j = 1,2,3$$

- By contrast, **flavor states** correctly predict CP-violation effects

$$\mathcal{A}_{CP}^{(e,\mu)} \equiv \Gamma_{\nu_e,\nu_\mu} - \Gamma_{\bar{\nu}_e,\bar{\nu}_\mu} = 4J\Big\{-\mathrm{Im}\,[\mathcal{A}_1\mathcal{A}_2^*] + \mathrm{Im}\,[\mathcal{A}_1\mathcal{A}_3^*] - \mathrm{Im}\,[\mathcal{A}_2\mathcal{A}_3^*]\Big\}$$

Three generations and CP-violation

- **Mass states** are inconsistent with CP-violation in neutrino oscillations

$$A_{CP}^{(e,j)} = \xcancel{\Gamma_{\nu_e,\nu_j} - \Gamma_{\bar{\nu}_e,\bar{\nu}_j} = |U_{ej}|^2 |\mathcal{A}_j|^2 - |U_{ej}^*|^2 |\mathcal{A}_j|^2} = 0\,, \qquad j = 1,2,3$$

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$$A_{CP}^{(e,j)} = \cancel{\Gamma_{\nu_e,\nu_j} - \Gamma_{\bar{\nu}_e,\bar{\nu}_j} = |U_{ej}|^2|\mathcal{A}_j|^2 - |U_{ej}^*|^2|\mathcal{A}_j|^2} = 0\,, \qquad j = 1,2,3$$

- By contrast, **flavor states** correctly predict CP-violation effects

$$\mathcal{A}_{CP}^{(e,\mu)} \equiv \Gamma_{\nu_e,\nu_\mu} - \Gamma_{\bar{\nu}_e,\bar{\nu}_\mu} = 4J\Big\{-\mathrm{Im}\left[\mathcal{A}_1\mathcal{A}_2^*\right] + \mathrm{Im}\left[\mathcal{A}_1\mathcal{A}_3^*\right] - \mathrm{Im}\left[\mathcal{A}_2\mathcal{A}_3^*\right]\Big\}$$

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Take-home message

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	Ahluwalia's approach	Matsas's approach	Our approach
Asympt. neutrinos in the laboratory frame	Flavor	Mass	Flavor
Asympt. neutrinos in the comoving frame	Mass	Mass	Flavor
Agreement between the decay rates	✗	✓	✓
Consistency with neutrino oscillations	✗	✗	✓
Consistency with CP-violation	✗	✗	✓

Outlook

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- **Beyond** the l.o. approximation

$$\Gamma_{in}^{p\to n} = \Gamma_{com}^{p\to n} \qquad\qquad \Gamma_{in}^{p\to n} \neq \Gamma_{com}^{p\to n}$$

$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

The paradox would be definitively solved

- Unruh effect for mixed fields is to be revised
- Pontecorvo treatment of mixing is not consistent with QFT

- Extension to **curved background** (gravity effects)
- Application to condensed matter systems (BdG equation for superconductors)


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
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TASHAKKUR ATU
YAQHANYELAY
SUKSAMA
EKHMET
BIYAN
SHUKRIA
TINGKI
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