Theory of Neutrino Oscillations

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- Brief Review of Standard Theory of Neutrino Oscillations in Vacuum.
- Flavor Neutrino States.
- Covariant Plane Wave Neutrino Oscillations in Vacuum.
- Neutrino Production and Detection.
- Questions:
  - Do Charged Leptons Oscillate?
  - Is the Standard Phase Wrong by a Factor of 2?
  - Are Flavor Neutrinos Described by Fock States?

Standard Theory of Neutrino Oscillations in Vacuum

[Eliezer, Swift, NPB 105 (1976) 45] [Fritzsch, Minkowski, PLB 62 (1976) 72] [Bilenky, Pontecorvo, SJNP 24 (1976) 316]
[Bilenky, Pontecorvo, Nuovo Cim. Lett. 17 (1976) 569] [Bilenky, Pontecorvo, Phys. Rep. 41 (1978) 225]

Flavor Neutrino Production: $j_\rho^{CC} = 2 \sum_{\alpha=e,\mu,\tau} \overline{\nu_{\alpha L}} \gamma_\rho \ell_{\alpha L}$

Fields: $\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL} \quad \Rightarrow \quad \overline{\nu_{\alpha L}} = \sum_k U_{\alpha k}^* \overline{\nu_{kL}}$ States: $|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle$

$$\mathcal{H}|\nu_k\rangle = E_k|\nu_k\rangle \quad \Rightarrow \quad |\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle \quad \Rightarrow \quad |\nu_\alpha(t)\rangle = \sum_k U_{\alpha k}^* e^{-iE_k t} |\nu_k\rangle$$

$\uparrow$

$$|\nu_k\rangle = \sum_{\beta=e,\mu,\tau} U_{\beta k} |\nu_\beta\rangle$$

$$|\nu_\alpha(t)\rangle = \sum_{\beta=e,\mu,\tau} \left(\sum_k U_{\alpha k}^* e^{-iE_k t} U_{\beta k} \right) |\nu_\beta\rangle = \sum_{\beta=e,\mu,\tau} \mathcal{A}_{\nu_\alpha \to \nu_\beta}(t) |\nu_\beta\rangle$$

Transition Probability: $P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = |\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t)|^2 = \left| \sum_k U_{\alpha k}^* e^{-iE_k t} U_{\beta k} \right|^2$

$$P_{\nu_\alpha \to \nu_\beta}(t) = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left[-i\left(E_k - E_j\right)t\right]$$

Relativistic Approximation + Assumption $p_k = p = E$ [neutrinos with the same momentum propagate in the same direction]

$$E_k = \sqrt{p^2 + m_k^2} \simeq p + \frac{m_k^2}{2p} = E + \frac{m_k^2}{2E} \implies E_k - E_j \simeq \frac{\Delta m_{kj}^2}{2E}$$

$$\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$$

Approximation $t \simeq L$ $\implies$

$$P_{\nu_\alpha \to \nu_\beta}(L) \simeq \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left[-i\,\frac{\Delta m_{kj}^2 L}{2E}\right]$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2$$ $\Leftarrow$ constant term

$$+ 2\text{Re} \sum_{k>j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i\,\frac{\Delta m_{kj}^2 L}{2E}\right)$$ $\Leftarrow$ oscillating term

$\Updownarrow$

COHERENCE

Main Assumptions of Standard Theory

(A1)

Neutrinos produced in CC weak interaction processes together with charged leptons α^+ are described by the flavor state $|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle$.

Correct approximation for ultrarelativistic ν's.

[Giunti, Kim, Lee, PRD 45 (1992) 2414]
[Giunti, hep-ph/0402217]

(A2)

Massive neutrino states $|\nu_k\rangle$ have the same momentum $p_k = p$ ("Equal Momentum Assumption") and different energies: $E_k \simeq E + \frac{m_k^2}{2E}$.

Unrealistic assumption, forbidden by energy-momentum conservation and Lorentz invariance, but gives correct result (as well as the "Equal Energy Assumption"). Irrelevant in covariant derivation.

[Winter, LNC 30 (1981) 101], [Giunti, Kim, FPL 14 (2001) 213], [Giunti, MPLA 16 (2001) 2363], [Giunti, FPL 17 (2004) 103]

(A3)

Propagation Time $t \simeq L$ Source-Detector Distance.

OK!
$\Updownarrow$
WAVE PACKETS

[Giunti, hep-ph/0402217]

Flavor Neutrino States

QFT: $|f\rangle = \hat{\mathsf{S}}\,|i\rangle$ $\quad |f\rangle = \sum_k \mathcal{A}_k\,|f_k\rangle$ $\quad \mathcal{A}_k = \langle f_k|f\rangle = \langle f_k|\hat{\mathsf{S}}|i\rangle$

consider for example the general decay $\quad P_I \longrightarrow P_F + \ell_\alpha^+ + \nu_\alpha$

$$|f\rangle = \hat{\mathsf{S}}\,|P_I\rangle \qquad |f\rangle = \sum_k \mathcal{A}_{\alpha k}\,|\nu_k, \ell_\alpha^+, P_F\rangle + \ldots = \left(\sum_k \mathcal{A}_{\alpha k}\,|\nu_k\rangle\right)|\ell_\alpha^+, P_F\rangle + \ldots$$

$$\mathcal{A}_{\alpha k} = \langle \nu_k, \ell_\alpha^+, P_F|f\rangle = \langle \nu_k, \ell_\alpha^+, P_F|\,\hat{\mathsf{S}}\,|P_I\rangle$$

normalized final state: $\quad |\nu_\alpha, \ell_\alpha^+, P_F\rangle = \left(\sum_k |\mathcal{A}_{\alpha k}|^2\right)^{-1/2} \left(\sum_k \mathcal{A}_{\alpha k}\,|\nu_k\rangle\right)|\ell_\alpha^+, P_F\rangle$

$$\Downarrow$$

$$|\nu_\alpha\rangle = \left(\sum_k |\mathcal{A}_{\alpha k}|^2\right)^{-1/2} \sum_k \mathcal{A}_{\alpha k}\,|\nu_k\rangle$$

[Giunti, hep-ph/0402217]

a flavor neutrino state is a coherent superposition of massive neutrino states $|\nu_k\rangle$ with coefficients $\mathcal{A}_{\alpha k}$ given by the process-dependent amplitudes of production of ν_k

$$\hat{\mathsf{S}} = 1 - i \int \mathrm{d}^4x \, \mathcal{H}_{\mathrm{I}}^{\mathrm{CC}}(x)$$

$$\mathcal{H}_{\mathrm{I}}^{\mathrm{CC}}(x) = \frac{G_{\mathrm{F}}}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \overline{\nu_\alpha}(x) \, \gamma^\rho \left(1 - \gamma^5\right) \ell_\alpha(x) \, J_\rho^{P_I \to P_F}(x) + \text{h.c.}$$

$$= \frac{G_{\mathrm{F}}}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \sum_k U_{\alpha k}^* \, \overline{\nu_k}(x) \, \gamma^\rho \left(1 - \gamma^5\right) \ell_\alpha(x) \, J_\rho^{P_I \to P_F}(x) + \text{h.c.}$$

$$\mathcal{A}_{\alpha k} = \langle \nu_k, \ell_\alpha^+, P_F | \, \hat{\mathsf{S}} \, | P_I \rangle = U_{\alpha k}^* \, \mathcal{M}_{\alpha k}$$

with $$\mathcal{M}_{\alpha k} = -i \frac{G_{\mathrm{F}}}{\sqrt{2}} \int \mathrm{d}^4x \, \langle \nu_k, \ell_\alpha^+, P_F | \overline{\nu_k}(x) \, \gamma^\rho \left(1 - \gamma^5\right) \ell_\alpha(x) \, J_\rho^{P_I \to P_F}(x) \, | P_I \rangle$$

$$|\nu_\alpha\rangle = \sum_k \frac{\mathcal{M}_{\alpha k}}{\sqrt{\sum_j |U_{\alpha j}|^2 \, |\mathcal{M}_{\alpha j}|^2}} \, U_{\alpha k}^* \, |\nu_k\rangle$$

in experiments which are not sensitive to the dependence of $\mathcal{M}_{\alpha k}$ on the different neutrino masses

$$\mathcal{M}_{\alpha k} \simeq \mathcal{M}_\alpha \quad \Longrightarrow \quad \boxed{|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* \, |\nu_k\rangle}$$

standard flavor states

Covariant Plane Wave Neutrino Oscillations in Vacuum

flavor is a Lorentz-invariant quantity

$\Downarrow$

the probability of flavor neutrino oscillations is Lorentz invariant

$\Downarrow$

a covariant derivation of neutrino oscillations is needed

$\Downarrow$

$$P_{\nu_\alpha \to \nu_\beta}(T, L) = |\langle \nu_\beta | e^{-i\hat{\mathsf{E}}T + i\hat{\mathsf{P}}L} | \nu_\alpha \rangle|^2 = \left| \sum_k U_{\beta k} \, e^{-iE_k T + i p_k L} \, U_{\alpha k}^* \right|^2$$

LORENTZ INVARIANT OSCILLATION PROBABILITY

[Dolgov, Morozov, Okun, Shchepkin, NPB 502 (1997) 3] [Giunti, Kim, FPL 14 (2001) 213] [Bilenky, Giunti, IJMPA 16 (2001) 3931]

[Dolgov, Phys. Rept. 370 (2002) 333] [Beuthe, Phys. Rept. 375 (2003) 105] [Giunti, hep-ph/0402217]

$$P_{\nu_\alpha \to \nu_\beta}(T, L) = \left| \sum_k U_{\beta k} \, e^{-iE_k T + ip_k L} \, U_{\alpha k}^* \right|^2$$

ultrarelativistic neutrinos $\implies$ $T = L$

$$E_k T - p_k L = (E_k - p_k) \, L = \frac{E_k^2 - p_k^2}{E_k + p_k} \, L = \frac{m_k^2}{E_k + p_k} \, L \simeq \frac{m_k^2}{2E} \, L$$

assumptions on the values of E_k and p_k are not needed!

$$P_{\nu_\alpha \to \nu_\beta}(L) = \left| \sum_k U_{\alpha k}^* \, U_{\beta k} \, e^{-im_k^2 L/2E} \right|^2$$

$$= \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\mathrm{Re} \sum_{k>j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i \, \frac{\Delta m_{kj}^2 L}{2E} \right)$$

STANDARD OSCILLATION PROBABILITY!

Lorentz Invariance of Standard Oscillation Probability

$$P_{\nu_\alpha\to\nu_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\text{Re} \sum_{k>j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$$

$\mathcal{O}'$ moves with respect to $\mathcal{O}$ with velocity v along the direction of neutrino propagation

$$L' = \gamma\,(L - v\,T) \qquad T' = \gamma\,(-v\,L + T)$$

$$L = T \quad \Longrightarrow \quad L' = T' = \gamma\,(1 - v)\,L$$

$$p' = \gamma\,(p - v\,E) \qquad E' = \gamma\,(-v\,p + E)$$

$$E = p \quad \Longrightarrow \quad E' = p' = \gamma\,(1 - v)\,E$$

$\frac{L}{E}$ IS LORENTZ INVARIANT!

[Giunti, physics/0305122]

Neutrino Production and Detection

number of transition events in a neutrino oscillation experiment

$$N_{\nu_\alpha \to \nu_\beta}(L) \propto \Gamma_\alpha \, P_{\nu_\alpha \to \nu_\beta}(L) \, \sigma_\beta \qquad \Gamma_\alpha = \sum_k \Gamma_{\alpha k} \qquad \sigma_\beta = \sum_k \sigma_{\beta k}$$

incoherent sums over the channels corresponding to different massive neutrinos which are the physical particles that propagate in space-time

consistent with

$$|\nu_\alpha\rangle = \left(\sum_k |\mathcal{A}_{\alpha k}|^2 \right)^{-1/2} \sum_k \mathcal{A}_{\alpha k} \, |\nu_k\rangle$$

? Yes:

$$\mathcal{A}_\alpha = \langle \nu_\alpha, \ell_\alpha^+, P_F | \, \hat{\mathsf{S}} \, | P_I \rangle = \left(\sum_k |\mathcal{A}_{\alpha k}|^2 \right)^{-1/2} \sum_k \mathcal{A}_{\alpha k}^* \, \langle \nu_k, \ell_\alpha^+, P_F | \hat{\mathsf{S}} | P_I \rangle = \left(\sum_k |\mathcal{A}_{\alpha k}|^2 \right)^{1/2}$$

$$|\mathcal{A}_\alpha|^2 = \sum_k |\mathcal{A}_{\alpha k}|^2 \quad \Longrightarrow \quad \Gamma_\alpha = \sum_k \Gamma_{\alpha k}$$

the coherent character of flavor states is irrelevant for decay probabilities and cross sections

[Giunti, hep-ph/0402217]

Q: Do Charged Leptons Oscillate?

the flavor of a charged lepton is defined by its mass!

mass is the only property which distinguishes e, μ, τ

charged leptons have definite mass $\Longrightarrow$ NO OSCILLATIONS!

[Giunti, Kim, FPL 14 (2001) 213]

a misleading argument

[Sassaroli, Srivastava, Widom, hep-ph/9509261] [Srivastava, Widom, hep-ph/9707268] [Srivastava, Widom, Sassaroli, EPJC 2 (1998) 769]

in $\pi^- \to \mu^- + \bar{\nu}_\mu$ the final state of the muon and antineutrino is entangled

$\Downarrow$

if the probability to detect the antineutrino oscillates as a function of distance, also the probability to detect the muon must oscillate

WRONG!

the probability to detect the antineutrino doe not oscillate as a function of distance

$$\sum_\beta P_{\bar{\nu}_\mu \to \bar{\nu}_\beta} = 1$$

conservation of probability (unitarity)

[Dolgov, Morozov, Okun, Shchepkin, NPB 502 (1997) 3] [Giunti, Kim, FPL 14 (2001) 213]

Λ oscillations from $\pi^- + p \to \Lambda + K^0$: [Widom, Srivastava, hep-ph/9605399] [Srivastava, Widom, Sassaroli, PLB 344 (1995) 436]

refuted in [Lowe et al., PLB 384 (1996) 288] [Burkhardt, Lowe, Stephenson, Goldman, PRD 59 (1999) 054018]

Q: Is the Standard Phase Wrong by a Factor of 2?

[Field, hep-ph/0110064] [Field, hep-ph/0110066] [Field, EPJC 30 (2003) 305] [Field, hep-ph/0303151]

$K^0 - \bar{K}^0$: [Srivastava, Widom, Sassaroli, ZPC 66 (1995) 601] [Srivastava, Widom, Sassaroli, PLB 344 (1995) 436] [Widom, Srivastava, hep-ph/9605399]

massive neutrinos propagate with velocities $v_k = \dfrac{p_k}{E_k} \implies t_k = \dfrac{L}{v_k} = \dfrac{E_k}{p_k} L$

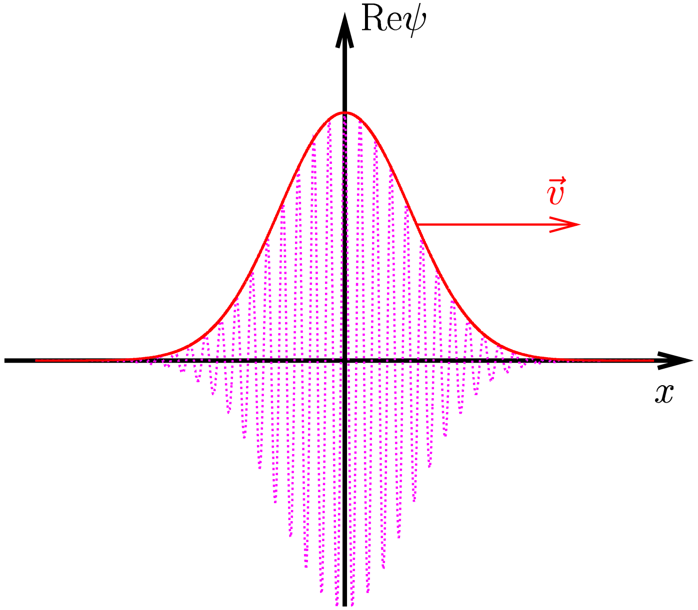
phases: $$\widetilde{\Phi}_k = p_k L - E_k t_k = p_k L - \frac{E_k^2}{p_k} L = \frac{p_k^2 - E_k^2}{p_k} L = \frac{m_k^2}{p_k} L \simeq \frac{m_k^2}{E} L$$

$$\Delta\widetilde{\Phi}_{kj} = -\frac{\Delta m_{kj}^2 L}{E}$$ twice the standard phase $$\Delta\Phi_{kj} = -\frac{\Delta m_{kj}^2 L}{2E}$$

WRONG!

group velocities are irrelevant for the phase!

group velocity is the velocity
of the factor which modulates
the amplitude of the wave packet



in the plane wave approximation the interference of different massive neutrino contribution must be calculated at a definite space distance L and after a definite time interval T

[Nieto, hep-ph/9509370] [Kayser, Stodolsky, PLB 359 (1995) 343] [Lowe et al., PLB 384 (1996) 288] [Kayser, hep-ph/9702327]

[Giunti, Kim, FPL 14 (2001) 213] [Giunti, Physica Scripta 67 (2003) 29] [Burkhardt, Lowe, Stephenson, Goldman, PLB 566 (2003) 137]

$$\Delta\widetilde{\Phi}_{kj} = \left(p_k - p_j\right) L - \left(E_k - E_j\right) t_k$$ WRONG!

$$\Delta\Phi_{kj} = \left(p_k - p_j\right) L - \left(E_k - E_j\right) T$$ CORRECT!

no factor of 2 ambiguity claimed in

[Lipkin, PLB 348 (1995) 604] [Grossman, Lipkin, PRD 55 (1997) 2760] [Lipkin, hep-ph/9901399]

[De Leo, Ducati, Rotelli, MPLA 15 (2000) 2057] [De Leo, Nishi, Rotelli, hep-ph/0208086] [De Leo, Nishi, Rotelli, hep-ph/0303224]

Q: Are Flavor Neutrinos Described by Fock States?

the flavor state

$$|\nu_\alpha\rangle = \left(\sum_k |\mathcal{A}_{\alpha k}|^2\right)^{-1/2} \sum_k \mathcal{A}_{\alpha k} |\nu_k\rangle \simeq \sum_k U^*_{\alpha k} |\nu_k\rangle$$

is not a quantum of the flavor field ν_α!

[Giunti, Kim, Lee, PRD 45 (1992) 2414]

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however, it is possible to construct Fock states of flavor fields

[Blasone, Vitiello, Ann. Phys. 244 (1995) 283] [Blasone, Henning, Vitiello, PLB 451 (1999) 140] [Blasone, Vitiello, PRD 60 (1999) 111302]

[Fujii, Habe, Yabuki, PRD 59 (1999) 113003] [Fujii, Habe, Yabuki, PRD 64 (2001) 013011] [Blasone, Capolupo, Vitiello, PRD 66 (2002) 025033]

$$\nu_\alpha(x) = \int \frac{\mathrm{d}\vec{p}}{(2\pi)^{3/2}} \sum_{h=\pm1} \left[a_{\nu_\alpha}(\vec{p},h)\, u_{\nu_\alpha}(\vec{p},h)\, e^{-iE_{\nu_\alpha} t + i\vec{p}\vec{x}} + b^\dagger_{\nu_\alpha}(\vec{p},h)\, v_{\nu_\alpha}(\vec{p},h)\, e^{iE_{\nu_\alpha} t - i\vec{p}\vec{x}} \right]$$

$$E_{\nu_\alpha} = \sqrt{\vec{p}^{\,2} + \widetilde{m}^2_{\nu_\alpha}} \qquad (\not{p} - \widetilde{m}_{\nu_\alpha})\, u_{\nu_\alpha}(\vec{p},h) = 0 \qquad (\not{p} + \widetilde{m}_{\nu_\alpha})\, v_{\nu_\alpha}(\vec{p},h) = 0$$

arbitrary definitions with arbitrary unphysical mass parameters $\widetilde{m}_{\nu_\alpha}$

$$a_{\nu_\alpha}(\vec{p},h) = \int \frac{\mathrm{d}\vec{x}}{(2\pi)^{3/2}}\, e^{iE_{\nu_\alpha}t - i\vec{p}\vec{x}}\, u^\dagger_{\nu_\alpha}(\vec{p},h)\, \nu_\alpha(x)$$

$$\begin{aligned} a_{\nu_\alpha}(\vec{p},h) = e^{iE_{\nu_\alpha}t} \sum_k U_{\alpha k} \Big[& a_{\nu_k}(\vec{p},h) \left(u^\dagger_{\nu_\alpha}(\vec{p},h)\, u_{\nu_k}(\vec{p},h) \right) e^{-iE_{\nu_k}t} \\ & + b^\dagger_{\nu_k}(-\vec{p},h) \left(u^\dagger_{\nu_\alpha}(\vec{p},h)\, v_{\nu_k}(-\vec{p},h) \right) e^{iE_{\nu_k}t} \Big] \end{aligned}$$

$$b_{\nu_\alpha}(\vec{p},h) = \int \frac{\mathrm{d}\vec{x}}{(2\pi)^{3/2}}\, \nu^\dagger_\alpha(x)\, v_{\nu_\alpha}(\vec{p},h)\, e^{iE_{\nu_\alpha}t - i\vec{p}\vec{x}}$$

$$\begin{aligned} b_{\nu_\alpha}(\vec{p},h) = e^{iE_{\nu_\alpha}t} \sum_k U^*_{\alpha k} \Big[& a^\dagger_{\nu_k}(-\vec{p},h) \left(u^\dagger_{\nu_k}(-\vec{p},h)\, v_{\nu_\alpha}(\vec{p},h) \right) e^{iE_{\nu_k}t} \\ & + b_{\nu_k}(\vec{p},h) \left(v^\dagger_{\nu_k}(\vec{p},h)\, v_{\nu_\alpha}(\vec{p},h) \right) e^{-iE_{\nu_k}t} \Big] \end{aligned}$$

$$\{a_{\nu_\alpha}(\vec{p},h)\,,\, a^\dagger_{\nu_\beta}(\vec{p}\,',h')\} = \{b_{\nu_\alpha}(\vec{p},h)\,,\, b^\dagger_{\nu_\beta}(\vec{p}\,',h')\} = \delta(\vec{p}-\vec{p}\,')\,\delta_{hh'}\,\delta_{\alpha\beta}$$

canonical anticommutation relations $\Longrightarrow$ Fock space of flavor neutrinos exists!

$a_{\nu_\alpha}(\vec{p},h)\,|0\rangle \neq 0$ $\quad$ $b_{\nu_\alpha}(\vec{p},h)\,|0\rangle \neq 0$ $\Longrightarrow$ flavor vacuum $\neq$ mass vacuum

infinity of flavor vacua and Fock spaces of flavor neutrinos
depending on the values of the arbitrary parameters $\widetilde{m}_{\nu_\alpha}$

flavor vacuums: $a_{\nu_\alpha}(\vec{p},h)\,|0_{\{\widetilde{m}\}}\rangle = 0 \qquad b_{\nu_\alpha}(\vec{p},h)\,|0_{\{\widetilde{m}\}}\rangle = 0$

can flavor Fock states describe real neutrinos? No!

☹ arbitrary and non unique construction

☹ measurable quantities depend on the arbitrary unphysical mass parameter $\widetilde{m}_{\nu_\mu}$

Example: $\pi^+ \to \mu^+ + \nu_\mu \qquad |\nu_\mu(\vec{p},h)\rangle = a_\mu^\dagger(\vec{p},h)\,|0_{\{\widetilde{m}\}}\rangle \qquad E_{\nu_\mu} = \sqrt{\vec{p} + \widetilde{m}^2_{\nu_\mu}}$

$$\mathcal{A} = \langle \mu^+(\vec{p}_\mu, h_\mu), \nu_\mu(\vec{p},h)| - i \int \mathrm{d}^4x\, \mathcal{H}_\mathrm{I}(x)\, |\pi^+(\vec{p}_\pi)\rangle$$

$$\mathcal{A} = 2\pi \frac{G_F}{\sqrt{2}}\, \vec{p}_{\pi\rho}\, f_\pi\, \cos\vartheta_C\, \delta^4(p_\pi - p_\mu - p)\, \overline{u_{\nu_\mu}}(\vec{p},h)\, \gamma^\rho\, (1-\gamma_5)\, v_\mu(\vec{p}_\mu, h_\mu)$$

flavor neutrino Fock spaces are clever mathematical constructs
without physical relevance

[Giunti, hep-ph/0312256]

Conclusions

- The flavor neutrino states $|\nu_\alpha\rangle = \left(\sum_k |\mathcal{A}_{\alpha k}|^2 \right)^{-1/2} \sum_k \mathcal{A}_{\alpha k} |\nu_k\rangle$ are appropriate for the description of flavor neutrino production, oscillations and detection.
- The Lorentz-invariant oscillation probability can be derived in a covariant way.
- Charged leptons do not oscillate.
- The standard phase of neutrino oscillations is correct.
- Flavor neutrinos are not described by Fock states.

Neutrino Unbound

http://www.nu.to.infn.it

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