Gravity, entanglement, and $\mathcal{CPT}$ violation in particle mixing

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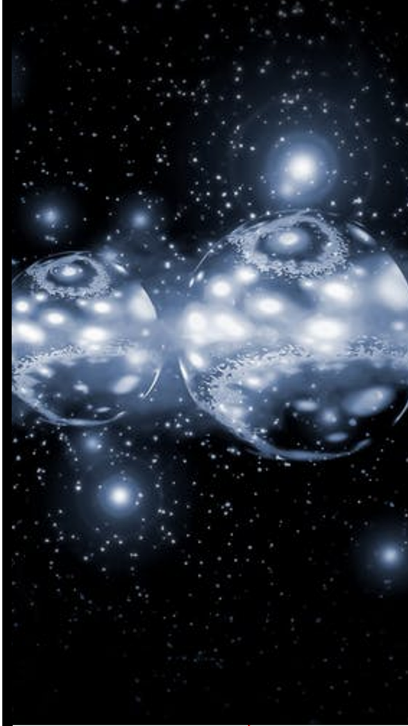

States of the art

- **particle mixing and oscillations: neutral kaons, B-mesons, neutrinos, neutrons, ...**
- physical fields are superpositions of free fields with different masses,
- small $\triangle m \longrightarrow$ weak perturbations are also relevant,
- idea: a system where the intensity of g. interaction depends on internal degrees of freedom,
- gravity is considered as one of the possible sources of decoherence in flavor oscillations that leads to many interesting effects, in particular, $\mathcal{CPT}$ violation.

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One flavored particle: Evolution

Mixing relations:

$$\begin{aligned} |n_A\rangle &= \cos\theta|m_1\rangle + e^{i\phi}\sin\theta|m_2\rangle, \\ |n_B\rangle &= -e^{-i\phi}\sin\theta|m_1\rangle + \cos\theta|m_2\rangle. \end{aligned}$$

Hamiltonian:

$$\hat{H}^{(1)} = E + \frac{c^2}{2E}\sum_{i=1,2} m_i^2 |m_i\rangle\langle m_i|. \quad (1)$$

Modified Hamiltonian:

$$\begin{aligned} \hat{H}^{(1)} &= \omega_0 \hat{\sigma}^z, \\ \omega_0 &= \frac{c^2}{2E}(m_1^2 - m_2^2), \\ \hat{\sigma}^z &= |m_1\rangle\langle m_1| - |m_2\rangle\langle m_2|. \end{aligned} \quad (2)$$

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$$P_{n_A \to n_B}(t) = \sin^2(2\theta)\sin^2(\omega_0 t), \quad (3)$$

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$\mathcal{T}$-symmetry is conserved!

Two flavored particles: Evolution

$$\hat{H}^{(2)} = \hat{H}_a^{(1)} + \hat{H}_b^{(1)} - \sum_{i,j=1,2} \frac{G m_i m_j}{d} |m_i, m_j\rangle\langle m_i, m_j|. \quad (5)$$

Modified Hamiltonian:

$$\begin{aligned} \hat{H}^{(2)} &= \omega(\hat{\sigma}_a^z + \hat{\sigma}_b^z) + \Omega \hat{\sigma}_a^z \hat{\sigma}_b^z, \\ \omega &= \omega_0 + g(m_1^2 - m_2^2), \\ \Omega &= g(m_1 - m_2)^2, \\ g &= -\frac{G}{4d}. \end{aligned}$$

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Interaction

Two flavored particles: Entanglement

Initial state:

$$|\psi(0)\rangle = |\boldsymbol{n}_\eta\rangle \otimes |\boldsymbol{n}_\chi\rangle. \tag{6}$$

We can measure the entanglement between the particles through:

$$\underbrace{\mathcal{P}(\rho_i(t)) = \mathrm{Tr}(\rho_i^2(t))}_{\text{purity of } \rho_i(t) = \mathrm{Tr}_j(|\psi(t)\rangle\langle\psi(t)|)} \implies \underbrace{S_2 = -\ln(\mathcal{P}(\rho_a(t)))}_{\text{2-Renyi entropy}} \tag{7}$$

Purity:

$$\mathcal{P}(\rho_i(t)) = 1 - \frac{1}{2}\sin^4(2\theta)\sin^2(2\Omega t). \tag{8}$$

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$$\left.\begin{array}{l} \theta \neq \frac{\pi n}{2} \text{ (flavor mixing)} \\ t \neq \frac{\pi n}{2\Omega} \\ n \in \mathbb{Z} \end{array}\right\} \implies |\psi(t)\rangle \text{ is entangled}$$

Two flavored particles: Oscillations

$$P_{n_A \to n_B}(t) = \frac{1}{2}\sin^2(2\theta)[1 - \cos(2\omega t)\cos(2\Omega t) + \cos(2\theta)\sin(2\omega t)\sin(2\Omega t)], \quad (9)$$

$$P_{n_B \to n_A}(t) = \frac{1}{2}\sin^2(2\theta)[1 - \cos(2\omega t)\cos(2\Omega t) - \cos(2\theta)\sin(2\omega t)\sin(2\Omega t)]. \quad (10)$$

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$\mathcal{T}$ violation:

$$\Delta_{\mathcal{T}}(t) = \sin^2(2\theta)\cos(2\theta)\sin(2\omega t)\sin(2\Omega t)$$

Two flavored particles: Oscillations

TOO WEAK!

Solution: considering more particles

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N flavored particles: Evolution

Hamiltonian:

$$\begin{aligned}
\hat{H}^{(2)} &= \sum_i \omega_i \hat{\sigma}_i^z + \sum_{i,j} \Omega_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z, \\
\omega_i &= \omega_0 + \sum_j g_{ij}(m_1^2 - m_2^2), \\
\Omega_{ij} &= g_{ij}(m_1 - m_2)^2, \\
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N flavored particles: Entanglement

Initial state:

$$|\psi(0)\rangle = \otimes_{i=1}^{M} |n_A\rangle_i \otimes_{j=M+1}^{N} |n_B\rangle_j. \quad (11)$$

Reduced density matrix:

$$\rho_i(t) = \frac{1}{2}\begin{pmatrix} 1+\zeta_i\cos(2\theta) & \zeta_i e^{-i\phi}\sin(2\theta)a_i^*(t) \\ \zeta_i e^{i\phi}\sin(2\theta)a_i(t) & 1-\zeta_i\cos(2\theta) \end{pmatrix}, \quad (12)$$

$$a_i(t) = e^{i\omega_i t}\prod_{j=1}^{N}\Big(\cos(2\Omega_{ij}t)+i\zeta_j\cos(2\theta)\sin(2\Omega_{ij}t)\Big),$$

$$\zeta_i = \mathrm{sgn}(M-i).$$

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N flavored particles: Oscillations

For $|\psi(0)\rangle = \otimes_{i=1}^{N} |n_{A/B}\rangle_i$:

$$P_{n_A \to n_B}(t) = \frac{1}{2}\sin^2(2\theta)[1 - \frac{1}{N}\sum_i \mathrm{Re}(a_i^{(A)}(t))],$$
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For small $\Omega_{ij} t$:

$$\Delta_{\mathcal{T}}(t) = \sin^2(2\theta)\cos(2\theta)\frac{2t}{N}\sum_{i,j=1}^{N}\sin(2\omega_i t)\Omega_{ij}$$
$$= \sin^2(2\theta)\cos(2\theta)2N\langle\sin(2\omega_i t)\Omega_{ij}\rangle_{ij} t. \quad (14)$$

For $|\psi(0)\rangle = \otimes_{i=1}^{N/2} |n_A\rangle_i \otimes_{j=N/2+1}^{N} |n_B\rangle_j$:

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many-body effect

Outlook

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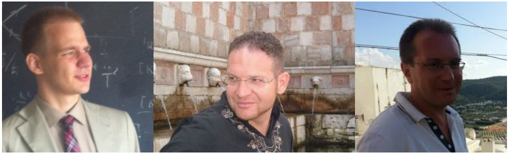

THANK YOU FOR YOUR ATTENTION!

K. Simonov, A. Capolupo, and S. M. Giampaolo, arXiv:1903.10266 (2019).