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INFN Gruppo Collegato di Salerno Sezione di Napoli Istituto Nazionale di Fisica Nucleare

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

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ECT*, Trento, Italy
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State 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:

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

Modified Hamiltonian:

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

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Pontecorvo formula:

$$P_{n_A \to n_B}(t) = \sin^2(2\theta)\sin^2(\omega_0 t), \quad (3)$$
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$\mathcal{T}$-symmetry is conserved!

Two flavored particles: Evolution

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

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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:

$$\underbrace{\mathcal{P}(\rho_{\boldsymbol{i}}(\boldsymbol{t})) = \mathrm{Tr}(\rho_{\boldsymbol{i}}^2(\boldsymbol{t}))}_{\text{purity of } \rho_{\boldsymbol{i}}(\boldsymbol{t}) = \mathrm{Tr}_{\boldsymbol{j}}(|\psi(\boldsymbol{t})\rangle\langle\psi(\boldsymbol{t})|)} \implies \underbrace{\boldsymbol{S}_2 = -\ln(\mathcal{P}(\rho_{\boldsymbol{a}}(\boldsymbol{t})))}_{\text{2-Renyi entropy}} \tag{7}$$

Purity:

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

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

Two flavored particles: Oscillations

$$
\begin{aligned}
\boldsymbol{P}_{\boldsymbol{n_A}\to\boldsymbol{n_B}}(\boldsymbol{t}) &= \frac{1}{2}\sin^2(2\theta)[1-\cos(2\omega\boldsymbol{t})\cos(2\Omega\boldsymbol{t}) \\
&\quad + \cos(2\theta)\sin(2\omega\boldsymbol{t})\sin(2\Omega\boldsymbol{t})], \qquad (9) \\
\boldsymbol{P}_{\boldsymbol{n_B}\to\boldsymbol{n_A}}(\boldsymbol{t}) &= \frac{1}{2}\sin^2(2\theta)[1-\cos(2\omega\boldsymbol{t})\cos(2\Omega\boldsymbol{t}) \\
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$$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)$$

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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

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

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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), \\
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N flavored particles: Entanglement

Initial state:

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

Reduced density matrix:

$$\begin{aligned} \rho_i(t) &= \frac{1}{2}\begin{pmatrix} 1+\zeta_i\cos(2\theta) & \zeta_i e^{-i\phi}\sin(2\theta)a_i^*(t) \\ \zeta_i e^{i\phi}\sin(2\theta)a_i(t) & 1-\zeta_i\cos(2\theta) \end{pmatrix}, \\ a_i(t) &= e^{i\omega_i t}\prod_{j=1}^{N}\Big(\cos(2\Omega_{ij}t)+i\zeta_j\cos(2\theta)\sin(2\Omega_{ij}t)\Big), \\ \zeta_i &= \mathrm{sgn}(M-i). \end{aligned} \tag{12}$$

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N flavored particles: Oscillations

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

$$\begin{aligned} P_{n_A \to n_B}(t) &= \frac{1}{2}\sin^2(2\theta)[1 - \frac{1}{N}\sum_i \mathrm{Re}(a_i^{(A)}(t))], \\ P_{n_B \to n_A}(t) &= \frac{1}{2}\sin^2(2\theta)[1 - \frac{1}{N}\sum_i \mathrm{Re}(a_i^{(B)}(t))]. \end{aligned}$$

For small $\Omega_{ij} t$**:**

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

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

$$\Delta_{\mathcal{T}} \sim \sqrt{N}. \tag{15}$$

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many-body effect

Outlook

- Gravity in a a system of mixed self-interacting particles leads to a $\mathcal{CPT}$ violation.
- The $\mathcal{CPT}$ violation is related to a non-zero entanglement among the particles due to the non-zero mass difference.
- In contrast to the open system approach, the $\mathcal{CPT}$ violation is caused by a $\mathcal{T}$ violation.
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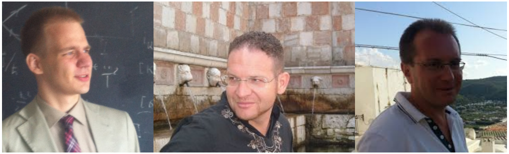

THANK YOU FOR YOUR ATTENTION!

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