Observability of spontaneous collapse

and its relation to CP and CPT symmetries

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Collapse models

Quantum state equation:

$$d|\psi_t\rangle = [-i\hat{H}dt + \sqrt{\lambda}\sum_i(\hat{A}_i - \underbrace{\langle\hat{A}_i\rangle_t}_{nonlin})\underbrace{dW_{i,t}}_{stoch} - \frac{\lambda}{2}\sum_i(\hat{A}_i - \underbrace{\langle\hat{A}_i\rangle_t}_{nonlin})^2]|\psi_t\rangle,$$

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Master equation for $\rho_t = \mathbb{E}[|\psi_t\rangle\langle\psi_t|]$**:**

$$\frac{d\rho_t}{dt} = -i[\hat{H}, \rho_t] - \underbrace{\frac{\lambda}{2}\sum_i\left[\hat{A}_i^2\rho + \rho\hat{A}_i^2 - 2\hat{A}_i\rho\hat{A}_i\right]}_{Lindblad\ evolution},$$

Mass-proportional CSL model:

$$\hat{A} = \frac{1}{(\sqrt{2\pi}r_C)^3}\int dy e^{-\frac{|x-y|^2}{2r_C^2}}\sum_i \frac{m_i}{m_0}\psi_i^\dagger(y)\psi_i(y),$$

Neutral kaons in Wigner–Weisskopf (WWA) framework

WWA Hamiltonian: $\hat{H}_{WWA} = \underbrace{\hat{M}}_{\text{mass}} + \underbrace{\frac{i}{2}\hat{\Gamma}}_{\text{decay}}$

with $|I\rangle = \frac{1}{\sqrt{2}}(|K^0\bar{K}^0\rangle - |\bar{K}^0 K^0\rangle)$

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Single-particle evolution:

$$P_{K^0\to K^0/\bar{K}^0}(t) = \frac{e^{-\Gamma t}}{2}\left(\cosh\left[\frac{\Delta\Gamma}{2}t\right] \pm \underbrace{\cos[t\Delta m]}_{\text{oscillations!}}\right)$$

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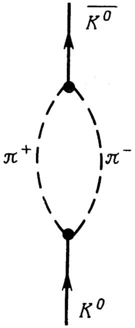

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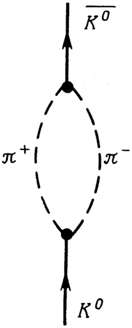
In KLOE:

$$P_{I \to K^0\bar{K}^0/K^0\bar{K}^0}(t_1, t_2) = \frac{e^{-\Gamma t}}{4}\left(\cosh\left[\frac{\Delta\Gamma}{2}\Delta t\right] + \cos[\Delta t \Delta m]\right)$$

with $|I\rangle = \frac{1}{\sqrt{2}}(|K^0\bar{K}^0\rangle - |\bar{K}^0K^0\rangle)$



CSL collapse in flavor oscillations

Single particle:

$$P_{K^0 \to K^0/\bar{K}^0}(t) = \frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) + e^{-\frac{\Lambda}{2}t}\cos(\Delta m t)\right],$$

Two particles:

$$P_{I \to K^0\bar{K}^0/\bar{K}^0 K^0}(t_1, t_2) = \frac{e^{-\Gamma(t_1+t_2)}}{4}\left[\cosh\left(\frac{\Delta\Gamma \Delta t}{2}\right) + e^{-\frac{\Lambda}{2}(t_1+t_2)}\cos(\Delta m \Delta t)\right],$$

Here $\Lambda = \lambda_{CSL}\frac{(\Delta m)^2}{m_0^2} \propto 10^{-38}s^{-1}$ is too weak!

S. Donadi, A. Bassi, C. Curceanu, A. Di Domenico, and B. C. Hiesmayr, *"Are Collapse Models Testable via Flavor Oscillations?"*, Found. Phys. **43**, 813 (2013).
M. Bahrami, S. Donadi, L. Ferialdi, A. Bassi, C. Curceanu, A. Di Domenico, and B. C. Hiesmayr, *"Are collapse models testable with quantum oscillating systems?"*, Sci. Rep. **3**, 1952 (2013).

CSL collapse with time-asymmetric noise

$\int_0^t dt_1 \int_0^{t_1} dt_2 \mathbb{E}[dW_{t_1} dW_{t_2}] = (1 - \beta) t$

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$P(t) = \frac{e^{-\tilde{\Gamma} t}}{2}[\cosh\left(\frac{\Delta\tilde{\Gamma} t}{2}\right) + e^{-\frac{\Lambda}{2}t}\cos(\Delta m t)]$

Decay: $\tilde{\Gamma}_i = \lambda_{CSL}(2\beta - 1)\frac{m_i^2}{m_0^2}$.

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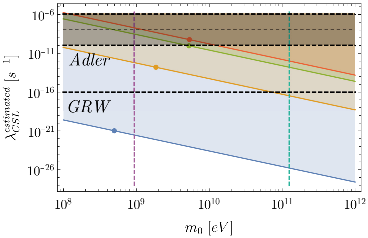

Time asymmetry in CSL noise allows one to recover decay mechanism and absolute masses of neutral kaons!

K. Simonov and B. C. Hiesmayr, *"Spontaneous collapse: a solution to the measurement problem and a source of the decay in mesonic systems"*, Phys. Rev. A **94**, 052128 (2016).
K. Simonov, *"Particle mixing and the emergence of classicality: A spontaneous collapse model view"*, Phys. Rev. A **102**, 022226 (2020).

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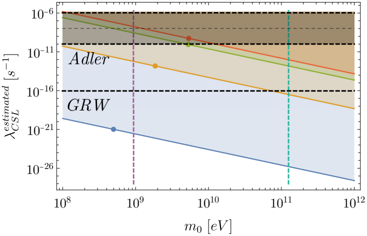

Discrete symmetries

WWA Hamiltonian: $\hat{H}_{WWA} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}$

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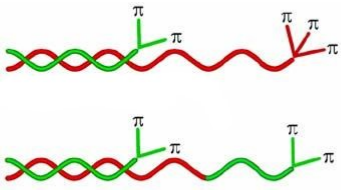

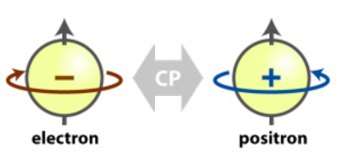

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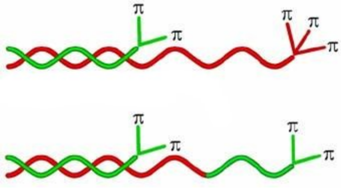

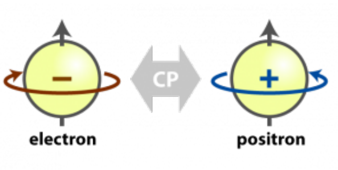

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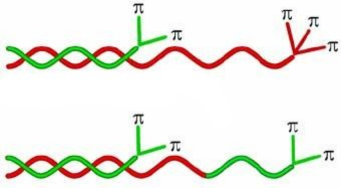
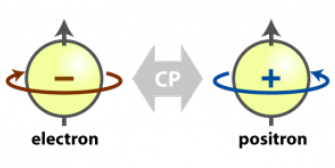
$\mathbb{A}_{QM}(t) = \frac{P_{K^0 \to K^0}(t) - P_{\bar{K}^0 \to \bar{K}^0}(t)}{P_{K^0 \to K^0}(t) + P_{\bar{K}^0 \to \bar{K}^0}(t)} \neq 0$





Asymmetry term for two particles

$$\mathbb{A}(t_1, t_2) = \frac{P_{I \to K^0 \bar{K}^0}(t_1, t_2) - P_{I \to \bar{K}^0 K^0}(t_1, t_2)}{P_{I \to K^0 \bar{K}^0}(t_1, t_2) + P_{I \to \bar{K}^0 K^0}(t_1, t_2)}.$$

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In standard quantum mechanics:

$$\mathbb{A}_{QM}(\Delta t) = \frac{2\Re z \sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + 2\Im z \sin(\Delta m \Delta t)}{(1+|z|^2)\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + (1-|z|^2)\cos(\Delta m\Delta t)},$$

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This coincide with the single-particle asymmetry term!

CSL collapse with CP violation

$$\mathbb{A}_\Lambda(t_1, t_2) \approx \frac{2\delta\frac{\Lambda}{\Delta m}\sin(\phi)}{\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + \cos(\Delta m \Delta t)}\Bigg[\sin(\phi)\Bigg(\sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right)$$
$$- \sinh\left(\frac{\Delta\Gamma}{2}t_2\right)\cos(\Delta m t_1) + \sinh\left(\frac{\Delta\Gamma}{2}t_1\right)\cos(\Delta m t_2)\Bigg)$$
$$+ \cos(\phi)\Bigg(\sin(\Delta m \Delta t) + \cosh\left(\frac{\Delta\Gamma}{2}t_2\right)\sin(\Delta m t_1)$$
$$- \cosh\left(\frac{\Delta\Gamma}{2}t_1\right)\sin(\Delta m t_2)\Bigg)\Bigg].$$

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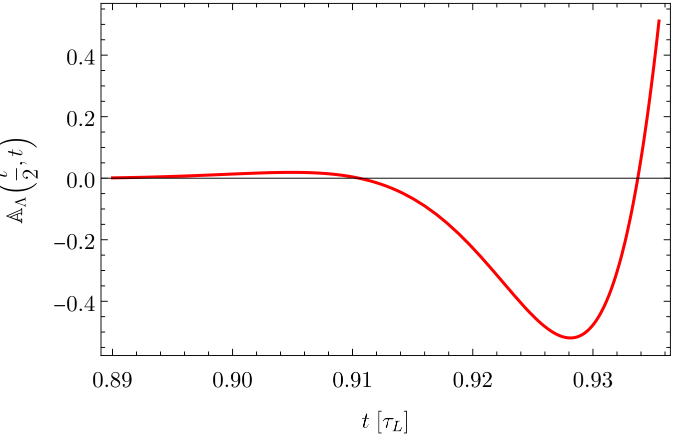

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Conclusions and outlook

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- While increasing the difference $\Delta\Gamma$ between the decay widths, spontaneous collapse effect on a neutral kaon system becomes stronger: hence, neutral kaons could provide a suitable setup to observe spontaneous collapse effect.

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- While increasing the difference $\Delta\Gamma$ between the decay widths, spontaneous collapse effect on a neutral kaon system becomes stronger: hence, neutral kaons could provide a suitable setup to observe spontaneous collapse effect.
- This suggests a further research of spontaneous collapse in a $\mathcal{CP}$-violating flavor oscillating system, in particular, how the effect of other types of collapse models, first of all, gravity-related collapse models.

THANK YOU FOR YOUR ATTENTION!