Coherence harvesting with moving qubits

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Our aim

We study the effects of motion on the coherence harvesting protocol [1,4], i.e., the process of extracting quantum superpositions (coherence) from a quantum field and storing it onto another quantum system.

Setup

We consider a two-level system with ground state $|g\rangle$, excited state $|e\rangle$ and energy gap Ω. The qubit is allowed to move along a trajectory $\mathrm{x}(\tau) = (t(\tau), x(\tau))$ in 1+1 dimensional flat spacetime–with τ the proper time of the qubit– while interacting with a massless scalar field through the Unruh-DeWitt interaction Hamiltonian [2]

$$\hat{H}_{\mathrm{int}}(\tau) = g\chi(\tau)\hat{\mu}(\tau) \otimes \hat{\phi}\left(\mathrm{x}(\tau)\right), \qquad (1)$$

where g is a small coupling constant, $\chi(\tau)$ is a Gaussian switching function

$$\chi(\tau) = e^{-\frac{\tau^2}{2T^2}}/\sqrt{2\pi T^2}$$

that specifies how the interaction between the qubit and the field is switched on and off (T is the mean interaction duration),

$$\hat{\mu}(\tau) = e^{i\Omega\tau}\,|e\rangle\langle g| + e^{-i\Omega\tau}\,|g\rangle\langle e|$$

is the qubit's monopole moment operator, and

$$\hat{\phi}(\mathrm{x}(\tau)) = \int_{-\infty}^{+\infty} \frac{dk}{\sqrt{4\pi|k|}}\left[\hat{a}_k e^{-i(|k|t(\tau)-kx(\tau))} + \mathrm{H.c.}\right]$$

is the field along the qubit's trajectory.

Qubit's motion

We investigate three different states of motion for the qubit: (i) a static qubit with coordinates $t(\tau) = \tau, x(\tau) = 0$, (ii) a qubit moving with constant speed υ, following the worldline

$$t(\tau) = \gamma\tau, \quad x(\tau) = \gamma\upsilon\tau,$$

where $\gamma = 1/\sqrt{1-\upsilon^2}$ is the Lorentz factor, and (iii) a uniformly accelerated qubit, following the hyperbolic trajectory

$$t(\tau) = a^{-1}\sinh(a\tau), \quad x(\tau) = a^{-1}\cosh(a\tau),$$

where a is the acceleration.

Dynamics

We suppose that the qubit starts out in its ground state and the quantum field in a coherent state $|\alpha\rangle$, defined by $\hat{a}_k|\alpha\rangle = \alpha(k)|\alpha\rangle$, where $\alpha(k)$ is a coherent amplitude distribution. We assume a Gaussian profile for the amplitude distribution. The combined qubit-field system evolves from the initial state according to the unitary operator $\hat{U}$ generated by the interaction Hamiltonian (1).

Initial state of the qubit-field system

$$\hat{\rho}_{tot,0} = |g\rangle\langle g| \otimes |\alpha\rangle\langle\alpha|$$

$$\hat{U} = \mathcal{T}\exp\left(-i\int_{-\infty}^{+\infty}\hat{H}_{\mathrm{int}}(\tau)d\tau\right)$$

Final reduced density matrix of the qubit after the interaction

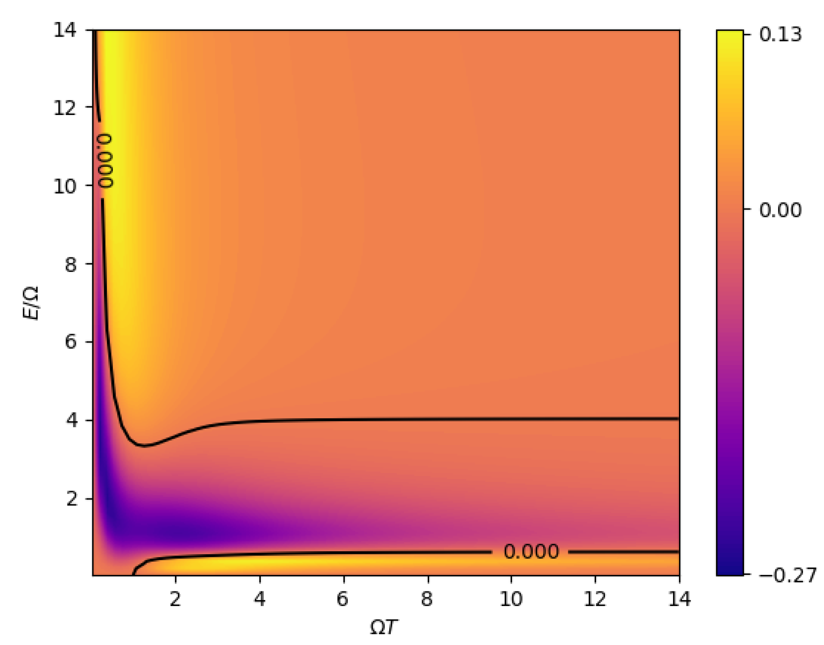
$$\hat{\rho} = \mathrm{tr}_{\hat{\phi}}\left(U\hat{\rho}_{tot,0}U^{\dagger}\right)$$

Quantifying Coherence

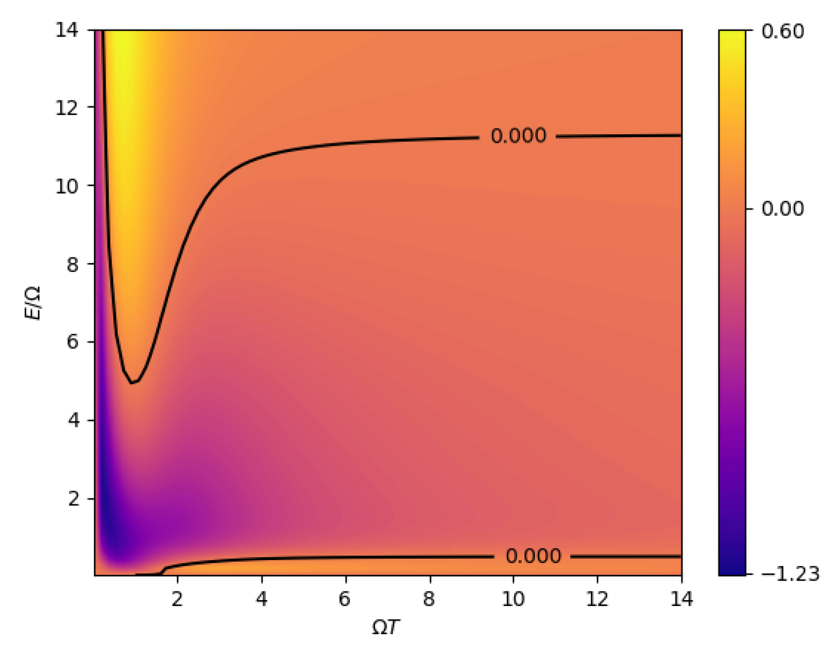
To measure the amount of coherent present in the qubit's final state $\hat{\rho}$ we employ the $\ell-1$ norm of coherence [3], which is equal to the sum of the modulus of its non-diagonal elements

$$C(\rho) = \sum_{i\neq j}|\rho_{ij}|.$$

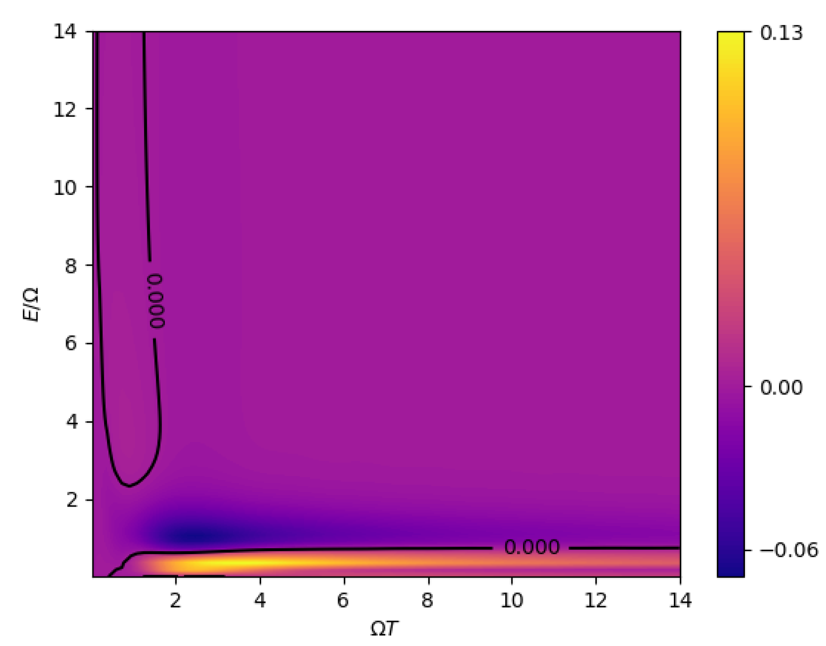
Coherence Harvesting



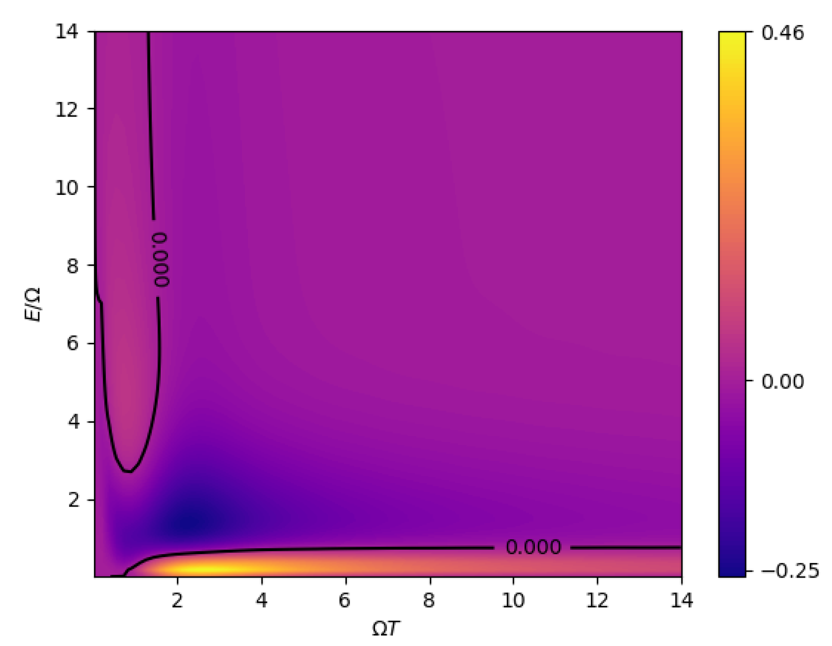
(a) $\upsilon = 0.7$



(b) $\upsilon = 0.99$

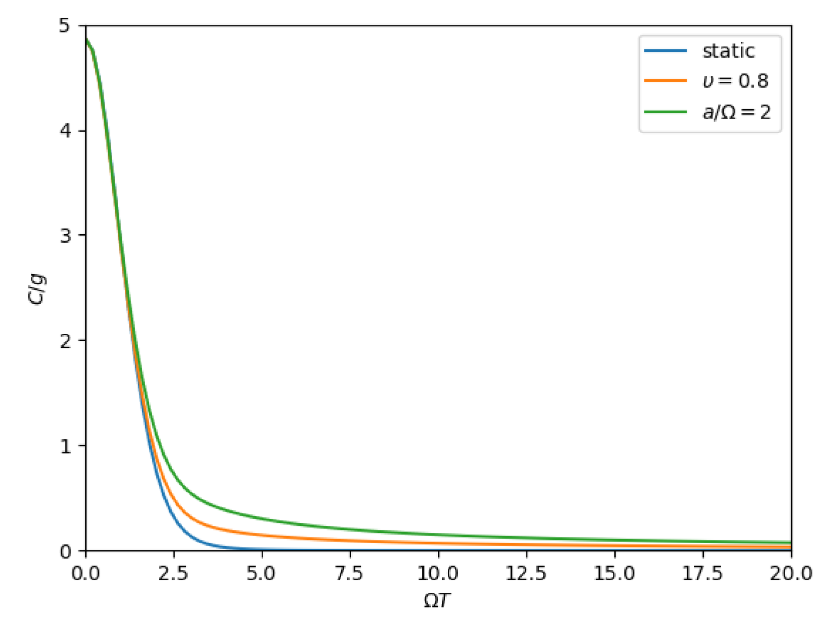


(c) $a/\Omega = 0.5$

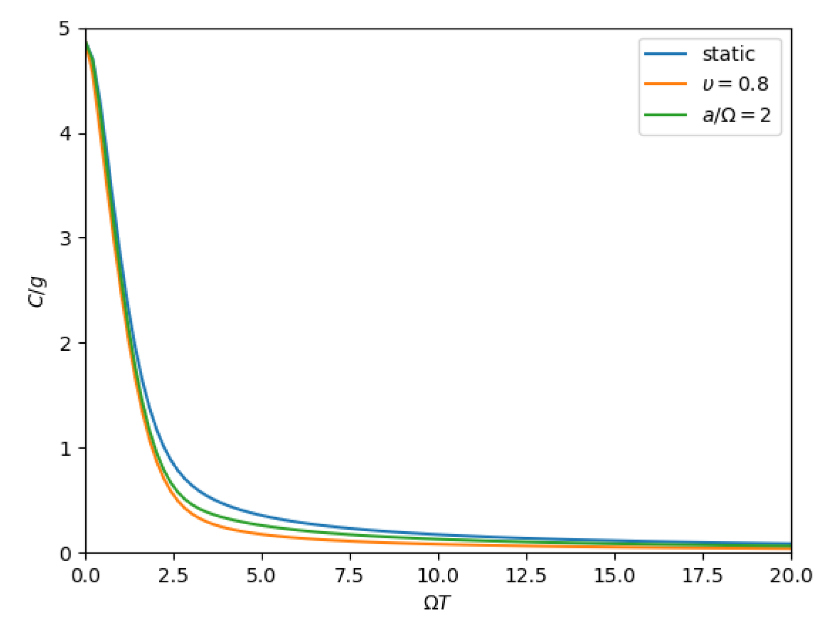


(d) $a/\Omega = 2$

Figure 1: Difference of the amount of coherence extracted scaled by the coupling constant between (a-b) the moving and the static case, $C_\upsilon - C_0$, and (c-d) the accelerated and the static case, $C_a - C_0$, as a function of the field's energy E/Ω and ΩT, for various values of speed υ and acceleration a. We observe "swelling" regions, where a moving qubit has more coherence than a static one, which are centered around short interaction duration $T \lesssim 1/\Omega$ when $E > \Omega$, and longer interaction times $T \gtrsim 1/\Omega$ when $E < \Omega$.



(a) $E = 0.25\Omega$



(b) $E = \Omega$

Figure 2: Comparison of the amount of extracted coherence scaled by the coupling constant between a static qubit, a moving qubit with velocity $\upsilon = 0.8$, and a uniformly accelerated one with acceleration $a/\Omega = 2$. Depending on the initial energy E of the field, the decoherence rate may be found to be smaller for a moving qubit than a static one.

References

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[2] N. D. Birrell and P. C. W. Davies, *Quantum Fields in Curved Space*, (Cambridge University Press, 1982).

[3] A. Streltsov, G. Adesso, and M. B. Plenio, Rev. Mod. Phys. 89, 041003 (2017).

[4] N. K. Kollas and D. Moustos, arXiv:2103.09165.

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