Cohering and decohering power of massive scalar fields under instantaneous interactions (Phys. Rev. A 107, 022420)

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Abstract

We employ a non-perturbative technique to investigate the ability of a quantum field to create or destroy coherence in a two level Unruh-DeWitt (UDW) detector. We observe that, above a critical value of the effective coupling constant, the maximum amount of coherence generated by a coherent field displays revival patterns with respect to the particle's radius. Extending previous perturbative results we demonstrate that even in the case of a strong coupling between detector and field, massive fields are better at shielding the detector against the decohering effects of a thermal environment. In both cases we show how it is is possible to probe the value of the field's mass by either measuring its cohering or decohering power.

1. Cohering and Decohering power

For any valid measure C of quantum coherence the *cohering* and *decohering* power of a completely positive and trace preserving operation Φ is equal to

$$\mathcal{C}(\Phi) = \max_{|i\rangle} C(\Phi(|i\rangle\langle i|))$$

and

$$\mathcal{D}(\Phi) = \max_{\boldsymbol{\theta}} [C(\psi_d(\boldsymbol{\theta})) - C(\Phi(\psi_d(\boldsymbol{\theta})))]$$

respectively. The maximum is taken over the set of incoherent bases in the first case and over the set of *maximally coherent states*

$$\psi_d(\boldsymbol{\theta}) = \frac{1}{\sqrt{d}} \sum_{j=0}^{d-1} e^{i\theta_j} |j\rangle$$

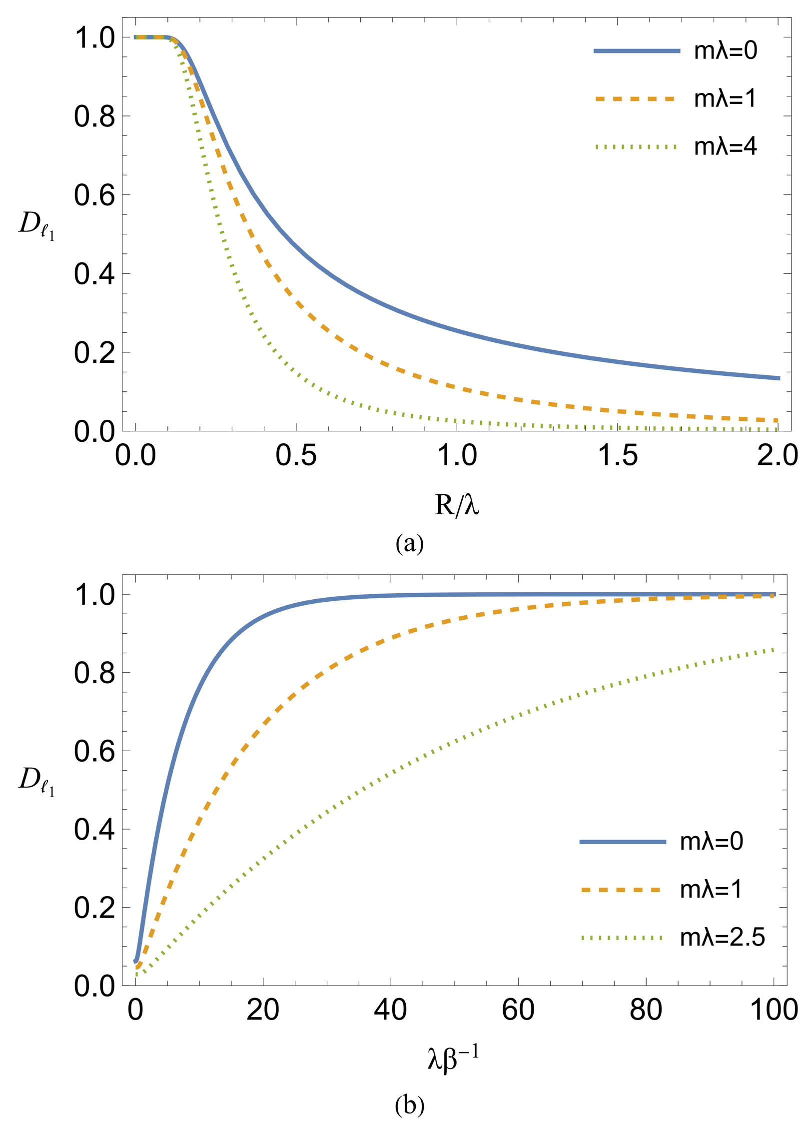
in the second.

4. Decoh. power of thermal fields

The ℓ_1 decohering power of a thermal field $\sigma_\phi \approx e^{-\beta \hat{H}_\phi}$ is equal to

$$\mathcal{D}_{\ell_1}(\Phi) = 1 - e^{-\lambda^2 I(\beta)}$$

with $I(\beta) = \frac{1}{2\pi}\int_0^\infty \frac{k^2 e^{-\frac{\pi k^2 R^2}{8}}}{\sqrt{k^2+m^2}} \coth\left(\frac{\beta\sqrt{k^2+m^2}}{2}\right) dk$.



2. Instantaneous interactions of UDW detectors with scalar fields

The interaction Hamiltonian is given by

$$\hat{H}_{\text{int}}(t) = \lambda\delta(t) \otimes \hat{\varphi}_f(t, \mathbf{x})$$

where $\hat{\mu}(t) = e^{i\Omega t}|e\rangle\langle g| + e^{-i\Omega t}|g\rangle\langle e|$ is the *monopole operator* of the detector and

$$\hat{\varphi}_f(t, \mathbf{x}) = \int \frac{d^3\mathbf{k}}{\sqrt{(2\pi)^3 2\omega(\mathbf{k})}} \left(F(\mathbf{k})\hat{a}_{\mathbf{k}} e^{i(\mathbf{k}\cdot\mathbf{x} - \omega(\mathbf{k})t)} + \text{H.c.}\right)$$

with $\omega(\mathbf{k}) = \sqrt{|\mathbf{k}|^2 + m^2}$ is a *smeared* massive scalar field of mass m. In this case one can drop the time-ordering operator and write the unitary evolution of the combined system as

$$\hat{U} = \exp[-i\lambda\hat{\mu}_0 \otimes \hat{\varphi}_{f_0}].$$

Evolving the system and tracing away the field degrees of freedom induces a quantum channel on the detector

$$\Phi(\rho) = (1 - |z|)B(\rho) + |z| V\rho V^\dagger$$

which is a convex combination of a bit-flip channel $B(\rho) = \frac{1}{2}(\rho + \hat{\mu}_0\rho\hat{\mu}_0)$ and a unitary rotation V of the form

$$V = \sqrt{\frac{|z| + \operatorname{Re} z}{2|z|}}\hat{I} - i\sqrt{\frac{|z| - \operatorname{Re} z}{2|z|}}\hat{\mu}_0,$$

with $z = \operatorname{tr}_\varphi[e^{i2\lambda\hat{\varphi}_{f_0}}\sigma_\varphi]$.

3. Coherence revival patterns

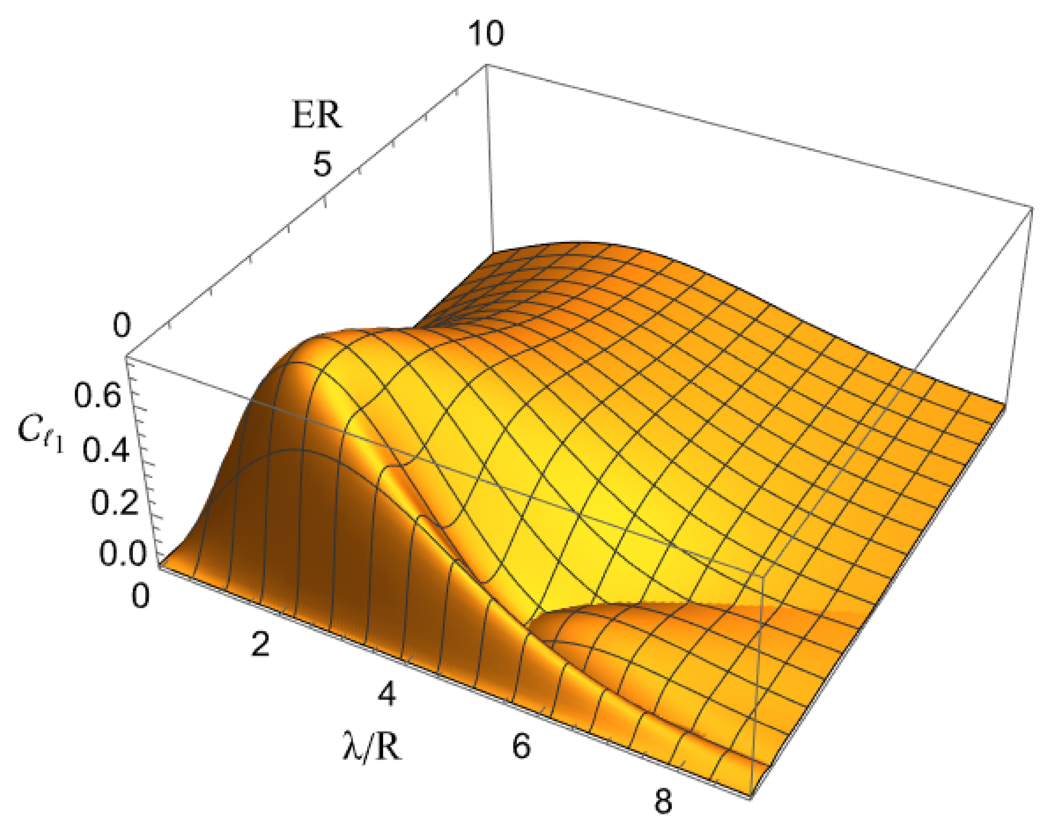
The ℓ_1-cohering power of a scalar field in a coherent state $|a\rangle$ (such that $\hat{a}_{\mathbf{k}}|a\rangle = a(\mathbf{k})|a\rangle$) with a cohering amplitude distribution and smearing function of the form

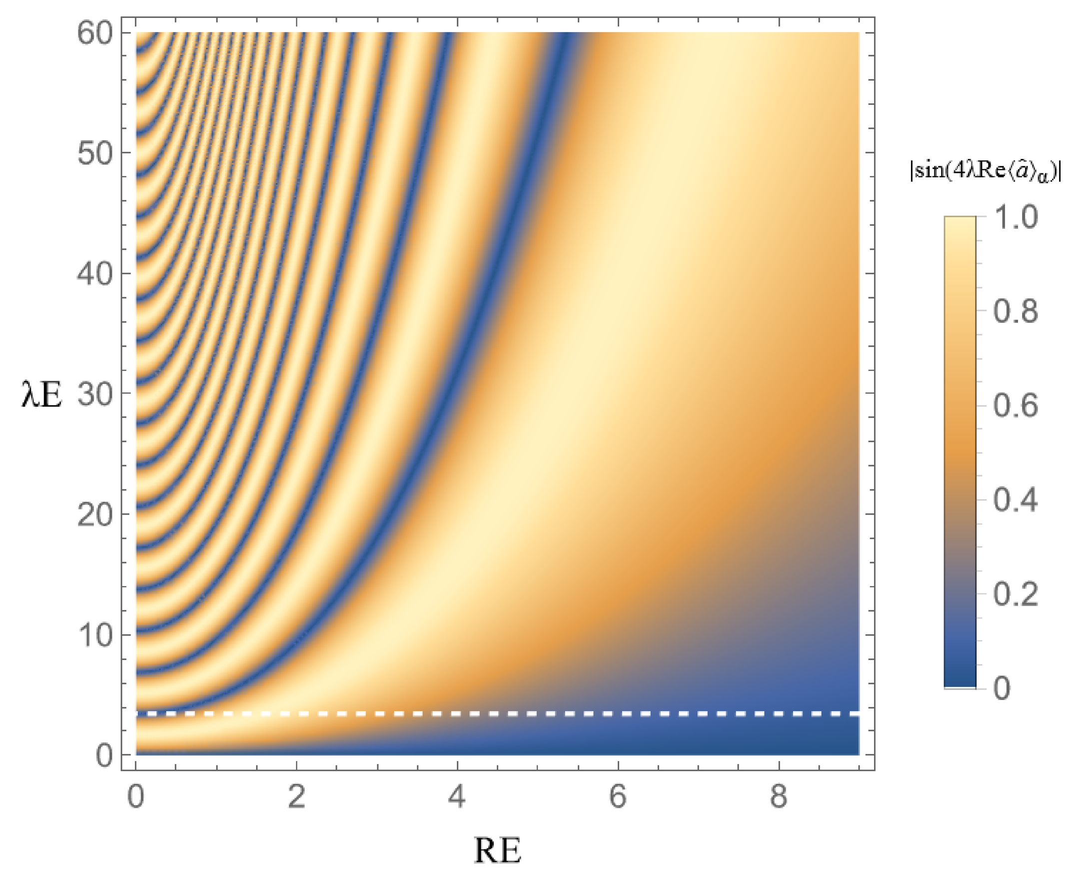
$$a(\mathbf{k}) = \sqrt{\frac{|\mathbf{k}|}{\omega(\mathbf{k})} \frac{\exp\left(-\frac{2|\mathbf{k}|^2}{\pi E^2}\right)}{(\pi E/2)^{3/2}}}, \quad F(\mathbf{k}) = \exp\left[-\frac{\pi|\mathbf{k}|^2 R^2}{16}\right]$$

given as a function of the mean energy E of the field and the mean radius R of the detector respectively, is equal to

$$\mathcal{C}_{\ell_1}(\Phi) = e^{-2\lambda^2[\hat{a},\hat{a}^\dagger]}|\sin(4\lambda \operatorname{Re}\langle\hat{a}\rangle_a)|$$

where $[\hat{a},\hat{a}^\dagger] = \frac{m^2}{16\pi^{3/2}} U\left(\frac{3}{2}, 2, \frac{\pi m^2 R^2}{8}\right)$ and $\operatorname{Re}\langle\hat{a}\rangle_a = m\sqrt{\frac{2m^3}{\pi^4 E^3}}\Gamma\left(\frac{7}{4}\right) U\left(\frac{7}{4}, \frac{9}{4}, \frac{m^2}{2\sigma^2}\right)$, with $U(a,b,z)$ denoting *Tricomi's confluent hypergeometric function.*





When $\lambda E \lesssim 3.44$ no revival patterns can occur. For a detector with an effective radius $R = 1/E$, when $\lambda E \lesssim 2.4$ the cohering power is in a one-to-one relation with respect to the mass of the field.