Effects of intrinsic decoherence on quantum coherence and correlations between spins within a two-dimensional honeycomb lattice graphene layer system

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ACHEP 2023 — Rabat - Salé - Kenitra Regional University Consortium Organizes The First Edition of the African Conference on High Energy Physics

Université Ibn Tofaïl — Université Mohammed V de Rabat — FSAC — Faculte des Sciences Ain Chock, Universite Hassan II de Casablanca

1. Introduction

Quantum information processing (QIP) based on solid-state systems is a dynamically developing field of research. The cutting-edge field of QIP technology is currently exploring graphene layer systems due to their exceptional electronic properties. The single layer graphene is a 2D and gapless material in which two independent energy valleys exist. Here, we denote $|K\rangle$ and $|K'\rangle$ as the two inequivalent Dirac points in the first Brillouin zone in the graphene band structure. This valley state can be used to encode quantum information as a two-level qubit for QIP. This work delves into the influence of intrinsic decoherence on the behavior of quantum coherence and correlations between two interacting qubits in a graphene-based system.

2. Measures

- Quantum coherence measures:
  - l_1-norm of coherence

$$C_{l_1}(\rho) = \sum_{i \neq j} |\rho_{i,j}| \quad (1)$$

  - Relative entropy of coherence

$$C_r(\rho) = H(\rho_{diag}) - H(\rho) \quad (2)$$

- Quantum corelations measure:
  - Local quantum uncertainty

$$U(\rho) = 1 - \max(\Omega_1, \Omega_2, \Omega_3) \quad (3)$$

▷ $\Omega_{i=1,2,3}$ are the eigenvalues of $\mathcal{W}$

$$\mathcal{W}_{ij} \equiv \mathrm{Tr}\left\{\sqrt{\rho}\left(\hat{\sigma}_{Ai} \otimes \hat{\mathbb{I}}_B\right)\sqrt{\rho}\left(\hat{\sigma}_{Aj} \otimes \hat{\mathbb{I}}_B\right)\right\} \quad (4)$$

3. Physical system

- Hamiltonian of the system

$$\hat{H} = \beta[\tau(\hat{\sigma}_x \otimes \hat{\mathbb{I}})\hat{k}_x + (\hat{\sigma}_y \otimes \hat{\tau}_z)\hat{k}_y] \quad (5)$$

- Milburn's evolution

$$\frac{d\rho_t}{dt} = \frac{1}{\gamma}\left(\exp(-i\gamma\hat{H})\rho_t \exp(i\gamma\hat{H}) - \rho_t\right) \quad (6)$$

- Evolved state

$$\rho_t = \sum_{j,k} \exp\left(-\frac{\gamma t}{2}(E_j - E_k)^2 - i(E_j - E_k)t\right) \times \langle u_j|\rho^{t=0}|u_k\rangle |u_j\rangle\langle u_k| \quad (7)$$

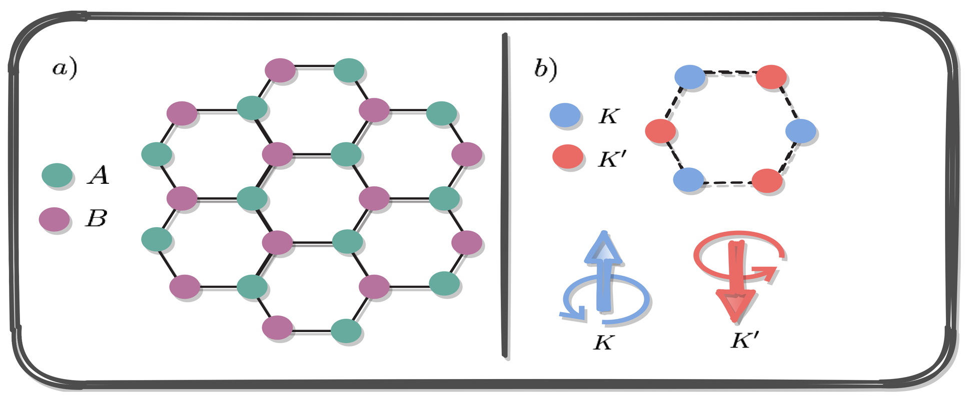
▷ where

$$\rho^{t=0} = \frac{1-p}{4}\,\hat{\mathbb{I}}_4 + p\,|\Psi\rangle\langle\Psi| \quad (8)$$

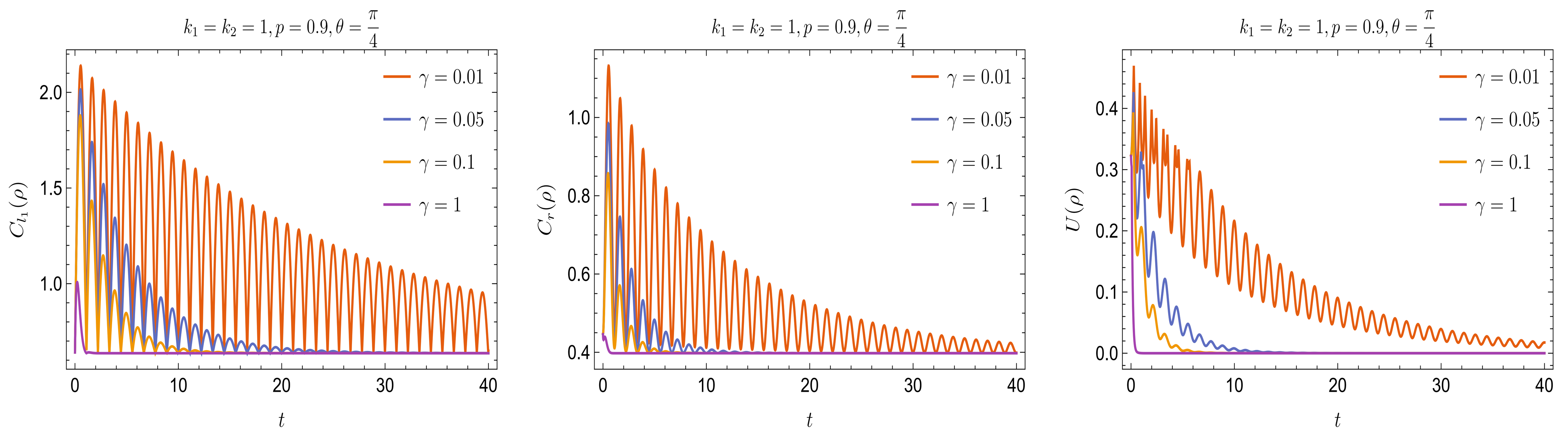
▷ and

$$|\Psi\rangle = \cos(\frac{\theta}{2})\,|00\rangle + \sin(\frac{\theta}{2})\,|11\rangle \quad (9)$$

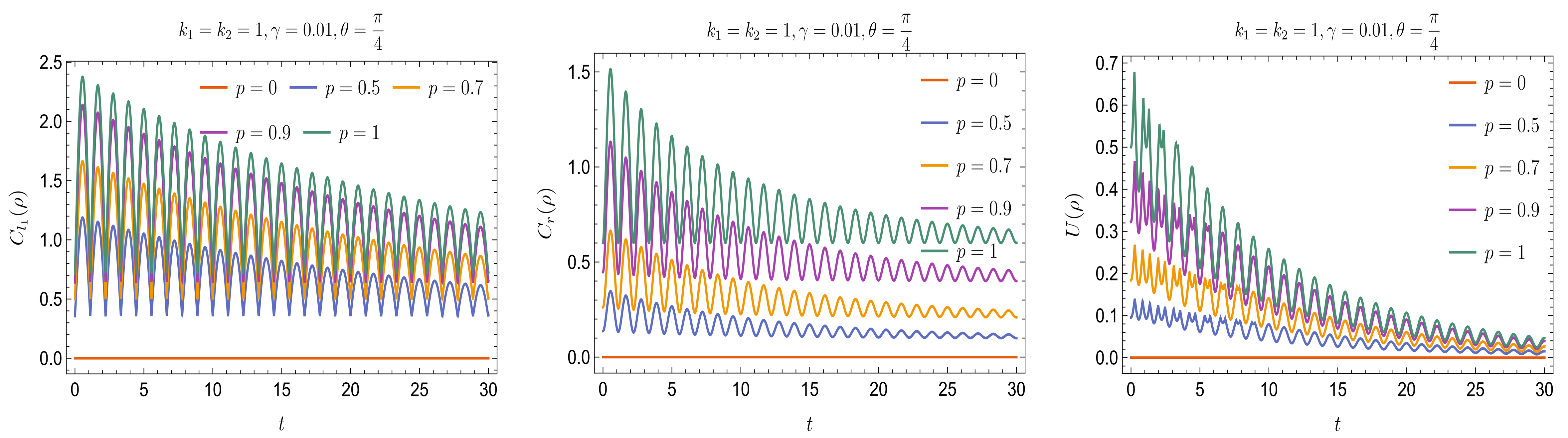
- Honeycomb lattice structure of a graphene layer and the locations of Dirac points K and K' on a single cell



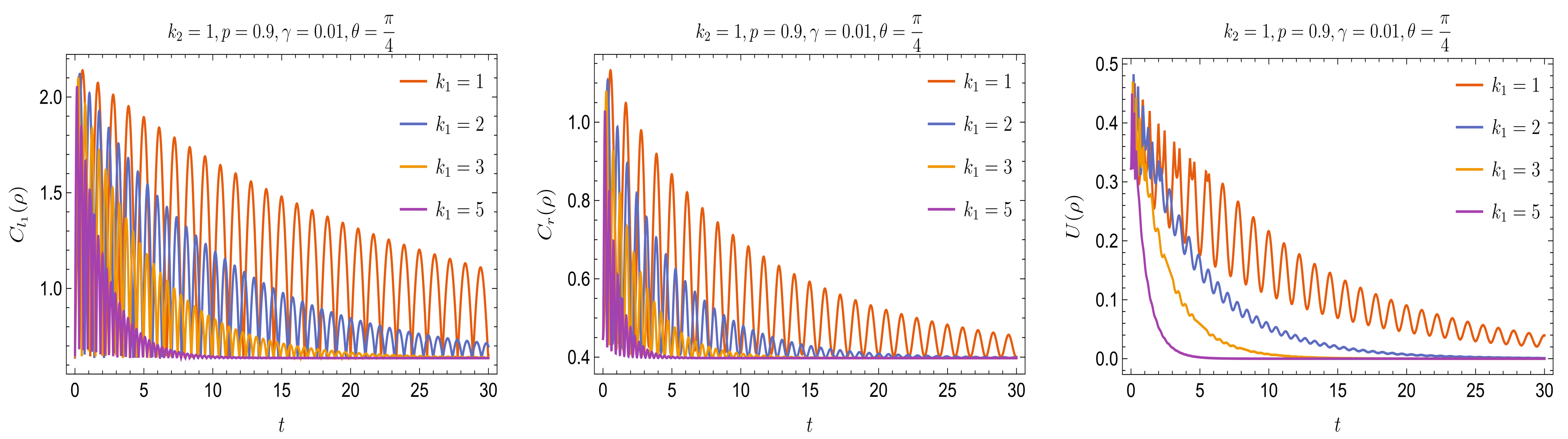
4. Results



- Over time, the amplitude of quantum coherence measures ($C_r(\rho)$ and $C_{l_1}(\rho)$) diminishes to a constant nonzero value as the intrinsic decoherence rate γ increases. Simultaneously, the quantity of quantum correlations quantified by $U(\rho)$ dwindles until it eventually becomes zero.



- These findings emphasize the exclusive dependence of quantum coherence and correlations on the degree of purity p.



- A reduction in k_1 induces a rise in quantum correlations and coherence within the system at $t \approx 0$.
- Decreasing k_1 has a more significant impact on improving quantum coherence than quantum correlations.

5. Conclusions

1. The evidence highlights that the impact of intrinsic decoherence on quantum correlations is more substantial than its effect on quantum coherence.
2. According to the results, enhancing the degree of purity heightened the quantum coherence and correlations within the system, notwithstanding the high intrinsic decoherence rates.
3. Our research shows that it is possible to have more robust quantum resources by engineering an appropriate initial state for the system.
4. By designing the initial state and certain system parameters properly, it is possible to achieve more resilient quantum coherence and local quantum uncertainty against the effects of intrinsic decoherence.

6. References

[1] Z. Bouafia, S. Elghaayda and M. Mansour, Mod. Phys. Lett. B (2023) 2350203.