Quantum Entanglement Between Excitons in 2D Materials

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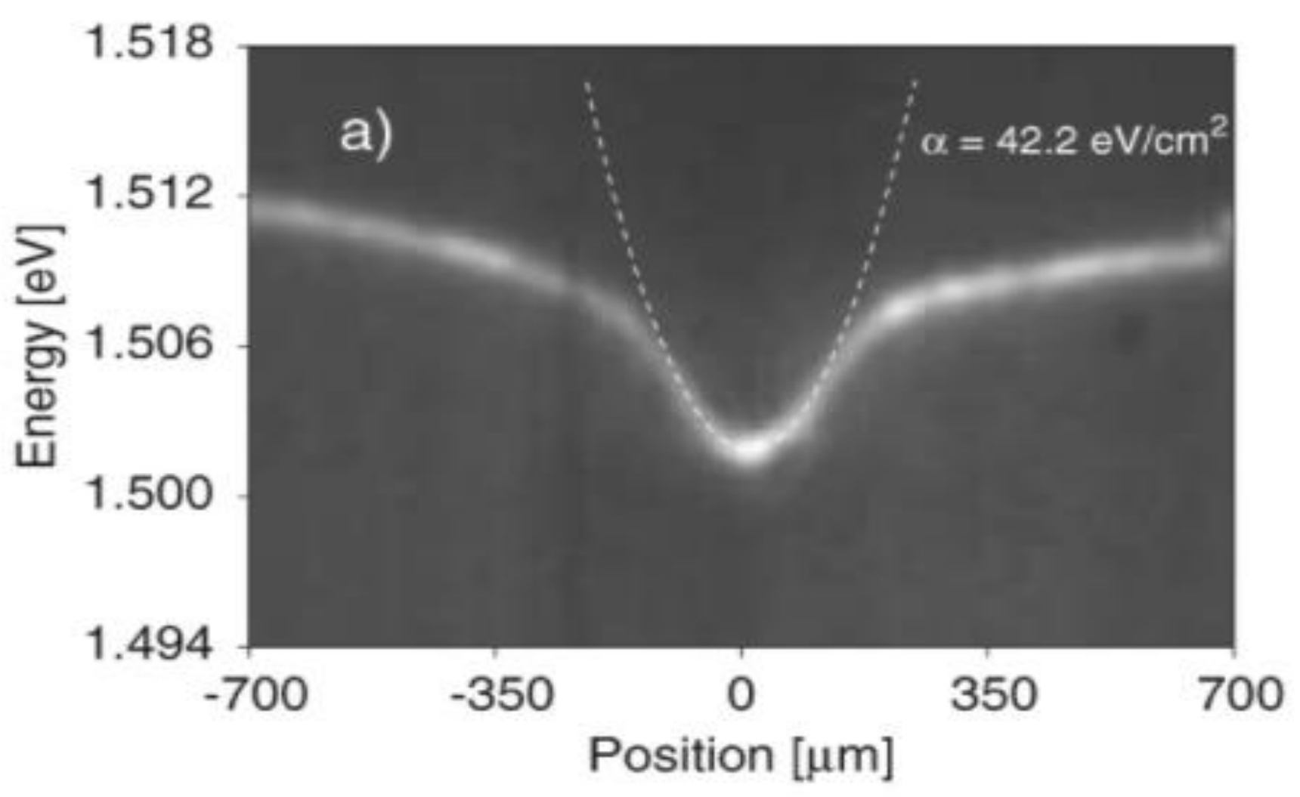
Abstract

Under specific conditions and in the absence of a quantizing magnetic field, the energy of excitons on a 2D material, is described by a discrete set of Landau levels. Two valid examples are excitons on a graphene sheet under strain [1] or excitons on a TMDC with trapping potentials [2]. In this work, we consider that 2 qubits consisting of such excitons in the ground or first excited state are confined to an optical microcavity. We devised a Jaynes-Cummings-like model to explain the interaction between such a system and the cavity. In order to find out how the entanglement between the excitons would evolve over time, we calculated the time evolution of the concurrence between them for many initial states for the cases with and without cavity decay. Through such calculations, we reached the interesting and counter intuitive result that, for some initial states, the presence of cavity decay can increase the average concurrence of the system.

Excitons with Discrete Energy Levels



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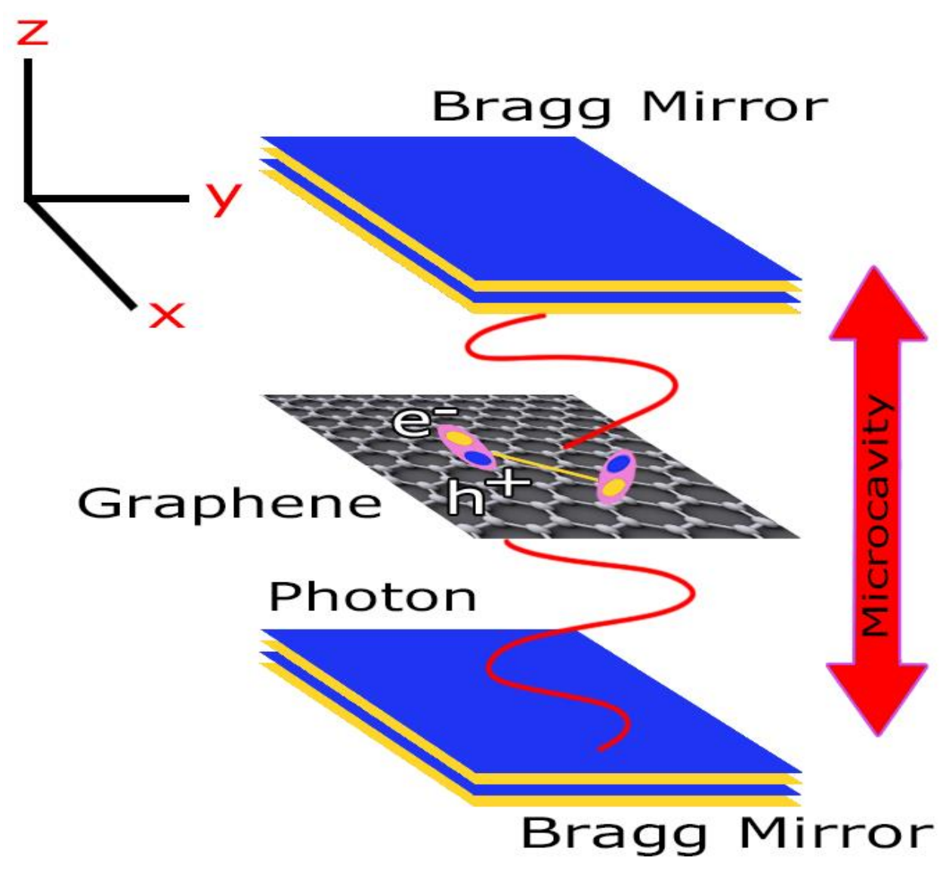


In general, the excitonic energy dispersion relations show continuous Landau Levels. However, under some special conditions, those levels can become discrete. Two examples are those of excitons under a strain-induced pseudomagnetic field on a sheet of graphene [1] or excitons in a trapping potential on a TMDC sheet [2]. Such an exciton can be treated as a qubit, when we considered only the first two energy levels. We considered a system of two such excitons that do not interact directly with one another, but were put inside the same optical microcavity. We study the quantum entanglement between such qubits due to their interaction with microcavity photons.

Model

We modeled our system by assuming that both excitons interact with a single cavity mode. We considered that the system follows the Jaynes-Cummings-like Hamiltonian Ĥ below:

$$\hat{H} = \hat{H}_0 + \hat{V}'_{RWA}$$

$$\hat{H}_0 = \hbar\left(\sum_{j=1}^{2}\omega_0 \left|e_j\right\rangle\left\langle e_j\right| + \omega_k \hat{a}^\dagger\hat{a}\right)$$

$$\hat{V}'_{RWA} = \hbar\lambda\sum_{j=1}^{2}\left(\hat{\sigma}_j^+\hat{a} + \hat{\sigma}_j^-\hat{a}^\dagger\right)$$

Where $|e_j>$ is the first excited state for exciton j, â is the anhilation operator for photons in the cavity, σ^+_j is the creation operator for excitations in exciton j. $\hbar\omega_0$ is the energy gap between the first and excited stated of the excitons, ω_k is the frequency of photons in the microcavity and ħλ is the Rabbi splitting induced by the interaction of the system and the cavity photons.

To take into account the possibility of cavity decay, we considered that the system evolved according to a Master Equation on Lindblad form

$$\dot{\rho} = -i[\hat{H}, \rho] + \kappa\mathcal{L}(\hat{a})\rho$$

$$\mathcal{L}(\hat{A})\rho = \hat{A}\rho\hat{A}^\dagger - \frac{1}{2}\left(\hat{A}^\dagger\hat{A}\rho + \rho\hat{A}^\dagger\hat{A}\right)$$

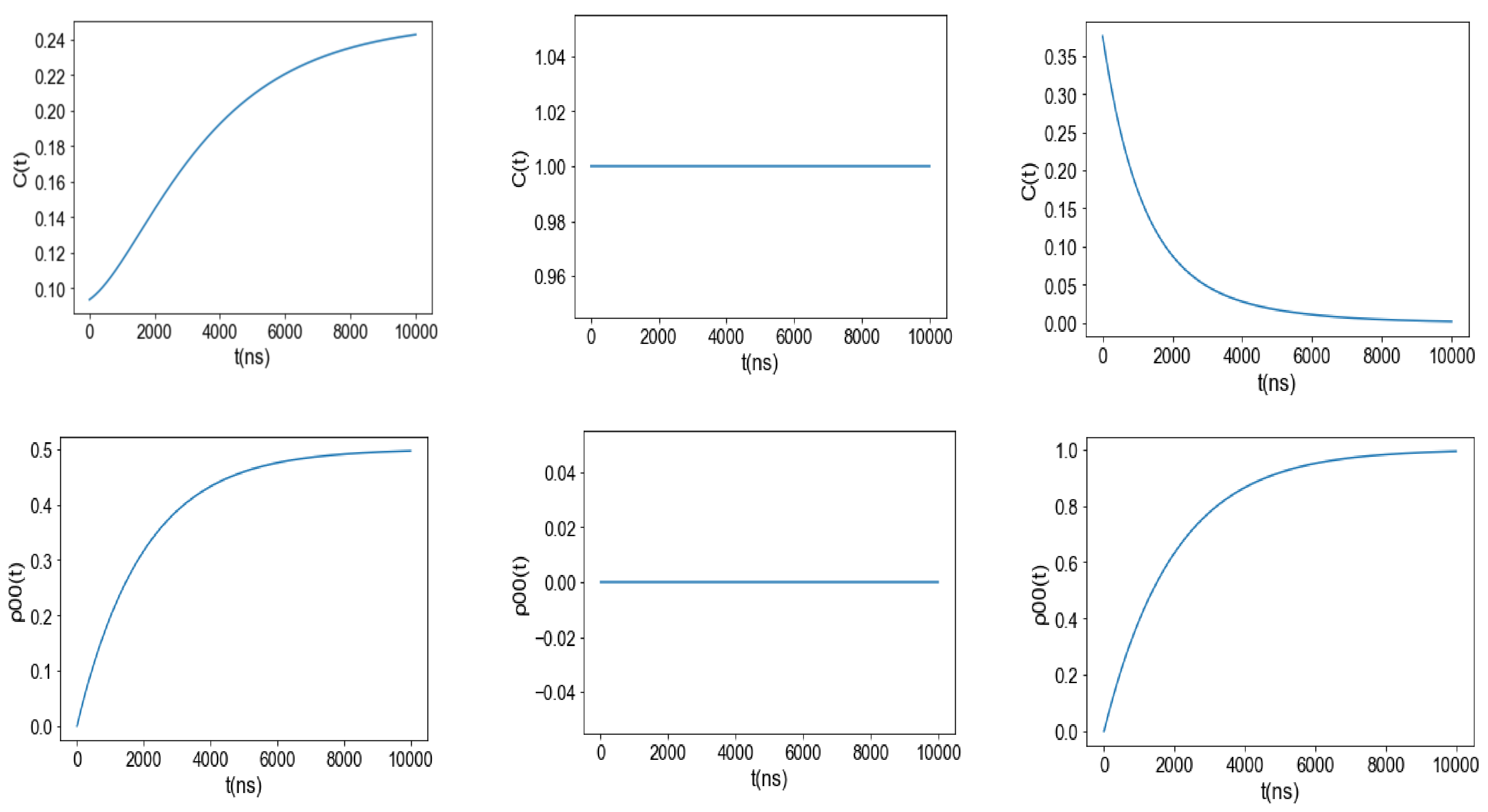
Where ρ is the density matrix of the system and κ is the cavity decay rate.

Entanglement

In order to track the entanglement between the qubits as a function of time, we do so by calculating the "cncurrence" of the system. The concurrence is a number between zero and one which measures how entangled two qubits are [3]. If it is zero, there is no quantum entanglement between them and they are found in a product state. If it is one, they are in a maximally entangled state.

Results

In the first row, plot of concurrence, C(t), as a function of time for 3 different initial states for the system averaged on a single Rabi cycle. In the second row, the probability ρ0 (t) for the system to decay to the ground state as a function of time for the same initial states. In all these simulations, we assumed that the system is subject to a strain-induced pseudomagnetic field of intensity B/e = 50 T inside a medium quality microcavity of volume W = 1,000 µm³ and average photonic lifetime of 1µs.



$|\Psi_0\rangle = |01\rangle$ $|\Psi_0\rangle = \frac{1}{\sqrt{2}}\left(|10\rangle - |01\rangle\right)$ $|\Psi_0\rangle = \frac{1}{\sqrt{2}}\left(|10\rangle + |01\rangle\right)$

Conclusion

We succeeded in calculating the time-evolution of the concurrence, a measure of entanglement, for a system consisting of excitons on strained monolayer graphene inside a leaky cavity. Our results show that such a structure presents a maximally entangled stationary state, whose lifetime can be as large as the lifetime of the excitons themselves. We also reached the very interesting and counter-intuitive conclusion that, for some initial states of the system, the fact that the cavity can lose photons does not end up destroying the concurrence between the excitons, but does the opposite and increases this value.

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