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Effects of temperature and hydrogen-like impurity on the coherence time of RbCl parabolic quantum dot qubit

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ABSTRACT

By using a variational method of Pekar type, the Fermi Golden Rule and the quantum statistics theory (VMPTFGRQST), we investigate the effects of the hydrogen-like impurity and temperature on the coherence time of a parabolic quantum dot (PQD) qubit with a hydrogen-like impurity at the center. We then derive the ground and the first excited states' (GFES) eigenenergies and the eigenfunctions in a PQD. A single qubit can be realized in this two-level quantum system. The phonon spontaneous emission causes the decoherence of the qubit. The numerical results show that the coherence time is a decreasing function of the temperature, the strength of the Coulombic impurity potential (CIP) and the polaron radius (PR).

1. Introduction

Quantum information processing devices outperform their classical counterparts by preserving and exploiting the correlated phases of their constituent quantum oscillators, which are usually two-state systems called as “qubits” [1]. An increasing number of theoretical proposals [2–4] have shown that such devices allow secure long-distance communication and improved computational power. Solid-state implementations of these devices are favored due to both scalability and ease of integration with existing hardware, although previous experiments [5–7] have shown limited coherence times for solid-state qubits. The development of quantum error-correcting codes and fault-tolerant quantum computation (QC) [8] showed that largescale quantum algorithms are still theoretically possible in the presence of decoherence. However, the coherence time must be dauntingly long: approximately 10^5 times the duration of a single quantum gate, and probably longer depending on the quantum computer architecture [1,9]. The question of whether a scalable implementation can surpass this coherence time threshold is not only important for the technological future of QC, but also for fundamental understanding of the border between microscopic quantum behavior and macroscopic classical behavior [9–11]. Recently, Sun [12] et al. obtained effects of magnetic field on the coherence time of a parabolic quantum dot qubit. Gale [13] et al. measured the coherence time in high energy Proton-Nucleus collisions. Hayashi et al. studied coherent manipulation of electronic states in a double quantum dot [14]. Effects of temperature and hydrogen-like impurity on the coherence time of a parabolic QD qubit, however, have not previously been investigated yet.

In this article, we investigate the effects of the temperature, the strength of CIP, PR of the PQD on the coherence time by using VMPTFGRQST. The temperature effects on the coherence time in parabolic QD under hydrogen-like impurity field are important subject in quantum information and quantum computing processing.

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2. Theoretical model and calculations

Consider the electron confined in the parabolic potential QD. The electrons are confined much stronger in one direction (taken as the Z-growth direction) than in the other two directions. Therefore, we will focus on the condition of the electron and LO phonon only on the X–Y plane [15,16]. The electron under consideration is moving in the RbCl crystal PQD. The Hamiltonian of an electron-phonon interaction system with a hydrogen-like impurity at the center takes the form of [17]:

$$H = -\frac{\hbar^2\nabla_\rho^2}{2m} + \sum_{\mathbf{q}} \hbar\omega_{LO} a_{\mathbf{q}}^+ a_{\mathbf{q}} + \frac{1}{2} m\omega_0^2\rho^2 + \sum_{\mathbf{q}} [V_q a_{\mathbf{q}} \exp(i\mathbf{q}\cdot\mathbf{r}) + h\cdot c] - \frac{\beta}{r}, \tag{1}$$

where $a_{\mathbf{q}}^+(a_{\mathbf{q}})$ denotes the creation (annihilation) operator of the bulk LO phonons with wave vector $\mathbf{q}$. $\mathbf{p} = (\mathbf{p}_\rho, p_z)$ and $\mathbf{r} = (\boldsymbol{\rho}, z)$ are respectively the momentum and position vectors of the electron. $-\beta/r$ denotes the CIP between the electron and the hydrogen-like impurity. The strength of the CIP β is $\beta = e^2/\varepsilon_0$. V_q and α in Eq. (1) are

$$V_q = i\left(\frac{\hbar\omega_{LO}}{q}\right)\left(\frac{\hbar}{2m\omega_{LO}}\right)^{\frac{1}{4}}\left(\frac{4\pi\alpha}{v}\right)^{\frac{1}{2}}, \alpha = \left(\frac{e^2}{2\hbar\omega_{LO}}\right)\left(\frac{2m\omega_{LO}}{\hbar}\right)^{\frac{1}{2}}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right) \tag{2}$$

Following the VMPT [18,19], the system's trial GFES' wavefunction is given by Refs. [20,21].

$$|\varphi_0(\lambda_0)\rangle = |0\rangle|\xi(z)\rangle\Big|0_{ph}\rangle = \frac{\lambda_0}{\sqrt{\pi}}\exp\left[-\frac{\lambda_0^2\rho^2}{2}\right]|\xi(z)\rangle\Big|0_{ph}\rangle, \tag{3}$$

$$|\varphi_1(\lambda_1)\rangle = |1\rangle|\xi(z)\rangle\Big|0_{ph}\rangle = \frac{\lambda_1^2}{\sqrt{\pi}}\rho\exp\left(-\frac{\lambda_1^2\rho^2}{2}\right)\exp(\pm i\phi)|\xi(z)\rangle\Big|0_{ph}\rangle, \tag{4}$$

where λ_0 and λ_1 are the variational parameters, $|\xi(z)\rangle$ is the electron's wavefunction in the z-growth direction, since the electrons are much more strongly confined in z-growth direction than in other two directions and considered to be confined in an infinitesimally narrow layer, so does $\langle\xi(z)|\xi(z)\rangle = \delta(z)$.The electron's GFES energies in a PQD can be derived in the following form:

$$E_0(\lambda_0) = \frac{\hbar^2\lambda_0^2}{2m} + \frac{\hbar^2}{2\lambda_0^2 m l_0^4} - \frac{1}{2}(2\pi)^{1/2}\alpha\hbar\omega_{LO} r_0\lambda_0 - \sqrt{\pi}\beta\lambda_0, \tag{5}$$

and

$$E_1(\lambda_1) = \frac{\hbar^2\lambda_1^2}{2m} + \frac{\hbar^2}{m\lambda_1^2 l_0^4} - \frac{11}{32}\alpha\hbar\omega_{LO}(2\pi)^{1/2} r_0\lambda_1 - \frac{\sqrt{\pi}}{2}\beta\lambda_1, \tag{6}$$

where $l_0 = (\hbar/m\omega_0)^{1/2}, r_0 = (\hbar/2m\omega_{LO})^{1/2}$, l_0, r_0 is the effective confinement length (ECL) and the PR, respectively. A single qubit can be realized in this two-level quantum system. The electron's superposition state reads

$$|\psi_{01}\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), \tag{7}$$

Under the dipole approximation, based on the Fermi Golden Rule [22], the spontaneous emission rate can be calculated using

$$\tau^{-1} = \frac{e^2(\Delta E)^3}{\varepsilon_0\hbar^4 C^3}|\langle 0|\rho|1\rangle|^2 = \frac{e^2(\Delta E)^3}{\varepsilon_0\hbar^4 C^3}\frac{16\lambda_0^2\lambda_1^4}{\left(\lambda_0^2+\lambda_1^2\right)^4}, \tag{8}$$

where $\Delta E = E_1 - E_0$ denotes the energy separation between the GFES and C is the speed of light in vacuum. $\varepsilon(\varepsilon_0)$ is the material (vacuum) dielectric constant and τ is the coherence time.

3. Temperature effect

At finite temperature, the properties of the polaron are statistical averages of various states. According to the quantum statistics theory, the statistical average number of the bulk LO phonons is in the following form