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Temperature effect on qubit in RbCl quantum rod

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ABSTRACT

We change the ellipsoidal boundary in a quantum rod (QR) into a spherical one by a coordinate transformation, and then study the influences of the ellipsoid aspect ratio and polaron radius on the probability density (PD) and oscillation period (OP) of an electron with the variational method of Pekar type (VMPT). By employing the quantum statistics theory (QST), we investigate the temperature effects on the PD and the OP. Numerical results denote that the electron probability density and the oscillation period increase (decay) with raising temperature in lower (higher) temperature regime. The electron probability density increases (decreases) with increasing ellipsoid aspect ratio when the temperature is in lower (higher) regime. The electron probability density decays (enhances) with increasing polaron radius when the temperature is in lower (higher) temperature regime. The oscillation period is an increasing function of the ellipsoid aspect ratio, whereas it is a decreasing one of the polaron radius.

1. Introduction

Ever since the shape controlled colloidal quantum rods (QRs) were realized in experiments by modifying the synthesis [1,2], it has become a hot investigation field in quantum functional devices due to its novel electronic structures, optical properties, and the linearly polarized emission. QRs constitute the bridges between two-dimensional quantum wells and zero- dimensional quantum dots (QDs) and one-dimensional quantum wires. The transition regime from quantum wells to QDs and to quantum wires is particularly of interest in the colloidal semiconductor QRs because the size and shape control enables the synthesis of QRs with precise length and diameter. [3,4] Therefore, by tuning the aspect ratio of the ellipsoid, one can follow the transition from two- to zero- and one-dimensional systems. Consequently, there has been a large amount of experimental work on QRs [5–7]. Many investigators studied the properties of the QRs in many aspects by a variety of theoretical methods [8,9]. For example, using linear-combination operator method, we [10] have studied the vibrational frequency and ground state binding energy of strong-coupling magnetopolaron in a QR. Several schemes have been proposed for realizing quantum computation in recent years [11,12]. It is known that the two energy levels in a QD can be viewed as a natural single qubit. For such a single electron QD qubit, Li et al. [11,13] proposed a parameter-phase diagram and defined the parameters' region based on a two-level qubit in InAs/GaAs QD. Using the VMPT, Wang [14] investigated the properties of the parabolic linear bound potential and optical phonon in parabolic QD qubit. In practice, the experimental works on qubits are usually performed at finite temperature [15,16]. However, quantum systems are very frail and the temperature destroys the quantum coherence of the stored information [17]. Due to the prolonged time of quantum coherence, the temperature effects of the QD qubit should be investigated. By utilizing the VMPT and QST, Chen and Xiao [18] theoretically

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investigated the temperature effect of the parabolic QD qubit. Xiao [19] employed the same method to examine the effect of temperature and Coulomb bound potential on QR qubit. The effects of the temperature, the ellipsoid aspect ratio and the polaron radius on the properties of the RbCl QR qubit, however, have not been investigated so far by employing VMPT and QST. Especially, the influence of the polaron radius on the properties of the quantum rod qubit have never been investigated yet. To obtain more information about temperature and electrons, the readers are referred to Refs. [20–22].

In the present paper, we study the effects of the temperature, the polaron radius and the ellipsoid aspect ratio on the qubit in RbCl QR by using VMPT and QST.

2. Theoretical model

Considering a RbCl QR of polar crystal in the presence of the electron-bulk longitudinal optical (LO) interaction, the Hamiltonian of an electron bound to a three-dimensional anisotropic harmonic potential can be written within the framework of effective mass approximation as: [23]

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

where the meanings of the physical quantities in Eq. (1) are the same with Ref. [23]. V_q and α in Eq. (1) are

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

Using the coordinate transformation [24], which changes the ellipsoidal boundary into a spherical one: $x'=x$, $y'=y$, $z'=z/e'$, where e' is the ellipsoid aspect ratio and (x', y', z') is the transformed coordinate. The Hamiltonian of the system in the new coordinate is varied to H'. Then, we carry out the following Lee-Low-Pines transformation to H'

$$U = \left[\sum_{\mathbf{q}} a_{\mathbf{q}}^+ f_q - a_{\mathbf{q}} f_q^*\right], \tag{3}$$

where $f_q(f_q^*)$ is the variational function. Following the Pekar [25–27] variational method, the trial ground state and the first-excited state wavefunctions of the electron can be described as [28–29]

$$|\phi_0(\lambda_0)\rangle = |0\rangle\left|0_{ph}\right\rangle, \tag{4}$$

$$|\phi_1(\lambda_1)\rangle = |1\rangle\left|0_{ph}\right\rangle, \tag{5}$$

where λ_0 and λ_1 are the variational parameters. The ground state and the first-excited state energies of electron in a RbCl QR can be given as

$$E_0(\lambda_0) = \frac{\hbar^2}{2m}\left(1 + \frac{e'^2}{2}\right)\lambda_0^2 + \frac{m\omega_{\rho'}^2}{2\lambda_0^2} + \frac{m\omega_{z'}^2}{4\lambda_0^2 e'^2} - \frac{\sqrt{2}}{\sqrt{\pi}}\alpha\hbar\omega_{LO}\lambda_0 R_0 A(e'), \tag{6}$$

$$E_1(\lambda_1) = \frac{\hbar^2}{2m}\left(1 + \frac{e'^2}{2}\right)\lambda_1^2 + \frac{m\omega_{\rho'}^2}{2\lambda_1^2} + \frac{3m\omega_{z'}^2}{4\lambda_1^2 e'^2} - \frac{7\sqrt{2}}{8\sqrt{\pi}}\alpha\hbar\omega_{LO}\lambda_1 R_0 A(e'), \tag{7}$$

where $R_0 = (\hbar/2m\omega_{LO})^{1/2}$ is the polaron radius. $A(e')$ is written as

$$A(e') = \begin{cases} \dfrac{\arcsin\sqrt{1-e'^2}}{\sqrt{1-e'^2}} & e' < 1 \\ 1 & e' = 1 \\ \dfrac{1}{2\sqrt{1-e'^2}}\ln\dfrac{e'+\sqrt{e'^2-1}}{e'-\sqrt{e'^2-1}} & e' > 1 \end{cases} \tag{8}$$

Based on the variational method, we can obtain λ_0 and λ_1 and thus to get the eigen levels and eigen wave-functions. So a two-level system as a single qubit is built up. The superposition state of electron in a QR can be expressed as

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), \tag{9}$$