Spin-orbit interaction and spin relaxation in lateral quantum dots

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We report results of calculations of the effect of spin-orbit interaction on electron spin in lateral quantum dot. These calculations are motivated by puzzling results of high source-drain transport measurements of singlet-triplet transition of two electrons in lateral [1] and vertical [2] devices. On the low magnetic field side of the singlet-triplet transition both the singlet ground state and the excited triplet state are observed. Once the triplet becomes the ground state, the singlet-excited state is no longer observed. We associate the quenching of the current through the upper (singlet) state with an inelastic spin-flip relaxation mechanism mediated by spin-orbit interaction and involving the emission of a longitudinal acoustic phonon [3]. This dephasing mechanism presents a built-in magnetic field asymmetry compatible with the experimental observations and predicts an accelerated decay of the excited levels in the vicinity of the single-triplet transition.

We consider a two-electron system in a lateral quantum dot device. The quantum dot is defined within a two-dimensional electron gas (2DEG), with an additional lateral confinement produced electrostatically by voltages applied to gates located above the 2DEG. Assuming a parabolic confinement potential, the Hamiltonian describing a two-electron system in the presence of the spin-orbit interaction is written as

$$H = H_{kin}^{(1)} + H_{kin}^{(2)} + H_P^{(1)} + H_P^{(2)} + H_{SO}^{(1)} + H_{SO}^{(2)} + H_{e-ph}^{(1)} + H_{e-ph}^{(2)} + V_C^{(1,2)}$$

Here, H_{kin} denotes the kinetic Hamiltonian, H_P represents the confining potential, H_{SO} the spin-orbit interaction and V_C, the Coulomb interaction between the electrons. The electrons are subject to a scattering mechanism associated with the emission and absorption of longitudinal acoustic phonons, which is described by $H_{e\text{-}ph}$. The spin-orbit interaction presents two distinct contributions, the first one related to the absence of the inversion symmetry of the underlying bulk material (Dresselhaus term) and the second one originating from asymmetry of the macroscopic confining potential of the 2DEG (Rashba term). Using exact diagonalization techniques, we evaluate the magnetic field evolution of the energy spectrum and total spin of the two-electron droplet in the presence of spin-orbit interaction. The spin orbit interaction mixes singlet and three triplet components. This mixing, combined with electron-phonon interaction, is responsible for spin relaxation. We evaluate the spin relaxation rates due to electron-phonon scattering in first-order perturbation theory.

In the absence of the spin-orbit interaction, the transitions between the singlet and triplet states through the relaxation channel involving the emission of an acoustic phonon are forbidden by the spin-conservation rules. Our study shows that the spin-orbit interaction provides an effective coupling between the spin-polarized triplet states ($|S=1,S_z=\pm1>$) and the singlet state ($|S=0,S_z=0>$). More specifically, the transition $|S=1,S_z=1> \leftrightarrow |S=0,S_z=0>$ is facilitated by the Dresselhaus contribution to the spin-orbit coupling, while the $|S=1,S_z=-1> \leftrightarrow |S=0,S_z=0>$ becomes possible due to the presence of the Rashba term in the spin-orbit interaction Hamiltonian. However, the transition involving spin unpolarized singlet and triplet states ($|S=1,S_z=1>$, $|S=0,S_z=0>$, respectively) remains forbidden even in the presence of spin-orbit interaction. The scattering rates from the excited states to the ground state of the two-electron system, shown in Fig. 2, clearly confirm this picture and reveal a μs time scale for the single-triplet relaxation through spin-orbit mediated acoustic phonon emission. The physical origin of this phenomenon can be easily traced to the functional dependence of the spin-orbit interaction Hamiltonian on the individual spins of the two electrons in the system. We then argue that, if the dwell time of the second electron in the dot (the effective life-time of the two-electron droplet) is longer than the relaxation time times predicted by our calculations, spin-orbit coupling may provide a direct interpretation of the unusual transport measurements. For magnetic fields below the single-triplet transition point, the spin unpolarized state from triplet manifold of excited states cannot relax to the ground state, and should be observed in transport measurements. For higher magnetic fields, the excited state, now a singlet, has two available relaxation channels ($|S=0,S_z=0> \rightarrow |S=1,S_z=-1>$ and ($|S=0,S_z=0> \rightarrow |S=1,S_z=1>$), and it may relax to the ground state before being experimentally resolved, thus causing a quenching of the measured excited state transport current.

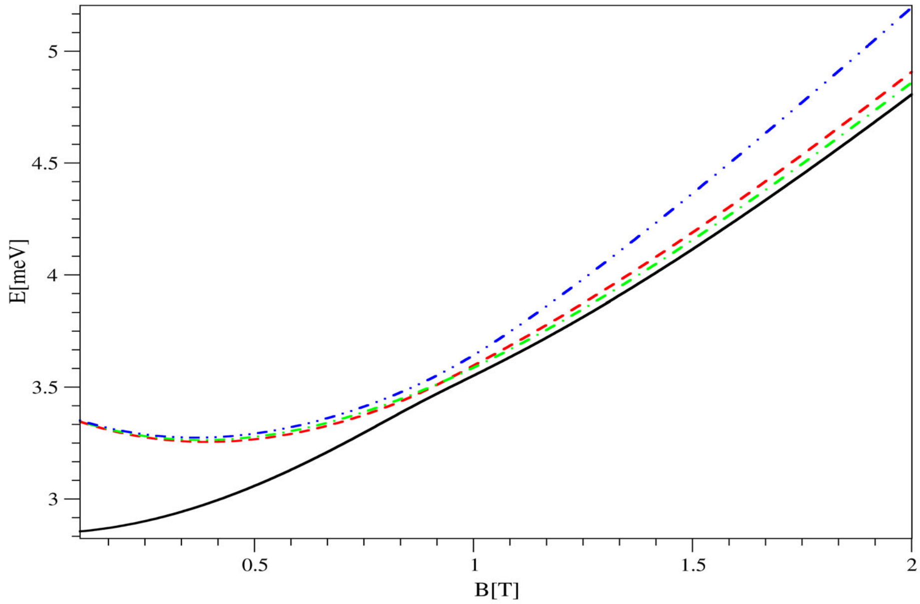

Figure 1. Lowest lying energy levels of the two-electron droplet as function of the magnetic field.

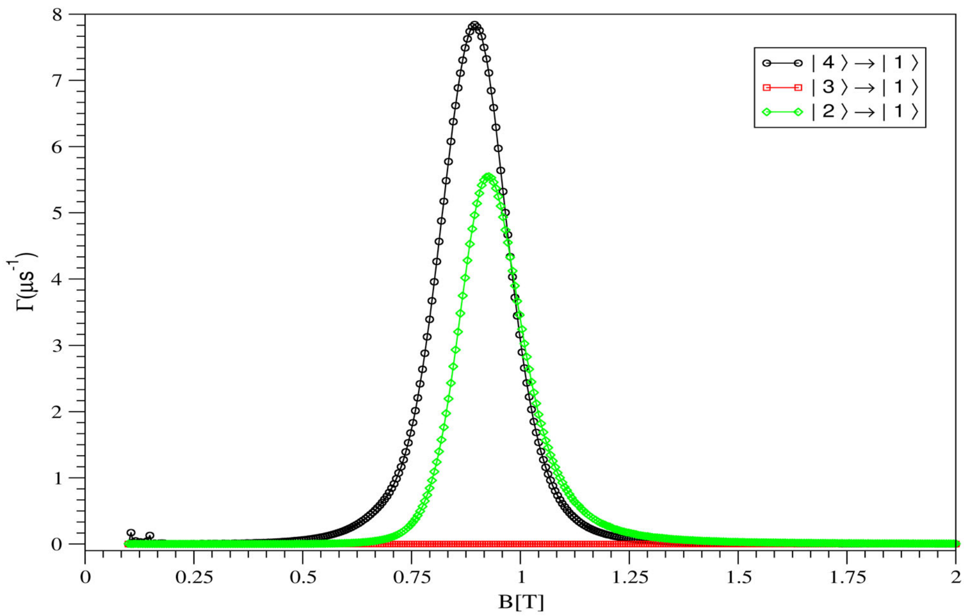

Figure 2. Electron-longitudinal acoustic phonon scattering rates from the excited states to the ground state of the two-electron system as a function of the applied magnetic field.

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