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Spin-conserved Single-electron Transport between Zeeman Sublevels in a Few-electron Quantum Dot

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Zeeman-splitting of an electronic state in a quantum dot is a fundamental characteristic for understanding spin-dependent phenomena [1-3]. In a magnetic field, an one-electron state (total spin $S = 1/2$) splits into two Zeeman sublevels (the spin z-component $S_z = \pm 1/2$), and more generally a many-body state with total spin S splits into $2S+1$ Zeeman sublevels. However, since single-electron tunneling transition can change S and S_z just by 1/2, Zeeman splitting should always appear as a 'doublet' independent of the actual spin state. This simple but fundamental observation is discussed in this presentation. We introduce two electrochemical potentials for raising and lowering S_z and discuss single-electron excitation spectra depending on whether S is increased or decreased. The difference can be used to identify S in an arbitrary quantum dot. We also discuss Zeeman splitting of the excited states.

The experiment was performed on a single quantum dot fabricated in a standard AlGaAs/GaAs heterostructure (labeled by 'd' in the scanning electron micrograph in the inset of Fig. 1) [4]. Current measurement was performed in a dilution refrigerator with a two-axis vector-rotation magnet. The primary magnet (x axis, up to 7 T) is used to induce sufficient Zeeman splitting to be resolved in the transport measurement, and the secondary magnet (z-axis, up to 1 T) is used to change orbital degree of freedom in the dot. The actual number of electrons, N, in the dot is monitored by a quantum point contact (PC) which acts as a charge detector [5]. We observed tunneling current for $N > 3$ by simultaneously changing four gate voltages to maintain the current in a reasonable range (~ 100 pA) as shown in Fig. 1. Stable and clear excitation spectrum was obtained for $N = 5 – 8$.

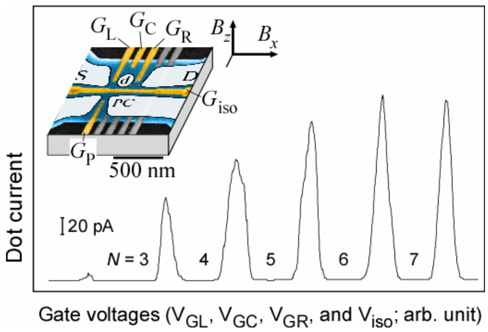

Fig. 1. Coulomb blockade oscillation of a single quantum dot for studying Zeeman splitting. The inset shows the sample orientation for the two-axis magnetic field (B_x and B_z). An SEM image of a device is attached.

Figure 2 shows the excitation spectrum of $N = 6$ quantum dot as a function of B_z. Some orbital characteristics of the states are resolved in Fig. 2(a) measured at $B_x = 0$ T. The spectrum around $B_z = 0$ T should strongly depend on the confinement potential of the dot, which is unpredictable for our deformed quantum dot. Above $|B_z| > 0.5$ T, the energy spacing of the states gradually decreases with increasing $|B_z|$, which often appear in similar quantum dots and are attributed to the states forming the lowest Landau level in the high-field limit [6,7]. When the in-plane field B_x is applied [Figs. 2(b)-(d)], almost all peaks (for instance, peaks A, β and γ) in the spectra split into two (Zeeman splitting). The effective g factor is about 0.28, which is within the variation of the reported value of similar GaAs quantum dots. However, one can notice that the peak α (the ground state at $|B_z| > 0.4$ T) does not show Zeeman splitting. As B_x is increased, peak α comes closer to the lower Zeeman branch of the peak β and coincides at 7 T [Fig. 2(d)]. It

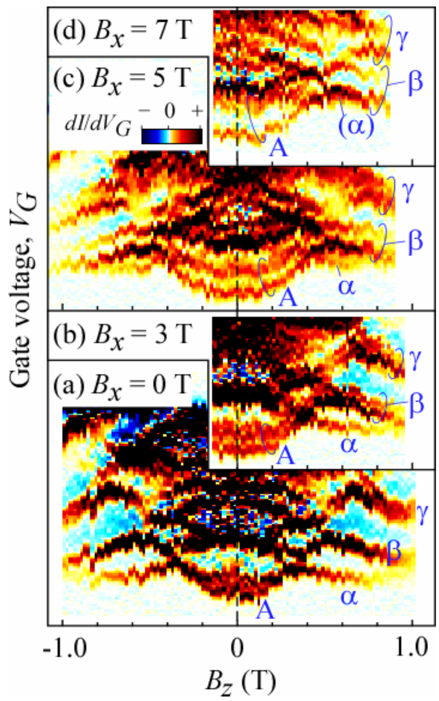

Fig. 2. Excitation spectrum of $N = 6$ quantum dot as a function of the gate voltage (vertical axis) and perpendicular magnetic field B_z. Peak A, β, and γ show Zeeman splitting at high in-plane field B_x, but no splitting is observed for peak α.

seems that the spacing between peak α and the upper branch of peak β is unchanged. Note that the ground state at $|B_z| < 0.3$ T (peak A) shows the Zeeman splitting.

These characteristics can be explained by considering electrochemical potential between Zeeman sublevels. Suppose the N-electron ground state has total spin S_0 and the (N-1)-electron ground state has total spin S_{-1}. The transport is allowed only for $S_0 = S_{-1} \pm 1/2$, where the total spin is either raised or lowered by 1/2. The spin degeneracy, $2S_0+1$ for N- and $2S_{-1}+1$ for N-1-electron systems, is lifted in a magnetic field as shown in Figs. 3(a) for the raised case ($S_0 = S_{-1} + 1/2$) and in 3(b) for the lowered case ($S_0 = S_{-1} - 1/2$). The spin selection rule on the z-component restricts the possible tunneling transitions to those shown by the arrows. Electrochemical potential for each transition is given by the energy difference of the final state and the initial state. If g-factor is identical for all states, the electrochemical potential takes μ_+ or μ_- respectively for all transitions that raise or lower the spin z-component. Here, $E_z = \mu_+ - \mu_-$ is the Zeeman energy. Although totally $2S_0 + 2S_{-1} + 1$ transitions are allowed, there are only two electrochemical potentials, μ_+ and μ_-, for the allowed transitions.

If the spin is raised [$S_0 = S_{-1} + 1/2$ in Fig. 3(a)], transition from the lowest Zeeman sublevel ($S_z = -S_{-1}$) of the (N-1)-electron system has two paths, i.e., to the lowest and second lowest Zeeman sublevel of the N-electron system. However, only one transition path exists in the lowered spin case [$S_0 = S_{-1} - 1/2$ in Fig. 3(b)]. This is the difference whether the Zeeman splitting shows up or not. In order to highlight the difference, we calculated the tunneling current, I, based on rate equations that involve different spin states of interest. To account for the Zeeman splitting of peaks α and β, we assumed a doublet ground state $S_{-1} = 1/2$ for $N = 5$, a singlet ground state $S_0 = 0$ and triplet excited state $S'_0 = 1$ for $N = 6$. The differential conductance dI/dV_{SD} is plotted as a function of the bias voltage V_{SD} and the gate voltage V_G in Fig. 3(c) in the presence of large Zeeman splitting E_Z. Here, asymmetric tunneling rate $\Gamma_R = 10\ \Gamma_L$ and larger rates for the excited state are assumed. Conductance appears at the resonance of the electrochemical potential of the dot ($\mu_\pm$ for the ground state and $\mu'_\pm$ for the excited state) to the lead (μ_S and μ_D respectively for the source and drain). When V_G is swept at a large V_{SD} (dashed line), Zeeman splitting does not appear around the ground state peak ($\mu_S = \mu_+$) but do appear around the triplet excited state ($\mu_S = \mu'_\pm$). Note that faint Zeeman splitting appears at the other side for the ground state ($\mu_D = \mu_\pm$), which is sometimes observed in our experiment (not shown).

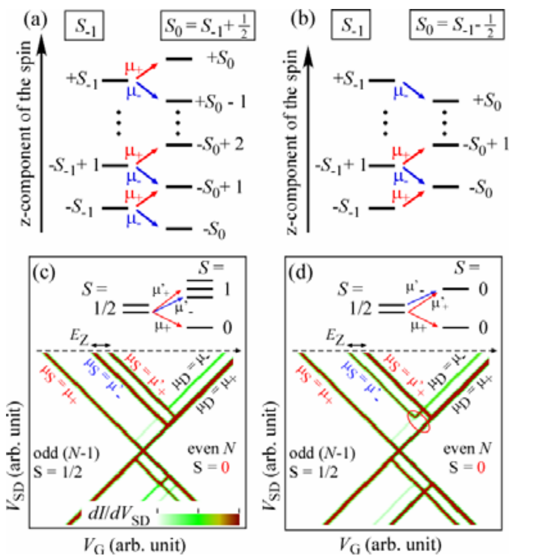

Fig. 3. (a) and (b) Schematic energy diagram of the tunneling transitions from spin state S_{-1} to S_0 for (a) the raised case ($S_0 = S_{-1} +1$) and (b) the lowered case ($S_0 = S_{-1} - 1$). (c) and (d) Calculated conductance in the V_G-V_{SD} plane for the lowered case. Triplet excited state is considered in (c), but singlet excited state in (d).

In contrast, Zeeman splitting of the ground state is expected at $\mu_S = \mu_\pm$, if it is a triplet state ($S_0 = 0$), which corresponds to peak A in Fig. 2. Other transitions that change the total spin more than 1/2 should be strongly suppressed (spin blockade). Therefore, one can identify whether the total spin is raised or lowered by 1/2 from the N-1 electron state. Observation in Fig. 2 implies a spin transition from singlet to triplet at $|B_z| = 0.4$ T. One can consecutively investigate spin state by starting from one-electron dot ($S = 1/2$).

Figure 3(c) also indicates that ‘two-fold’ Zeeman splitting is appeared for the *triplet* excited state. If we replace the triplet excited state with a singlet, similar ‘two-fold’ Zeeman splitting is reproduced for the *singlet*. The difference appears in the small region (inside the red circle), where the excitation from the upper Zeeman sublevel of N-1 dot to the singlet excited state (μ'_-) is not allowed for $\mu_- < \mu_D < \mu_+$. This difference can be used to identify the excited state.

In summary, single-electron transport through a few-electron quantum dot is investigated under in-plane and perpendicular magnetic fields. Zeeman splitting always appears as two conductance peaks, whose conditions depend on whether the total spin is raised or lowered by single-electron tunneling. The total spin of the state can be identified by analyzing Zeeman spitting.

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