Zeeman splitting in single-electron transport through a few-electron quantum dot

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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 ground state can be identified by consecutively investigating the Zeeman splitting from a known spin state. Zeeman splitting for some excited states is also discussed.

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Many-body electronic states in a few-electron quantum dot can be characterized by the number of electrons, N, and the total spin, S, in the presence of Coulomb interactions.1 Actually, spin states have been identified in a well-defined two-dimensional harmonic potential,2,3 in a moderate magnetic field where electrons occupy some orbitals associated with the first and second Landau levels,4 and in a double quantum dot where electrons occupy spatially separated orbitals.5 The assignment of these spin states is based on the orbital characteristics, which strongly depends on the magnetic field or electric potential, but not on the direct spin effect. Spin states can hardly be identified at arbitrary conditions in typical distorted quantum dots.6 The determination of spin states (spin degeneracy) is important for understanding spin-dependent phenomena6 and studying spin-orbit and hyperfine interactions.7,8 Here, we propose and demonstrate Zeeman splitting measurement as a way to identify the total spin at least for the ground state. Since spin relaxation time (>100 µs) is much longer than the typical characteristic time of the transport (0.1–10 ns),9,10 we expect spin-conserved single-electron tunneling, where S and its z component Sz are raised or lowered just by 1/2, otherwise the tunneling is forbidden (spin blockade).11,12 The conductance peak for the N-electron ground state splits into two (independent of the degeneracy 2S+1) when S is raised from that for N−1 electron number, while no splitting (independent of S) appears when S is lowered. Therefore, as long as the transport is allowed, one can examine the total spin of a few-electron quantum dot by consecutively investigating the appearance of Zeeman splitting starting from the one-electron spin state (S=1/2).

Suppose the N-electron ground state has total spin S0 and the (N−1)-electron ground state has total spin S−1. We have previously demonstrated using pulse-induced tunneling transitions that the transport is allowed only for S0=S−1±1/2.12 Therefore, our aim is to distinguish whether the total spin is raised or lowered by 1/2. The spin degeneracy for (N−1) and N-electron systems is lifted in a magnetic field as shown in Fig. 1(a) for the raised case (S0=S−1+1/2) and in Fig. 1(b) for the lowered case (S0=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 μi,j=Ei(Sj)−En−1(Sj), where Ei(Sj) is the total energy of the N-electron system with spin z component Sz. Assuming the same Lande g factor for both systems, the electrochemical potential μi,j takes μ+ or μ−, respectively, for all transitions that raise or lower the spin z component. Here, Ei=μ−μ0 is the Zeeman energy. Although totally 2S0+2S−1+1 transitions are allowed, there are only two electrochemical potentials, μ+ and μ−, for the allowed transitions.

We calculated the tunneling current I based on rate equations that describe all possible transitions.13 We considered the asymmetric tunneling rate ΓL=10ΓR, which is close to our experimental condition described below. The smaller injection rate (ΓL≤ΓR) at positive VDS in our case is preferred to investigate N-electron excitation spectra, where conductance peaks appear at the alignment of the source chemical potential μS to N-electron electrochemical potentials [see the inset to Fig. 1(c) at μS=μ+]. The transconductance dI/dVDS is

FIG. 1. (Color) (a), (b): Allowed tunneling transitions between Zeeman sublevels in the N−1 (left) and N (right) electron systems. Total spin S0 for the N electron system is raised from total spin S−1 for the N−1 electron system in (a), but lowered in (b). (c), (d): Calculated transconductance in the VDS-VG plane, respectively, for the situations in (a) and (b). The inset to (c) is a schematic energy diagram at μS=μ+ and VDS>0.
plotted as a function of the bias voltage $V_{DS}$ and the gate voltage $V_G$ in Fig. 1(e) for a typical raised case ($S_0=1$ and $S_{-1}=1/2$) and Fig. 1(d) for a typical lowered case ($S_0=0$ and $S_{-1}=1/2$). The Zeeman splitting appears in a different way as clearly shown. When the gate voltage is swept along the dashed line in this situation, conductance peaks for Zeeman splitting appear at $\mu_S=\mu_k$ only for the raised case. A faint peak at $\mu_D=\mu_-$ may be visible for the lowered case ($\mu_D$ being the chemical potential of the drain), but can be distinguishable from the condition $\mu_k=\mu_S$. We use this difference to investigate the total spin of the system.

Figure 2(a) shows a scanning electron micrograph (SEM) of a control device. A single quantum dot is formed in the upper channel, and the number of electron $N$ in the dot is monitored by the quantum point contact (PC) in the lower channel. The PC conductance ($10-20 \mu S$) in the tunneling regime is influenced by the charge state of the dot. Figure 2(b) shows the PC current as a function of the gate voltage $V_{GL}$ for the dot, where small jumps correspond to electron depletion from the dot. $N$ can be decreased to 0 by securing the depleting path at least to the drain contact. Observation of the last jump before the depleting path is quenched ensures the zero electron state ($N=0$) in the leftmost region in the figure, and thus we can identify $N$ by counting the jumps. We adjusted all gate voltages to control the dot potential and the two tunneling barriers to allow transport measurement with asymmetric tunnel rates ($\Gamma_R \sim 10\Gamma_L$). Since the dot current was noisy and thus unreliable for $N<5$, we had to discuss excitation spectrum for $N=5-8$. In order to demonstrate the Zeeman splitting at various conditions, we used a two-axis vector magnet to apply perpendicular magnetic field $B_z$ (up to $\pm 1$ T) to change orbital degree of freedom and to apply in-plane magnetic field $B_x$ (up to $\pm 9$ T) to induce Zeeman splitting.

Figure 3 shows $B_z$ dependence of excitation spectra from the $N=5$ system [Fig. 3(d)] to the $N=8$ system [Fig. 3(a)] measured at $B_z=5$ T. Clear Zeeman splitting marked by “$\uparrow”s is observed in all spectra, and the splitting is almost proportional to the magnetic field. For instance, the $B_z$ dependence of the spectra for $N=6$ system is shown in Fig. 3(e) at $B_z=0$ T and Fig. 3(f) at 0.65 T. The observed $g$ factor, $|g|=0.2-0.3$ depending on the states and fields, is within the variation of the reported values for GaAs quantum dots.

Now, we carefully investigate the appearance of Zeeman splitting from $N=5$. The ground state [lowest splitting, labeled $5g$ in Fig. 3(d)] and excited state $5e$ are clearly resolved, and no level crossing is observed in this magnetic field range. Here, to investigate systems with larger $N$ we assume spin doublet ($S=1/2$) for the $N=5$ ground state, in which four electrons form two spin pairs leaving the last electron unpaired. The next $N=6$ spectra in Fig. 3 shows level crossing at $B_z \approx \pm 0.4$ T. In the low field region $|B_z| \leq 0.4$ T, clear Zeeman splitting is observed [labeled $6g$ in Figs. 3(c) and 3(e)]. From the above discussions, the appearance of the Zeeman splitting indicates that $S$ is raised by 1/2, and thus the $N=6$ ground state is a spin triplet ($S=1$) in this region. In contrast, no Zeeman splitting is observed for the ground state at $|B_z| > 0.4$ T [labeled $6g^*$ in Figs. 3(c) and 3(f)], indicating a spin singlet ($S=0$) ground state.

Similarly, the total spin can be determined consecutively for larger electron numbers. The ground state of the $N=7$ spectrum in Fig. 3(b) exhibits no Zeeman splitting at $|B_z| \leq 0.6$ T (labeled $7g$), indicating a spin doublet ($S=1/2$) by lowering the total spin $S=1$ for $N=6$ in the same field region. Zeeman splitting is observed at $|B_z| > 0.6$ T (labeled by $7g^*$), indicating spin doublet ($S=1/2$) by raising $S=0$ for...
spin 1/2 in our example, but this ambiguity can be removed consecutively. We started from the this way, the total spin of the ground states can be identified as asymmetry current with respect to the polarity of the bias given by the allowed tunneling probabilities and the Clebsch-Gordan coefficients. The ratio of the incoming and outgoing tunneling rates is given by \((2S+1)/(2S',+1)\), which can be used to identify the spin. However, the ratio is often affected by voltage-dependent barriers. The appearance of Zeeman splitting used in our work avoids quantitative measurement and provides an alternate way to determine the spin state.

In general, high spin states appear when the exchange energy exceeds the kinetic energy, which is known as generalized Hund’s rule. One would expect there to be a relation between the effective one-electron energy spectrum for the kinetic energy and the two-electron spectrum including the Coulomb interaction. The low energy spectrum of the \(N=7\) quantum dot [Fig. 3(b)] can be regarded as for the effective one-electron case, where the orbital crossing \((7g\text{ and }7g')\) for the same spin 1/2 is observed. The triplet ground state \((8g'\text{)}\) observed in the \(N=8\) dot may be associated with the spin-triplet correlation between the orbitals. However, the \(N=6\) ground state shows a triplet at zero magnetic field even when the two levels \((5g\text{ and }5e)\) for \(N=5\) are well separated. Further discussions are out of the scope of the paper, but we believe that, from the Zeeman splitting analysis, we can identify the total spin of the system without knowledge of orbital characteristics.

Next, we discuss Zeeman splitting for excited states. We cannot apply the same rule to the excited states. The two chemical potentials \(\mu_+^{(e)}\) and \(\mu_-^{(e)}\), which are now for an excited state, appear as Zeeman splitting in the single electron transport regime even if the excited state is a singlet. Actually, all excited states in Fig. 3 exhibit Zeeman splitting. The question then is as follows: Can we determine the spin state of excited states? Figures 4(a) and 4(b) show the calculated transconductance when the total spin of the ground state is lowered \((S_0=S_{-1}=1/2; S_0=0\text{ and }S_{-1}=1/2)\). We considered an \(N\)-electron excited state with spin singlet for the calculation in Fig. 4(a) and triplet for that in Fig. 4(b). The conductance pattern is more or less the same except inside the circles, where the conductance peak at \(\mu=\mu_+^{(e)}\) for \(\mu_+^{(e)}<\mu_-^{(e)}\) appears only for the triplet excited state. As illustrated in the inset of Fig. 4(a), excitation from the lowest Zeeman sublevel of the \(N-1\) electron system to the \(N\)-electron singlet excited state is allowed only with electro-

chemical potential \(\mu_+^{(e)}\) (the red line). In contrast, the inset of Fig. 4(b) illustrates that the excitation to the triplet state is allowed with both \(\mu_+^{(e)}\) and \(\mu_-^{(e)}\) (the red and blue lines, respectively). This difference can be used to identify the excited states. Except for the special case in Fig. 4, however, it may be hard to identify an excited state without a quantitative discussion of the conductance. When the \(N\)-electron ground state is raised, the excited state transport can be obtained only when higher Zeeman sublevels of the \(N-1\) electron system can be occupied. This prevents identifying the excited state.

Figure 5 shows the transconductance profile \(dI/dV_G\) in the \(V_G-V_D\) plane at (a) \(B_x=0\) T and (b) \(B_x=5\) T. At zero magnetic field, transconductance peaks (or dips) associated with the ground state (electrochemical potential \(\mu_+^{(g)}\)), the first excited states (\(\mu_+^{(e)}\) for \(N=6\), and the excited state (\(\mu_+^{(e)}\)) for \(N=5\) are clearly resolved. These peaks in the positive and negative \(V_D\) regions are extrapolated to \(V_D=0\), where the corresponding potentials are labeled. When the in-plane field is applied [Fig. 5(b)], all electrochemical
potentials exhibit Zeeman splitting ($\mu_B$) and corresponding transconductance peaks are identified by tracking their in-plane field dependence. The appearance of the Zeeman splitting for the ground state transport is similar to the pattern in plane field dependence. The appearance of the Zeeman split-transconductance peaks are identified by tracking their in-

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identify the total spin of the

$\text{ground state is raised}$

from the lowest Zeeman sublevel of $N=6$, which is magnified in Fig. 5(d), suggests the excitation

$\text{and different } S \text{ [for instance, the singlet state crosses } S_z=1 \text{ of the triplet state at } B_x=7 \text{T in Fig. 3(f)], where spin-orbit and hyperfine interaction would play an important role in electron dynamics.}$

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In summary, we have proposed and demonstrated a way to identify the total spin of the ground states and some excited states of a few-electron quantum dot by considering single-electron tunneling transitions between Zeeman sublevels. This scheme is useful in identifying level crossing with different spin states. Actually, we see some conductance peaks associated with different $S$, and different $S_e$ for in-

$\text{plane field dependence.}$

In this case, we cannot

$\text{identify } S=3/2 \text{ for the } N=5 \text{ excited state. Instead, the}$

$\text{excitation from the lowest Zeeman sublevel of } N=6 \text{ to the lowest Zeeman sublevel of } N=5$, as illustrated by the red line in Fig. 5(c). This identifies $S=3/2$ for the $N=5$ excited state. In this way, the spin state of the first excited state can be determined.

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