Multi-orbital Kondo Effect in a Vertical Quantum Dot

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Rich aspects of the Kondo physics have recently been explored in quantum dots owing to the tunability of relevant parameters. One typical example of such new aspects is the singlet-triplet (S-T) Kondo effect realized in a vertical quantum dot holding even number of electrons [1]. The Kondo effect is strongly enhanced by the orbital degeneracy.

In this paper, we present a new mechanism for the Kondo effect when a magnetic field induces an orbital degeneracy in a vertical quantum dot holding odd number, N, of electrons and spin S=1/2. The vertical dot sample is fabricated from an AlGaAs/InGaAs/AlGaAs double-barrier structure with a gate electrode wrapped around a circular pillar to change N (Fig.1). A standard lock-in technique is employed for the transport measurement in a dilution refrigerator with a base temperature of about 60 mK. Figure 2 shows a schematic magnetic field dependence of the electrochemical potential from N+1 (odd) to N+4 (even) occupying two crossing orbitals. Coulomb interaction favors a spin triplet state in the vicinity of the single particle level crossing for N+2, and the S-T degeneracy occurs on the dotted lines. Figure 3 shows a gray scale plot of the linear conductance as a function of gate voltage and magnetic field at 60 mK. The S-T Kondo effect is observed in the N=16 Coulomb blockade gap. As for N=15 and 17, the conventional S=1/2 Kondo effect is not clearly observed due to the too low Kondo temperature. However, the Coulomb blockade region shows high conductance at specific magnetic fields corresponding to the dashed lines in Fig.2. There, four states with the total angular momentum $M=M_1$, M_2 ($M_1 \neq M_2$) and $S_Z=\pm 1/2$ are degenerate if one neglects the Zeeman splitting, and the strong Kondo effect is expected as in the S-T Kondo effect. We define this new mechanism as "doublet-doublet" (D-D) Kondo effect. Figure 4 shows the temperature dependence of the dI/dV_{sd} vs. V_{sd} characteristic for the S-T and the D-D Kondo effect with the gate voltage fixed in the center of the respective Coulomb blockade gap. A clear zero-bias peak is observed at low temperatures, and its height is reduced as the temperature increases as expected. The temperature dependence of the Kondo peak height normalized by the low temperature limit value, G_0, is shown in Fig.5. No-Kondo cotunneling background is subtracted from each trace in Fig.4. Dotted lines are the theoretical curves [2] fitted to the data. The estimated Kondo temperatures for the S-T and the D-D Kondo effect are similar, indicating that four-fold spin and orbital degenerate states contribute to raise the Kondo temperature.

[1] S. Sasaki, S. De Franceschi, J. M. Elzerman, W. G. vander Wiel, M.Eto, S. Tarucha and L. P. Kouwenhoven, Nature 405, 764. (2000).
[2] T. A. Costi and A. C. Hewson, Phil. Mag. B **65**, 1165 (1992).

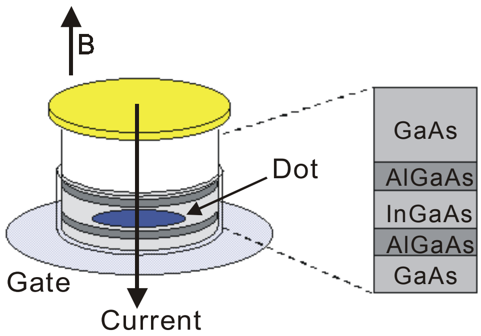

Fig.1

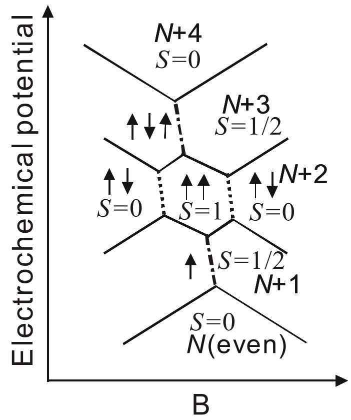

Fig.2

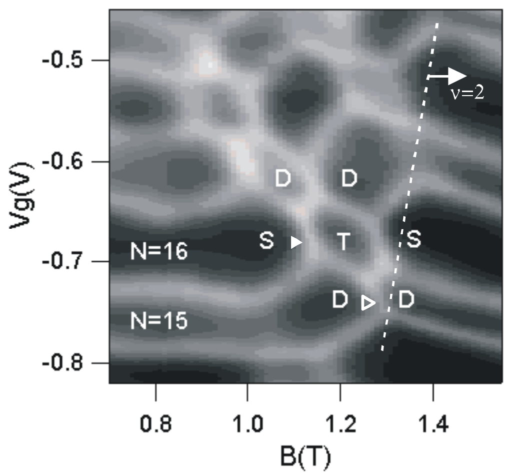

Fig.3

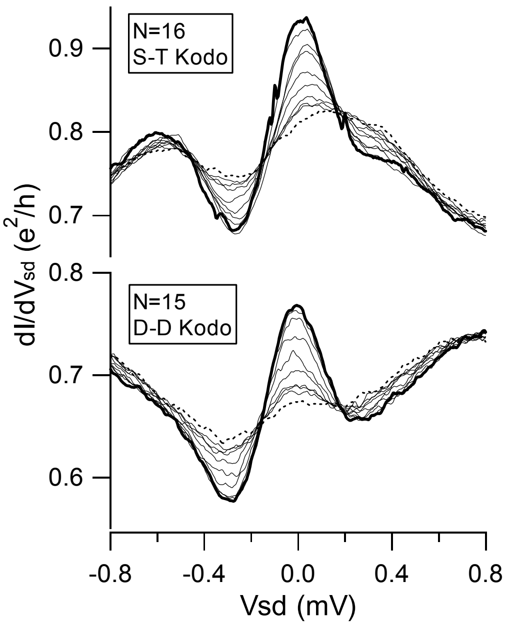

Fig.4

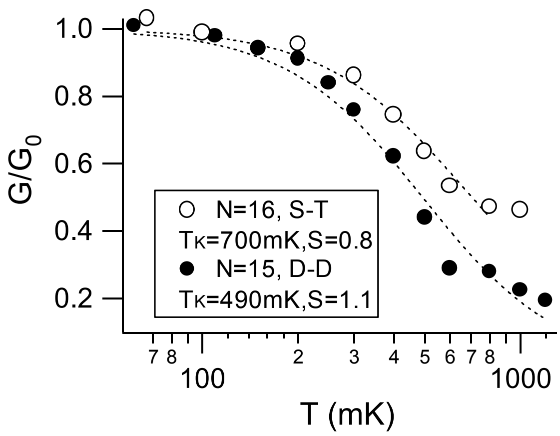

Fig.5