Asymmetry induced Singlet-Triplet Transitions in a Many-Electron Quantum Ring

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In quantum dots with only a few electrons the experimental addition spectra can be compared with advanced theories taking exchange interaction effects into account. Experimentally, singlet-triplet transitions have been observed in such systems as a function of magnetic field [1]. Addition spectra of many-electron dots are more difficult to understand quantitatively and most experimental studies compare with a statistical analysis based on random-matrix theory. We have shown [2] that the experimental spectrum of a Coulomb-blockaded quantum ring displays many features of the theoretically expected single-particle spectrum. Individual states can be identified by their angular momentum quantum number. Here we report a new set of experiments which allow us to draw conclusions about the evolution of the ground state spin of the many-electron quantum ring in the Coulomb-blockade regime as a function of the ring asymmetry.

The two-terminal ring structure (see Fig. 1(a)) was fabricated on a high mobility shallow Ga[Al]As heterostructure by AFM-lithography. Two in-plane plunger gates (pg1 and pg2) allow us to tune the number of electrons occupying the ring and the left/right symmetry of the ring. A metallic top gate covers the entire structure. Measurements were performed in a dilution refrigerator at a temperature of 100 mK.

The position of several conductance peaks in the Coulomb blockade regime oscillates as a function of magnetic field B applied normal to the plane of the electron gas reflecting the magnetic field dispersion of states with well defined angular momenta. We frequently observe so-called spin-pairs, i.e. pairs of neighboring conductance peaks moving in parallel (see Fig. 1(c)) as a function of magnetic field. In this case the current is carried by the same orbital state and the two involved state have a different spin like in a singlet state.

Applying voltages asymmetrically to the two plunger gates, i.e. $U_{\rm pg1} \neq U_{\rm pg2}$, we tune the asymmetry of the quantum ring. With a careful calibration of the lever arms we can extract the addition spectrum of the ring as a function of an asymmetry parameter α as shown in Fig. 1(d). An average charging energy has been subtracted between neighboring conductance peaks. We find clear kinks in conductance peak positions as a function of α indicating crossings of single-particle levels (thin grey lines). Spin pairs identified at $\alpha = 0$ from magnetic field sweeps show the same behavior as a function of α at $B = 77mT$ as expected for identical orbital wave functions. An interesting situation arises when another single-particle ($E_2(\alpha)$ inset Fig. 1(b)) level crosses the level of the spin pair ($E_1(\alpha)$ inset Fig. 1(b)).

At the start of the dashed arrow (lower left) we assume that the two topmost electrons in the dot form a singlet state and occupy the same orbital state. We then come to the conclusion that a change of α and δ along the arrow leads to a singlet-triplet transition beyond the first level crossing due to the exchange interaction favoring parallel spins. When the crossing level has passed also the second conductance peak of the spin pair, the singlet state of the spin-paired electrons is restored. The identification of a spin pair in B therefore allows us to construct a phase diagram of the ground state spin as a function of energy and asymmetry α as shown in Fig. 1(b). A similar diagram can be constructed starting from a finite ground state spin of the dot. In addition to these observations we find that the kinks due to level crossings induced by asymmetry depend also on magnetic field. The magnetic field dependence of the Kondo effect in this regime, i.e. a splitting of the zero bias anomaly at zero magnetic field, is consistent with our interpretation of an asymmetry induced singlet-triplet transition.

References:

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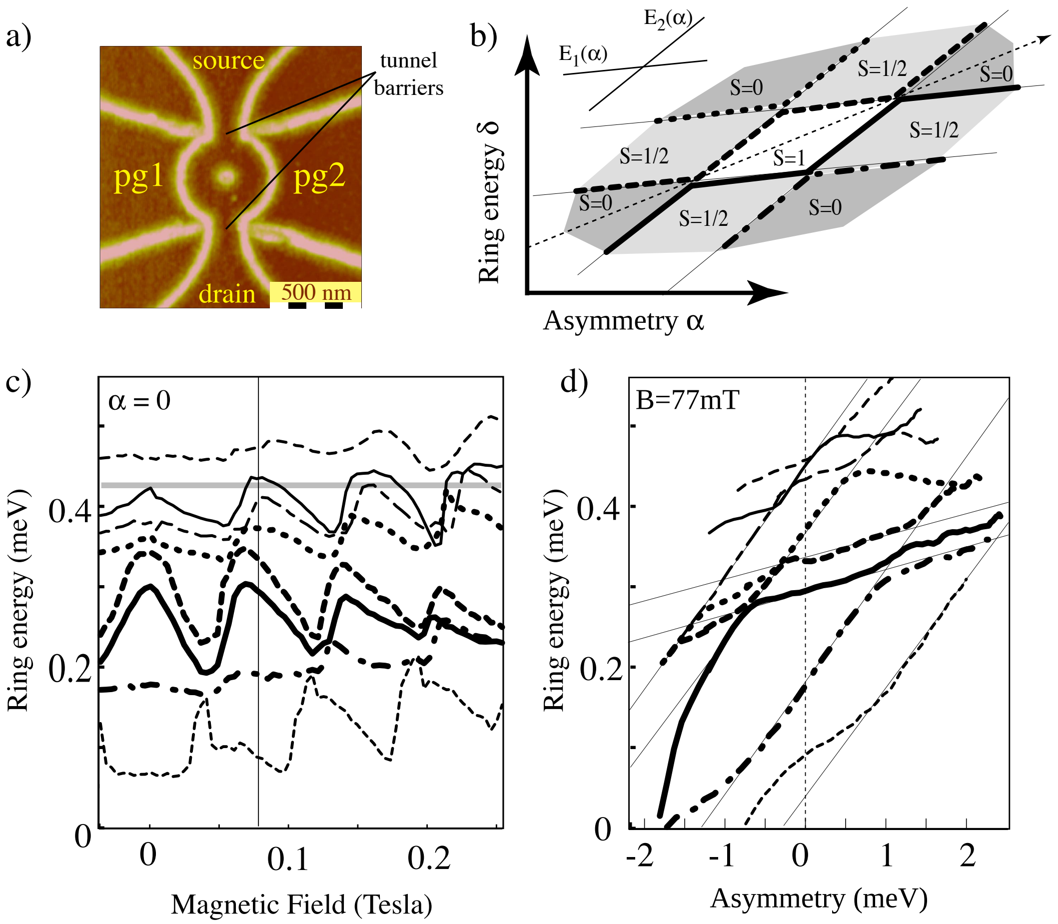

Figure 1: (a) Quantum ring sample defined by AFM-lithography. The plunger gates pg1,pg2 are used to tune the energy δ and asymmetry α of the ring. (b) Possible phase diagram for the groundstate spin of the ring in a situation where two orbital levels cross (see inset). Along the dashed line in the Coulomb blockade valley the groundstate spin of the ring is changed from a singlet to a triplet state. (c) Measured peak positions as a function of magnetic field after subtracting a constant charging energy. The two zig-zag peaks in the middle can be clearly identified as a spin pair. (d) Coulomb peak positions as a function of gate asymmetry for the same peaks as in a). Due to asymmetry induced level crossings no clear spin pairs can be observed. The thin lines are a guide to the eye to indicate the dispersion of the crossing orbital levels.