

Consistently Repeating Two-Orbital Level Crossing in a Quantum Dot with Many Occupied Orbitals

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Abstract

We perform an investigation to bridge the gap in understanding between the studies of quantum dots containing few and many electrons. The experimental technique, Single Electron Capacitance Spectroscopy, permits examination of dots' addition spectra while tuning the electron occupancy N from one to hundreds in *one* sample. To probe the nature of the states occupied by electrons, we follow the evolution of the addition spectrum with perpendicular magnetic field B .

The first few electrons fill well-known Darwin-Fock (DF) single-particle states as is typical for a small dot with parabolic confinement [1-3]. These levels exhibit multiple crossing as B grows. We find that near *every* crossing, the electron interaction becomes the dominant energy scale, even in a small dot for a small number of electrons. Thus, *four* successively added electrons redistribute between *two* different crossing spatial states. We describe the observed resulting patterns using simple Hartree-Fock model with a small exchange interaction between electrons in different states [4]. By gradually filling the dot with electrons, we decrease the single particle level separation, hence increasing the relative importance of the Coulomb repulsion. As the result, the regions of the spectrum strongly affected by the interactions expand until, at high enough N , no signature of DF states remains observable [5]. Our study presents a unifying picture for the two limits: the small N regime with dominant confinement and the large N regime with prevailing interactions.

The picture that we develop also applies to crossings near zero magnetic field. Contrary to the Hund's rule model observed in experiments with dots containing 3, 4, 5, and 6 electrons[3], we observe, neither large (greater than two-fold) symmetry-related degeneracy of orbitals at zero magnetic field nor corresponding filling of the dot with three or more parallel spin electrons. Instead, the simple picture of interactions between electrons in pairs of discrete, single particle-like, orbitals applies throughout the spectrum.

In Figure 1, we show that we can collapse the addition spectrum for small N by simply subtracting constant electron addition energies from each trace. This collapse produces a spectrum in which traces from successive electron additions nearly perfectly align and touch at level crossings points throughout the image but nowhere do they cross. Hence, if the two highest energy electrons are treated independently of the others, the strength of the Coulomb interaction between them appears nearly constant in B . This occurs because neighboring crossings reflect transitions of electrons between respectively similar orbitals. A key feature of the data is that the spectrum shown contains two replicas of each Darwin-Fock state, as even traces do not collapse on top on the odd ones. Contrary to the single-particle model even and odd addition traces differ in shape, particularly in the vicinity of the orbital crossing points.

In essence, the single particle picture of filling quantum dots appears to fit our data well except for a specific type of failure that occurs at each level crossing. The Coulomb interaction *always* mixes each level crossing, and simple Hartree-Fock model considering only two levels describes well deviations from a single-particle DF picture. In our talk, we discuss how the same model accounts for erosion of even-odd asymmetry for the large N regime [5].

Figure 1. Collapsed addition traces *N*7-23. Traces for odd numbered electrons are shown in blue, even in magenta. Notice that throughout the image, blue and magenta traces meet at several points along each trace, but they never cross. The addition spectrum appears to collapse nearly perfectly, presenting a single-particle-like spectrum.

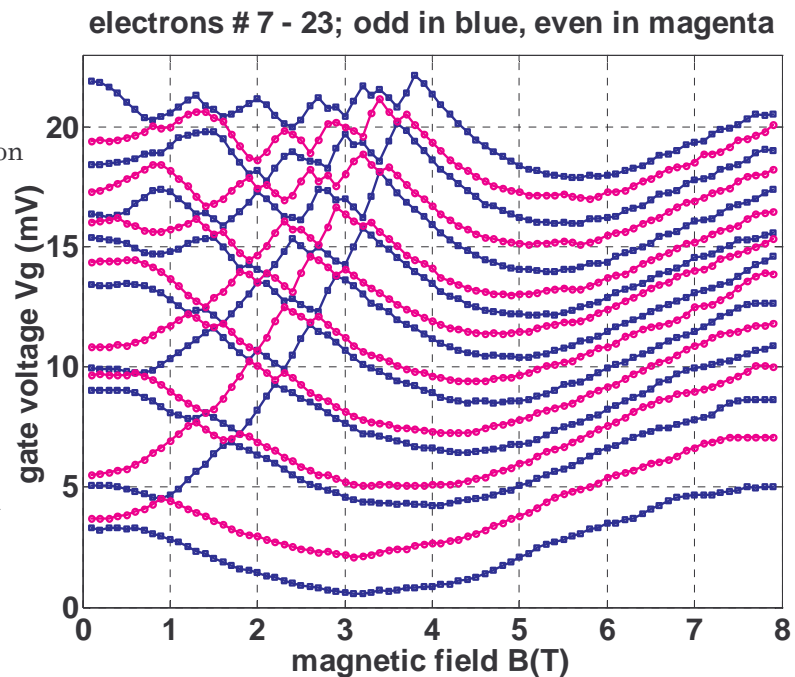
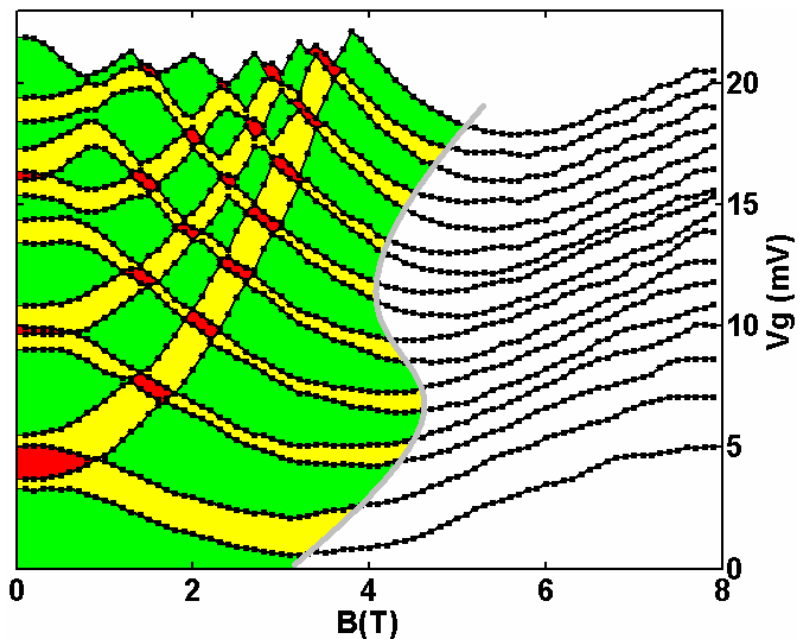


Figure 2. Collapsed addition spectrum as in Fig. 1. Green demarcates regions of the spectrum where our model indicates that the system has total spin zero. Yellow indicates spin $\frac{1}{2}$, and red indicates spin 1. Notice that, in contrast with expectations from a model considering Hund's rule, the spin never exceeds 1 for the range of *N* shown.



References

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