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Branch Current Behavior at Two Level Anti-crossings in Vertical Quantum Dot Single-particle Spectra

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Abstract. We study single-electron-elastic-resonant-tunneling through two weakly coupled vertical quantum dots and investigate the branch current behavior at anti-crossings between two single-particle energy levels in the constituent dot spectra that are induced to approach each other by application of an out-of-dot-plane magnetic field. We observe both the familiar case of monotonic transfer of the resonant current strengths between the two branches as well as the less familiar case of concurrent enhancement and suppression (ideally complete cancellation) of the resonant current in the two branches. These two situations can be explained in terms of a simple coherent tunneling model.

Keywords: Coherent level mixing, Quantum dots, Resonant tunneling
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INTRODUCTION

Anti-crossings between two approaching states are common to many different fields of physics. Representative examples in the solid-state arise at the crossing between direct (bright) exciton and indirect (dark) exciton states in coupled quantum dots in an electric field [1, 2], and for superconducting qubit-transmission line cavity coupling in a magnetic (B-) field [3].

Here, we outline our study of two level anti-crossings, and show two contrasting cases, one familiar and one less familiar, for the behavior exhibited by the branch currents.

EXPERIMENT

The device used in this study is a vertical double quantum dot molecule located in a sub-micron gated mesa made from a double quantum well triple barrier structure with weak inter-well tunnel coupling [4]. Using the ground state of one of the dots as an energy filter, we can probe the out-of-dot-plane B-field evolution of the single-particle energy spectrum of the other dot in the single-electron-elastic-resonant-tunneling regime [5, 6]. Overall, the spectra can be well modelled by the single-particle spectrum for a dot with an ideal elliptical two-dimensional parabolic confining potential [7] *except* in the regions where two (or more) single-particle states approach each other. In these regions, we commonly observe pronounced level mixing and quantum superposition effects which are unexpected in a picture of an ideal lateral confinement potential. These symmetry breaking effects are attributed to non-negligible anisotropy and anharmonicity in the dot confining potential [8].

We focus on two two-level-anti-crossings from single-particle dot spectra. These two anti-crossings, referred to hereafter as AX1 and AX2, have familiar-looking energy dispersions with distinct upper and lower branches (each branch is a mixed state made up of a linear combination of two basis states) with energy splittings ~0.5 meV for AX1 in Fig. 1(a) and ~0.2meV for AX2 in Fig. 1(b). However, the branch current dependences are very different. For AX1, we see in Fig. 1(c) the familiar monotonic exchange of strength between the two branches on passing through the anti-crossing. Namely, to the left (right) of the crossing point, the lower branch is strong (weak) and the upper branch is weak (strong). In contrast, for AX2, we see in Fig. 1 (d) that to the left and right of the crossing point, the upper and lower branches have roughly the same current values (~1.1 pA), while at the crossing point, the upper branch is enhanced (~2.2 pA) and the lower branch is essentially completely suppressed.

In order to understand the underlying difference in the branch current behavior of AX1 and AX2, and the general behavior at many other measured anti-crossings, we have developed a simple 2x2 matrix Hamiltonian level mixing model which allows us to compute the branch currents using a Fermi's golden rule argument within a simple coherent tunneling picture. Ultimately the branch current is computed as the square of the overlap integral of the prober dot's ground state with the probed dot's mixed state. Full details of our model will be given elsewhere [8]. The key difference between the two cases of AX1 and AX2 lies in the strength of the current carried by the two basis states, I_1 and I_2, effectively the branch currents well away from the crossing point. For the familiar case of monotonic exchange, AX1, the current through one basis state is much larger than the current through the other basis state, while for AX2, the two basis states carry similar currents. Although our model and the fitting of the experimental data is much more sophisticated, for illustration purposes, we simply show in Fig. 2 a simulation of the branch current dependences that reproduce the cases of monotonic exchange (AX1) and ideal enhancement and suppression (AX2). In these simulations, I_1=1 and I_2=0 (in arbitrary units) for AX1, and I_1=I_2=0.5 for AX2. Furthermore, I_1 and I_2 are assumed to be B-field independent.

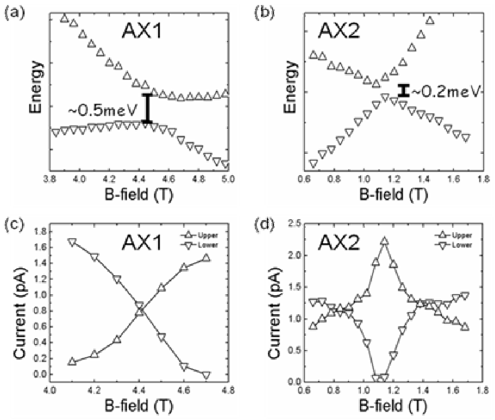

FIGURE 1. (a), (b) Energy dispersions for two two-level anti-crossings AX1 and AX2. (c), (d) Upper and lower branch currents for AX1 and AX2.

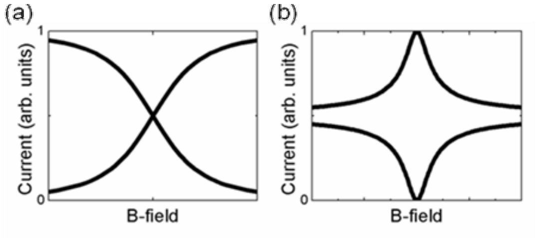

FIGURE 2. Simulated branch current dependences showing the cases of (a) monotonic exchange and (b) ideal enhancement and suppression (cancellation).

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