Transport Spectroscopy of a Spin-Coherent Dot-Cavity System


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Quantum engineering requires controllable artificial systems with quantum coherence exceeding the device size and operation time. This can be achieved with geometrically confined low-dimensional electronic structures embedded within ultraclean materials, with prominent examples being artificial atoms (quantum dots) and quantum corrals (electronic cavities). Combining the two structures, we implement a mesoscopic coupled dot-cavity system in a high-mobility two-dimensional electron gas, and obtain an extended spin-singlet state in the regime of strong dot-cavity coupling. Engineering such extended quantum states presents a viable route for nonlocal spin coupling that is applicable for quantum information processing.

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Transport spectroscopy provides an access to low-dimensional electronic and quantum structures with increased weight at the tunnel barrier [3]. Therefore, applying a voltage $V_{\text{cav}}$ generates an electronic mirror that confines quantized ballistic cavity modes with increased weight at the tunnel barrier [3]. Notably, we designed a cavity gate with a relatively small opening angle of 45° in order to confine only fundamental one-dimensional modes; i.e., high angular-momentum modes leak out into the drain. This guarantees unique identification and addressability of individual cavity modes.

We perform equilibrium transport spectroscopy of the dot-cavity system at an electronic temperature $T_{\text{el}} < 20$ mK [14,15]. The dot is tuned to the Coulomb blockade of the third electron-charge state. In this configuration, linear transport is dominated by the Kondo effect arising due to screening of the unpaired electron spin on the dot by the lead electrons [7,16,17]. In Figs. 1(b) and 1(c), we report on two measurements of the differential conductance $dI/dV_{SD}$ as a function of $V_{\text{cav}}$ with weak coupling and strong coupling between the dot and the drain-cavity system, respectively. In both configurations, we observe a constant Kondo conductance as long as the cavity gate does not deplete the 2DEG. Once the 2DEG below the cavity gate is depleted, an electronic cavity is formed with its states filled up to the chemical potential. Taking the lithographically defined length of $L_{\text{cav}} = 1.9$ μm and the Fermi wavelength $\lambda_F \approx 53$ nm, we estimate that upon formation $n_{\text{cav}} \approx 2L_{\text{cav}}/\lambda_F \approx 70$ states are filled. Applying increasingly negative $V_{\text{cav}}$, the cavity becomes shorter and its states rise in energy. As these states are focused on the tunnel barrier of the dot, they effectively enhance the tunnel...
In the strong-coupling cavity hybrid that competes with the Kondo screening. The reduction as the result of a spin-singlet formation within the dot and Kondo transport is quenched. We interpret this reduction in differential conductance as due to the Kondo effect. As the cavity voltage 

\[ V_{\text{cav}} \] changes, the energies and occupancies of the dot and cavity; \[ V_{\text{TBS}} \] and \[ V_{\text{TBD}} \] tune the coupling \[ \Gamma_S \] of the dot to source lead, whereas \[ V_{\text{TBD}} \] and \[ V_{\text{TBS}} \] tune the couplings \[ \Gamma_D \] and \[ \Omega \] of the dot to both drain and cavity modes simultaneously. We report measured differential conductance \[ g = dI/dV_{\text{SD}} \] of the dot-cavity system obtained at small bias \[ V_{\text{SD}} \approx -10 \text{ mV} \] in two coupling configurations \[ \Gamma_D \ll \Gamma_S \] (b) and \[ \Gamma_D \gg \Gamma_S \] (c). The dot is tuned to the Coulomb valley of the third charge state. As long as the cavity is not defined \( (V_{\text{cav}} > 50 \text{ mV}) \), constant transport is due to the Kondo effect. As the cavity voltage \[ V_{\text{cav}} \] depletes the 2DEG, a mirror forms that focuses quantized modes onto the tunnel barrier of the dot. (b) Tuning \[ V_{\text{cav}} \], the cavity modes are pushed through the chemical potential, causing peaks of increased Kondo conductance. These peaks are separated by a cavity-mode spacing \[ \delta_{\text{cav}} \approx 220 \text{ \mu eV} \] and have a width \[ \Gamma_{\text{cav}} \approx 40 \text{ \mu eV} \]. (c) Increasing \[ \Gamma_D \], signatures of strong coupling develop when the coupling \[ \Omega \] increases beyond the decay rate \[ \Gamma_{\text{cav}} \]. This strong coupling manifests in the appearance of split peaks with a gap \[ \Delta \approx 80 \text{ \mu eV} \], indicating the formation of a spin singlet on the dot-cavity hybrid that competes with and suppresses the Kondo effect. Different gray shades are applied to the background to highlight the effect of each cavity mode crossing the chemical potential. Note that the two measurements (b) and (c) are slightly shifted and stretched in \[ V_{\text{cav}} \] to correct for the different settings of \[ V_{\text{TBS}} \] and \[ V_{\text{TBD}} \].

Inferred extent of this coherent singlet state over the entire dot-cavity system is the main result of this Letter.

To better illustrate the impact of the cavity on standard dot transport, we compare finite-bias measurements of \[ g = dI/dV_{\text{SD}} \] in the absence [Fig. 2(a)] and presence [Fig. 2(b)] of the cavity as a function of a plunger gate voltage \[ V_{\text{dot}} \] that shifts the dot levels. The drain tunnel barrier is tuned to strong coupling with \[ \Gamma_S \approx \Gamma_D \]. Without the cavity \( (V_{\text{cav}} = +200 \text{ mV}) \), the typical pattern of a few-electron dot exhibits regions of suppressed conductance (Coulomb diamonds), resulting from blockade of the respective charge states \[ N = 2e^- \text{, } 3e^- \text{, } 4e^- \]. As the occupation of the dot increases, its orbital wave function is spatially more extended, thus enabling stronger tunnel coupling to the leads [6]. A pronounced zero-bias Kondo resonance appears in the Coulomb valley of \[ N = 3e^- \]. With the cavity switched on \( (V_{\text{cav}} = -200 \text{ mV}) \), we observe additional features in Fig. 2(b), i.e., new lines of increased conductance that pass through the regions of the Coulomb blockade, as well as pronounced modulation of the direct transport at the boundaries of the Coulomb diamond. Tuning \[ V_{\text{cav}} \] (not shown) sweeps these novel features horizontally through the Kondo resonance leading to its controlled modulation seen in Fig. 1(c). Notably, Figs. 2(a) and 2(b) allow us to characterize the system (see also Supplemental Material [18]), i.e., determine the tunnel coupling constants \[ \Gamma_S \approx \Gamma_D \approx 87 \text{ \mu eV} \] for this configuration, its charging energy \[ U \approx 700 \text{ \mu eV} \], and the cavity level spacing \[ \delta_{\text{cav}} \approx 220 \text{ \mu eV} \].
FIG. 3 (color online). (a) A sketch of an Anderson model depicting a dot with energies $e_i^{(j)}$, on-site interaction $U$, constant coupling $\Gamma_S$ to the source, and energy-dependent coupling $\Gamma_D(\epsilon)$ to the drain due to focused cavity modes [19]. In this model the effect of the cavity mirror on the dot is encoded as a structured tunneling amplitude, $\Gamma_D(\epsilon)$, into the drain lead. (b) A sketch of a coherent dot-cavity model where the $\Gamma_D(\epsilon)$ of the previous model is replaced by a noninteracting cavity with a discrete spectrum $e_c^{(j)}$ effectively coupled to the dot with $\Omega$ and to the drain lead by $\Gamma_{cav}$. (c) Calculated ground state map $|N_{cav}, N_{dot}\rangle$ of the dot-cavity hybrid as a function of $V_{cav}$ and $V_{dot}$ with (relative) occupation numbers $N_{dot}$ ($N_{cav}$) determining the ground state of the dot (cavity) for $\delta_{cav}/U = 0.5$ and $\Omega/U = 0.1$. Dark red shading marks the regimes of spin-singlet formation on the dot-cavity hybrid, where the Kondo resonance (orange) is suppressed. (d) Measurement of the linear conductance (with $V_{SD} = -10 \mu V$) in the strong-coupling regime. Lines of resonant transport match the boundaries between ground states in (c).

The cavity modes in the drain exhibit a remarkable coherence in view of the various relaxation and scattering processes within the drain. These modes affect the dot transport by modulating the tunneling density of states to the drain. A theoretical model that corresponds to this picture is sketched in Fig. 3(a). Analyzing the structure of the tunnel coupling to the drain, we are able to distinguish separated coherent cavity modes that are broadened by coupling to a bath [19]. The latter indicates that the cavity modes constitute an additional degree of freedom that is coupled to the dot, as described by the theoretical model sketched in Fig. 3(b). We assume that charging effects coupled to the dot, as described by the theoretical model modes constitute an additional degree of freedom that is coupling to a bath [19]. The latter indicates that the cavity separated coherent cavity modes that are broadened by tunnel coupling to the drain, we are able to distinguish picture is sketched in Fig. 3(a). Analyzing the structure of transport by modulating the tunneling density of states to processes within the drain. These modes affect the dot coherence in view of the various relaxation and scattering processes occurring when the dot changes its occupancy is similarly split by the strong coupling to the cavity modes. The compliance between the transport measurements and the coherent model in Fig. 3(b) suggests that the dot-cavity spin singlet. Using the model depicted in Fig. 3(b), we predict this gap to be $\Delta \approx 1/\Gamma'$ along with a decrease of $\Omega$. This explains the gap formation discussed in Fig. 1(c). Finally, the resonant transport (Coulomb peaks) occurring when the dot changes its occupancy is similarly split by the strong coupling to the cavity modes. The compliance between the transport measurements and the coherent model in Fig. 3(b) suggests that the dot-cavity setup constitutes a novel realization of the Kondo model [11], where a magnetic impurity (the dot spin) is screened by a metallic grain with a discrete spectrum (the cavity).

Equipped with this knowledge, we revisit the results of Fig. 1 and extend them to include out-of-equilibrium signatures as a function of $V_{SD}$. Figures 4(a)–4(c) present a controlled crossover from weak to strong coupling between the dot and the drain-cavity system (see also the Supplemental Material [18]). This is obtained by a stepwise increase of $\Omega$ and $\Gamma_D$ alongside a decrease of $\Gamma_S$. The zero-bias Kondo resonance is modulated [see Fig. 4(a)] as the cavity modes cross the leads’ Fermi level. At finite bias, cotunneling transport is enhanced whenever the cavity modes are aligned with the source lead. The enhanced cotunneling lines connect at zero bias to Kondo transport that benefits from the same enhanced coupling. At stronger coupling [see Figs. 4(b)–4(c)] the transport exhibits a
entire device. This has important ramifications for both which manifests as a spin singlet extended over the setup point to coherent coupling between its constituents with the model defined in Fig. 3(b). Additional parallel lines at opposite features, such that one cavity mode gives rise to two cotunneling via the dot

cavity. The dot transport in the two-electron state exhibits an additional signature at finite bias voltage due to inelastic cotunneling through the triplet states of the dot. Note the adjusted color scales in (d), (e), and (f) to improve the visibility of the cotunneling currents. Dashed lines in (b) and (e) indicate the correspondence to Figs. 2(a) and 2(b).

The emerging dot-cavity model is similar in structure to the Kondo box problem that predicts splitting of the Kondo peaks with anomalous scaling [11]. Thus, our setup conforms to a controllable experimental realization of such a mechanism competing with the standard Kondo resonance. This places our results alongside notable mechanisms that compete with the standard Kondo effect, such as Ruderman-Kittel (-Kasuya)-Yosida interactions [22], two-channel Kondo [23], and singlet–triplet switching on a molecule [24]. In the future, it will be interesting to study the temperature and magnetic field scaling of the Kondo splitting [11–13]. On the quantum engineering front, the cavity modes can be shaped to connect distant dots [25,26]. As the spin coherence is conserved, and spin-polarized currents may be produced [13], this platform holds great promise for quantum information processing applications.

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[18] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.115.166603 for (i) the description of how the tunnel rates are tuned and determined, and (ii) the complete data set of the dot-cavity system being tuned from weak to strong coupling.