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Detector backaction on the self-consistent bound state in quantum point contacts

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Bound-state (BS) formation in quantum point contacts (QPCs) may offer a convenient way to localize and probe single spins. In this Rapid Communication, we investigate how such BSs are affected by monitoring them with a second QPC, which is coupled to the BS via wave-function overlap. We show that this coupling leads to a unique detector backaction, in which the BS is weakened by increasing its proximity to the detector. We also show, however, that this interaction between the QPCs can be regulated at will by using an additional gate to control their wave-function overlap.

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The manner in which a measurement affects a quantum system is central to philosophical discussions of quantum theory. Mesoscopic devices are well adapted to study this issue since their properties are sensitive to their mutual coupling. Quantum dots (QDs) (Ref. 1) and quantum point contacts (QPCs) (Ref. 2) have been used, for example, as capacitively coupled charge detectors to count electrons on a nearby electrically isolated dot. In a solid-state realization of the which-path experiment,[3] this approach was used to study the decoherence in an Aharonov-Bohm ring due to the *backaction* exerted on carriers in one of its arms by a capacitively coupled-QPC "detector." Charge sensing with QPCs has also been used to read out the results of spin-sensitive manipulation of single electrons on QDs (Refs. 4–6) and QD molecules,[7–10] all important steps for the implementation of solid-state quantum computing. A general problem with the capacitive-sensing scheme, however, arises from the backaction of the detector—the shot noise in whose current can induce undesirable transitions in the system under study.[11,12]

Interdevice coupling has also been used to study spin transport in QPCs,[13–18] which are thought to spontaneously spin polarize near pinch off.[19] This behavior has been attributed to the ability of the QPC to function as a single-spin trap[20–22] that confines an electron to a bound state (BS), formed by Friedel oscillations[22,23] in the QPC potential. Evidence of this spin binding has been provided by studying the conductance of a (detector) QPC in close proximity to another (swept QPC).[13–15] A resonance that occurs in the detector conductance when the swept QPC pinches off has been attributed[16,17] to an unusual Fano effect[24,25] due to the wave-function overlap between the BS and the detector. This coherent tunnel correlation arises between the QPCs, with electrons continuously being swapped between them, when the BS is driven through the Fermi level by the swept-QPC gate voltage [Fig. 1(a)]. The interference of these partial waves can then be shown[16] to give rise to a detector resonance, just as seen in experiment. The resonance develops Zeeman splitting in a magnetic field,[14] consistent with occupation of the BS by a single well-defined spin.[17]

While the use of QPCs as an all-electrical single-spin system could have important applications in areas such as spintronics and quantum computing, realizing these will require a full understanding of how the bound spin is influenced by the

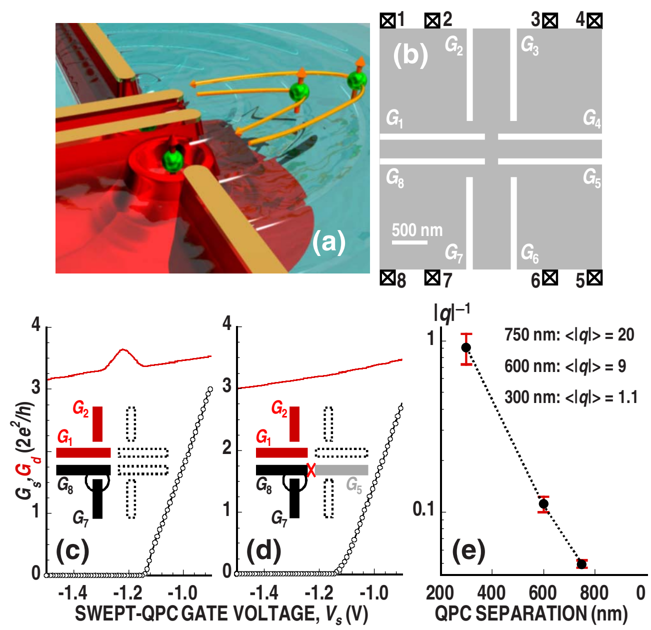

FIG. 1. (Color online) (a) Schematic of the resonance when electrons tunnel back and forth between a BS on the swept QPC (foreground) and the detector (background). (b) Device schematic. G_1-G_8 are gates and Ohmic contacts are numbered 1–8. (c) Variation in G_d and G_s (line with open circles) at 4.2 K. G_d is measured by passing current (I) from 1 to 4 and measuring voltage (V) between 2 and 3. G_s uses 8 and 5 for I and 7 and 6 for V. Circle in schematic indicates BS location. (d) Same as (c) but with gate G_5 biased to pinch off the region between G_5 and G_8. (e) $|q|^{-1}$ vs QPC separation. Dotted line is an interpolation between points. Each data point is an average obtained by using different pairs of QPCs to implement equivalent configurations, and the error bars for each point indicate the range of values contributing to the average.

coupling to its detector. For capacitive charge sensing, the backaction is due to the multielectron shot noise.[5,8–10] The spin-binding resonance, on the other hand, has been attributed to *single-particle* interference, arising from the wave-function overlap of the QPCs.[16] We show here that this results in an unusual backaction, in which increasing the wave-function overlap—which we quantify via the q parameter [Fig. 1(e)] related to the BS-continuum coupling in the Fano effect[24]—dramatically suppresses the resonance. This behavior is shown to be inconsistent with shot noise and is argued to arise instead from a weakening of the confinement of the BS due to its increased overlap with the detector. Our results thus demonstrate how the formation of BSs in QPCs is sensitive to their local environment, an important finding for discussions of the microscopic origins of the 0.7 feature,[19] and the use of QPCs as a single-spin system. They also have implications for general discussions of quantum measurements by demonstrating how increasing the coupling between a measurement device (the detector QPC) and a quantum object (the BS) renders this object less robust to decoherence.

We studied the GaAs/AlGaAs device of Ref. 14 (Sandia sample EA750), whose QPCs were 200 nm wide and 150 nm long [Fig. 1(b)] and whose two-dimensional electron gas (2DEG) has density of 2.3×10^{11} cm^{-2}, mobility of 4×10^{6} cm^2/V s, and Fermi wavelength of 53 nm. The mean-free path of 31 μm at 4.2 K decreased to 4 μm by 77 K, still much longer than the largest inter-QPC spacing ($\sim$750 nm). All measurements were made after cooling in the dark without illuminating the 2DEG. Figure 1(b) labels the different gates and Ohmic contacts used in our experiments, which involved applying fixed voltage (V_d) to a pair of gates to form the detector QPC while varying that (V_s) used to form the swept QPC. The conductance (G_s) of this QPC was first measured as a function of V_s while leaving the detector Ohmics floating. Then, the detector conductance (G_d) was measured for the same range of V_s but with the swept-QPC Ohmics floating. Previous work showed that G_d exhibits a resonance as the swept QPC pinches off,[14,15] which is observed in QPCs with various configurations.[13,14] G_s and G_d were measured between 4.2 and 60 K using lock-in detection (11 Hz) with an excitation of 30 μV (unless stated otherwise).

A key observation for our analysis of the backaction due to the detector is provided in Fig. 1, in which we demonstrate that its resonance is consistent with a mechanism involving wave-function overlap between the QPCs rather than Coulomb coupling. Figure 1(c) shows the resonance obtained with the QPCs coupled via their common 2DEG.[14] In Fig. 1(d), we repeat this measurement using gate G_5 to fully deplete its surrounding 2DEG. The detector resonance is completely quenched, inconsistent with an electrostatic interaction between the QPCs but consistent with their wave-function overlap. (In contrast, the linear background on which the resonance is superimposed[14] is unaffected by cutting off the 2DEG. This feature is therefore likely due to the electrostatic influence of V_s on G_d.) The coupling of the QPCs through their intervening 2DEG yields a distinct *configuration* dependence to the detector resonance. Figures 2(a) and 2(b) show the resonance obtained[14] for the largest QPC separation achievable in our device, while Figs. 2(e) and 2(f) show that for the smallest separation ($\sim$300 nm). Figures 2(c) and 2(d) are for the intermediate configuration, and a comparison of these data shows that the resonance evolves systematically with QPC separation. While the resonance has been attributed[16,17] to a Fano effect, this is not obvious in Figs. 2(a) and 2(b), whose resonances do not exhibit the pronounced asymmetry usual of Fano resonances.[24,25] Figures 2(e) and 2(f) show classic Fano resonances, however, with a deep minimum in immediate proximity to a local maximum. While prior work has suggested the existence of a BS in QPCs,[26,27] our observation of a clear Fano effect due to this BS is the most direct evidence for its existence to date.

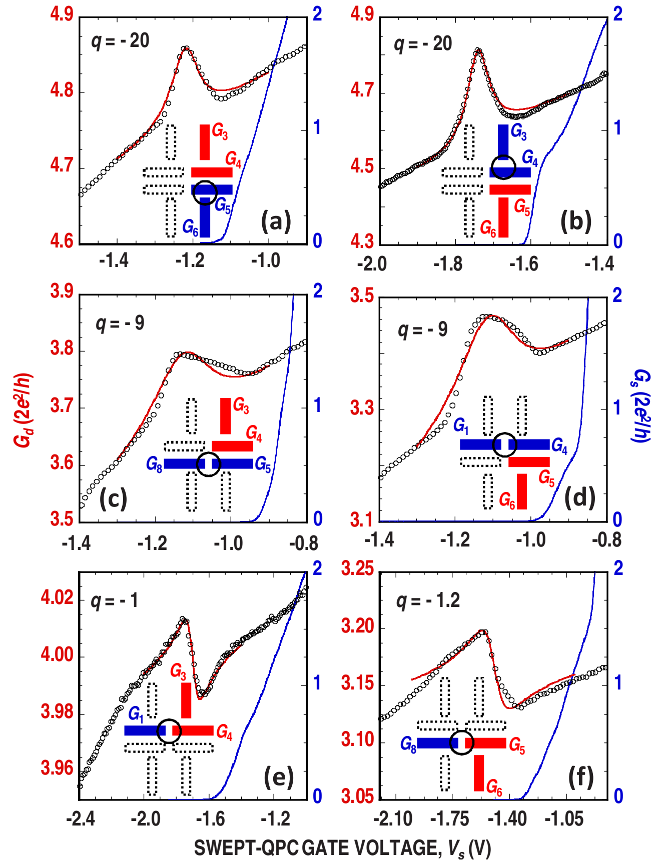

FIG. 2. (Color online) Resonance in G_d (open symbols) (solid line through symbols denotes fit to Fano form) and variation in G_s for different QPC configurations at 4.2 K. The corresponding Fano factor (q) is shown. Circle in schematics indicates where BS is formed. (a) G_d: *I*—1 and 4, *V*: 2 and 3; G_s: *I*—8 and 5, *V*: 7 and 6. (b) G_d: *I*—8 and 5, *V*: 7 and 6; G_s: *I*—1 and 4; *V*: 2 and 3. (c) G_d: *I*—1 and 4, *V*: 2 and 3; G_s: *I*—1 and 8, *V*: 2 and 7. (d) G_d: *I*—8 and 5, *V*: 7 and 6; G_s: *I*—1 and 8, *V*: 2 and 7. (e) G_d: *I*—1 and 4, *V*: 2 and 3; G_s: *I*—1 and 8, *V*: 2 and 7. (f) G_d: *I*—8 and 5, *V*: 7 and 6; G_s: *I*—1 and 8, *V*: 2 and 7.

Figure 2 shows that the detector-resonance line shape is not unique to any QPC but is a property of the coupled-QPC configuration. Consider Figs. 2(d) and 2(e), in which the swept QPC is the same but in which the distance to the detector is different. A clear Fano form is obtained with the swept QPC close to the detector [Fig. 2(e)], while for an

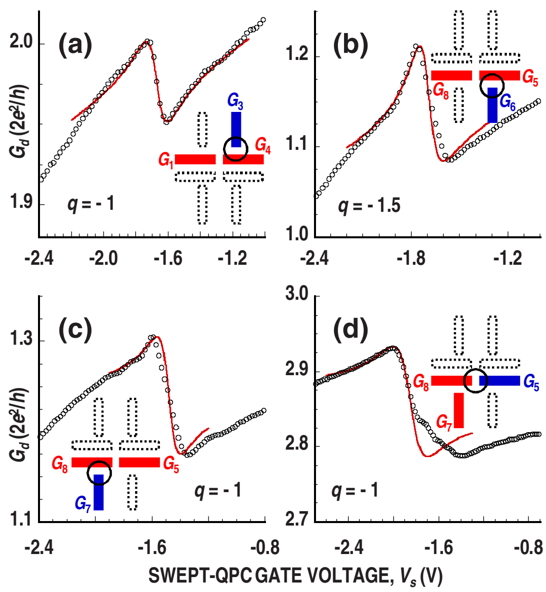

FIG. 3. (Color online) Resonance in G_d (open symbols) (solid line through symbols denotes fit to Fano form) and variation in G_s for equivalent QPC configurations at 4.2 K. The corresponding Fano factor (q) is shown. Circle in schematics indicates where BS is formed. (a) G_d: I—1 and 8, V: 2 and 7; G_s: I—1 and 4, V: 2 and 3. (b) G_d: I—1 and 8, V: 2 and 7; G_s: I—8 and 5, V: 7 and 6. (c) G_d: I—4 and 5, V: 3 and 6; G_s: I—8 and 5, V: 7 and 6. (d) G_d: I—8 and 5, V: 7 and 6; G_s: I—4 and 5, V: 3 and 6.

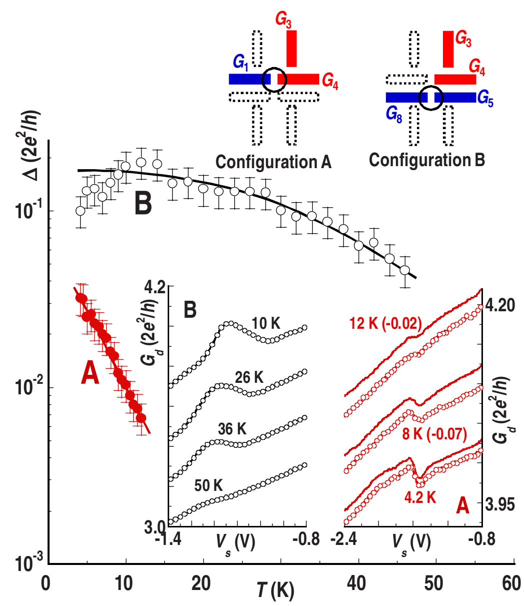

FIG. 4. (Color online) Main panel: temperature dependence of detector-resonance amplitude for gate configurations A and B (indicated on the upper right-hand side). Insets: resonance at different temperatures in the two configurations. Configuration A: G_d: I—1 and 4, V: 2 and 3; G_s: I—1 and 8, V: 2 and 7. Configuration B: G_d: I—1 and 4, V: 2 and 3; G_s: I—1 and 8, V: 2 and 7. Results for configuration A are shown for a measurement excitation of 30 μV (solid line) and 300 μV (line with open symbols).

increased separation [Fig. 2(d)] the Fano asymmetry is less pronounced. The systematic dependence on detector proximity is confirmed by the similar resonances in Figs. 2(c) and 2(d) and in Figs. 2(e) and 2(f), which use different gates to realize equivalent QPC configurations. It is further confirmed in Fig. 3, which shows resonances obtained using different gates to implement equivalent multi-QPC configurations, corresponding to the minimum possible separation between the two QPCs. In all four cases, the detector resonance shows a very-similar Fano form to that in Figs. 2(e) and 2(f).

Quite generally, the symmetry of Fano resonances is related to the coupling of their resonant and nonresonant channels, becoming more asymmetric for increased coupling.[24] Our finding (Fig. 2) that the detector resonance is more asymmetric for closer QPCs, corresponding to stronger wave-function overlap, is quite consistent with this. For further analysis, we fit the detector resonance to the Fano form,[24,25] $G_d(\varepsilon)\propto(\varepsilon+q)^2/(\varepsilon^2+1)$, where $\varepsilon\equiv 2(V_g-V_o)/\Gamma$ and V_o and Γ are, respectively, the resonance position and width. The parameter q is inversely proportional to the BS-continuum coupling and determines the resonance symmetry. A symmetric resonance is obtained for $q=\infty$, where the BS dominates the transmission, but, with increase in the coupling, the value of q decreases and the asymmetry of the resonance grows more pronounced, becoming maximal when $q=1$.[24,25] In our fitting, we account for the linear background to G_d [Fig. 1(d)], which we have noted is separate to the interference effect that yields the detector resonance, and use V_o, q, and Γ as parameters. Fits are shown in Figs. 2 and 3 and reproduce the experiment. In spite of the multiparameter nature of these fits, we emphasize that it is clear in Fig. 2 that the Fano asymmetry is more pronounced for closer QPCs. Figure 1(e) plots $|q|^{-1}$ for different configurations and shows a systematic increase as the QPC spacing is reduced. This is again consistent with a wave-function-based interaction,[16,17] which is enhanced by reducing the separation of the QPCs. It also emphasizes that even the weakly asymmetric peaks in Figs. 2(a)–2(d) must be viewed as Fano resonances, albeit ones with weaker coupling due to the larger QPC separation.

The wave-function-based QPC interaction results in an unusual detector backaction, revealed in temperature-dependent studies of its resonance. For configurations such as those of Figs. 2(a) and 2(b), the resonance persists to $\sim$40 K, indicating a robust ($\sim$meV) confinement of the BS on the swept QPC.[14] While surprising for a coherent effect, the survival of the resonance (albeit strongly damped) likely results from the proximity of the QPCs, which should allow even a small fraction of carriers entering the 2DEG from the detector to scatter coherently from the BS at higher temperatures. In Fig. 4, however, we demonstrate that bringing the QPCs *too close* together can actually *suppress* their resonance. In this figure, configuration B exhibits a resonance that is similarly robust to that found previously. In configuration A, however, with the QPCs in maximal proximity, the wash out of the resonance is dramatically suppressed to $\sim$10 K. This behavior is not specific to any QPC but is common to configurations in which the QPCs are in close proximity ($\sim$300 nm). The same behavior is obtained, for example, by reversing the swept and detector QPCs or by using other sets of gates to implement the same configuration (as in Fig. 3). Since the resonance arises from the interference of partial waves that travel directly from the detector to the drain, via the 2DEG, and those that scatter from the BS [Fig. 1(a)],[16,17] the weakened resonance in configuration A could be caused by enhanced detector-induced dephasing when the QPC separation is reduced. The right inset of Fig. 4 shows the resonance in this configuration, however, with the detector excitation voltage (and current) increased by a factor of 10. While the increased current should enhance shot-noise-induced dephasing, the wash out of the Fano resonance is unaffected. We thus conclude that shot noise is not responsible for the rapid wash out of the resonance when the QPC separation is reduced.

BS formation has been argued to occur when spin-dependent self-consistent interactions among carriers localize a single spin in a potential well on the QPC.[20–22] We find here that the act of "observing" this BS with another QPC progressively weakens its confinement as the QPC separation is reduced. Accompanying this is a growth in the Fano-resonance asymmetry, in itself directly indicative of increased wave-function overlap between the QPCs.[24] Such results suggest a backaction in which the confinement of the BS is weakened by its enhanced wave-function overlap with the detector. Generally speaking, BS formation in QPCs is thought to result from multiple scattering of electron waves from their bare potential,[20–22] analogous to the Friedel oscillations that arise near impurities or solid surfaces. The presence of a second QPC in close proximity may modify this self-consistent scattering, although it is not clear how this could weaken the BS. We have previously suggested that the BS-induced scattering of electron waves emanating from the detector is responsible for its resonant response.[16] This suggests that as the wave-function overlap is increased by decreasing the inter-QPC spacing, this scattering itself weakens the BS. One possibility is that as the proximity of the QPCs increases, the overlap of their Friedel oscillations modifies the BS. Expressed in terms of the Fermi wavelength (λ_F), the BS-detector separation is $12\lambda_F/6\lambda_F$ for configuration B/A. By decreasing the QPC separation over this range, the role of the Friedel-type oscillations could indeed be enhanced.[21,22] Regardless of the actual mechanism, however, our experiment unambiguously demonstrates the sensitivity of the BS properties to the local environmental conditions, consistent with the notion that the BS forms self-consistently. We have also seen that the wave-function coupling of the QPCs can be cutoff at will [Fig. 1(d)], and this control could possibly allow implementation of a spin-readout scheme with low detector-induced decoherence.[17]

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