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2008 J. Phys.: Condens. Matter 20 164216

(http://iopscience.iop.org/0953-8984/20/16/164216)

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **20** (2008) 164216 (9pp) doi:10.1088/0953-8984/20/16/164216

Detecting bound spins using coupled quantum point contacts

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Received 27 September 2007, in final form 30 October 2007
Published 1 April 2008
Online at stacks.iop.org/JPhysCM/20/164216

Abstract

For many years now, there has been ongoing interest in the manifestations of many body phenomena in the conductance of strongly confined, one-dimensional (1D) electron systems. One important aspect of this research has centered on the study of the so-called '0.7 feature' in the low-temperature conductance of 1D conductors known as quantum points (QPCs). There have been numerous reports in the literature suggesting that the 0.7 feature should be related to some kind of spontaneous spin polarization in the QPCs, which persists even at zero magnetic field. In this report, we review the results of our recent work on this problem, in which we make use of coupled QPCs to probe the properties of transport very close to pinch off. We observe a resonant interaction between two QPCs whenever one of them pinches off, which we believe is associated with the binding of a single spin to the QPC that is pinching off. A phenomenological theoretical model is developed that relates the observed resonance to a tunnel-induced correlation that arises from the interaction between a presumed bound spin on one QPC and conducting states in the other. Building on these ideas, we use this measurement technique to probe the microscopic properties of the bound spin, finding it to be robustly confined and to show a Zeeman splitting in a magnetic field. The spin binding occurs for stronger gate confinement than the 0.7 feature, and we therefore suggest an alternative scenario for understanding the formation of this feature. In this, one considers the evolution of the self-consistent bound state as the gate potential is weakened from pinch off to allow for electron transmission through the QPC. The suggestion of this work is that a QPC may serve as a naturally formed single-spin system with electrical readout, a finding that may be useful for the development of future generations of single-spin electronics.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The quantization of the linear conductance of non-interacting one-dimensional (1D) systems [1, 2], in integer units of the spin-degenerate quantum $2e^2/h$ ($\equiv G_0$), is one of the cornerstone results underpinning our understanding of mesoscopic systems. The origins of this quantization may be explained within the framework of a surprisingly simple model, the key feature of which is a cancelation of energy-dependent terms in the current when the carrier group velocity is multiplied by the non-interacting 1D density of states. A consequence of this cancelation is an equipartition of the total current among the different transverse subbands for transport, with each occupied subband contributing G_0 to the total conductance. This behavior is most strikingly manifested in the low-temperature conductance of quantum point contacts (QPCs), which are essentially nanoscale constrictions through which electrons move ballistically between two macroscopic charge reservoirs. The QPCs are typically realized by the split-gate technique [3], in which a variation of the voltage (V_g) applied to nanoscale surface gates induces a 1D confinement of the two-dimensional electron gas (2DEG) in a heterostructure (most frequently the GaAs/AlGaAs system). By applying the gate voltage in such a manner as to reduce the effective width of the 1D constriction, initially occupied 1D subbands may be depopulated one at a time, causing a step-like decrease in the linear conductance in units of G_0 [1, 2]. This behavior continues until the gate voltage is increased to such an extent that the last 1D subband depopulates, at which point the conductance should decrease smoothly from G_0 to zero as the QPC pinches off.

In addition to the quantized conductance steps described above, many experiments have been found to show an additional, unexpected, feature, which occurs below the last integer plateau at a conductance value that ranges from $\sim$0.5 to $0.7G_0$ (see [4–20], as well as the other papers in this special issue). The spin-related origin of this so-called '0.7 feature' was first investigated in [4] and subsequent experiments have provided support for this idea, suggesting that the 0.7 feature is related to some *spontaneous spin polarization* that arises when the QPC is biased close to pinch off. While there are many theoretical models that attempt to account for the nature of this feature [21–40], there is at present no definitive consensus on its microscopic origins. Most of the experimental studies that have sought to clarify the role of spin effects in 1D channels have focused directly on the behavior observed in the region where the 0.7 feature occurs, where the QPC is *partially* transmitting. It has recently been suggested, however, that a precursor to this regime should involve the binding of single spins on QPCs for stronger gate confinement where their conductance is *quenched* [39]. While this regime is inaccessible in experiments performed on single QPCs, we have recently been able to provide evidence for the spin binding by studying the interaction between coupled QPCs, one of which is biased in the regime where the spin binding is expected to occur [41–45]. In our experiments [41, 43, 45], we showed that the 'detector' QPC exhibits a resonance that occurs as the 'swept' QPC is pinching off. A theoretical model [42] developed to account for these observations was motivated by suggestions in the literature that the self-consistent potential of the QPC may develop a spin-dependent, quantum-dot-like, form near pinch off [29, 31]. By assuming that this form supports a bound state (BS) for a single electron, and considering how the coupling of the BS to the detector QPC modifies its conductance, we were able to obtain a resonant feature similar to that found in our experiments. Our studies therefore suggest that a QPC may be used as a naturally formed single-spin system that may be probed and manipulated electrically. In this report, we review the results of these studies, and also present new results that provide us with a clearer picture of the microscopic origins of the 0.7 feature.

2. Resonant interaction of coupled QPCS

In [41], we first reported on the observation of the resonant interaction between two quantum wires. The device utilized to study this phenomenon consisted of a pair of QPCs, which were coupled to each other via a quantum dot, as we show in figure 1(a). (It should be mentioned here that the original purpose for which this device was fabricated was to investigate quantum-interference effects due to coupling 1D systems via zero-dimensional states. In our later work [45], however, we have made use of an improved device design that eliminates the quantum dot.) The main panel of figure 1(b) shows the result of measuring the conductance along a current path that passes through the two QPCs and the quantum dot. This measurement was made by passing current, and measuring voltage, using the Ohmic contacts indicated schematically in the lower inset of figure 1(b). A fixed voltage was applied to the upper three gates of the device to form the detector QPC, while the voltage applied to the lower gate, which forms the swept QPC, was varied. While the conductance measured in this way exhibits a number of clear plateaus, these do *not* occur at the expected integer values of G_0. This is easy to understand, however, since the total conductance measured in this case is determined by contributions from the two QPCs and the quantum dot. By subtracting a fixed series resistance from the measured conductance variation in figure 1(b), we found that the resulting curve could be made to fall close to the expected quantized values [41]. This therefore confirmed that the main effect of the gate voltage variation is to deplete the swept QPC, without strongly affecting the average conductance of the rest of the structure.

In the upper left inset to figure 1(b), we show the detector conductance measured using the nonlocal configuration indicated in the upper right inset, while varying the swept-wire gate voltage over the same range as that shown in the main panel. While there is little variation of the detector conductance for a wide range of gate voltage, a resonant peak is clearly observed that is correlated to the pinch off of the swept wire. This resonant phenomenon was first reported in [41], where it was shown that the resonance interaction between the two wires was always manifested as an *enhancement* of the detector *conductance*. Moreover, by grounding one of the gates that form the quantum dot, the experiment could be repeated under conditions where the coupling between two wires was provided by a region of two-dimensional electron gas. In spite of this, however, we found essentially the same resonant interaction between the QPCs, indicating that the presence of the quantum dot is *not* critical to this effect.

A quantitative theoretical explanation of the resonant interaction between the coupled QPCs was first provided in [42]. In this work, a phenomenological model was proposed that started from the *a priori* assumption that a BS, capable of supporting a net spin moment, forms in the swept QPC close to pinch off. The following Hamiltonian was then formulated to

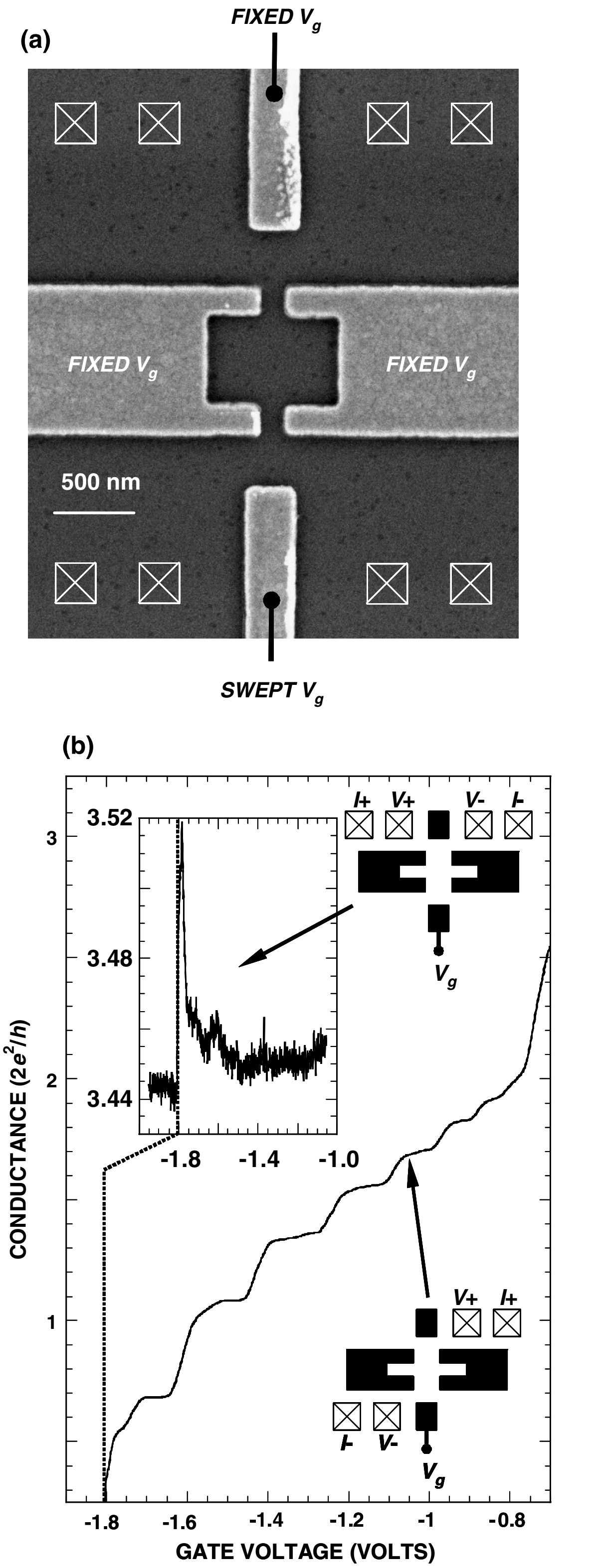

Figure 1. (a) A scanning-electron micrograph of a device used to detect BS formation in QPCs. The device may be measured with a number of different Ohmic contacts as schematically indicated. (b) The main panel shows the measured variation of the conductance at 0.1 K using the local geometry in the lower inset, under condition where a fixed voltage is applied to the upper three gates while the voltage applied to the lower gate is swept. The upper left inset shows the variation of the conductance of the upper wire for the same fixed-gate-voltage conditions, measured using the configuration indicated in the upper right inset.

describe the interaction between electrons in the detector QPC and the resulting *local magnetic moment* in the swept QPC:

$$\hat{H} = \sum_{\sigma} \varepsilon_\sigma n_\sigma + \tfrac{1}{2} U \sum n_\sigma n_{\bar{\sigma}} + \sum_{q,\sigma} \varepsilon_{q\sigma} n_{q\sigma} + \sum_{q,\sigma} E_{k\sigma} c^+_{k\sigma} c_{k\sigma} + \sum_{k,\sigma} (V_{k\sigma} c^+_{k\sigma} a_\sigma + V^*_{k\sigma} a^+_\sigma c_{k\sigma}) + \sum_{k,\sigma} (v_{kq\sigma} c^+_{k\sigma} a_{q\sigma} + v^*_{kq\sigma} a^+_{q\sigma} c_{k\sigma}). \quad (1)$$

The first two terms on the right-hand side of equation (1) are the usual Anderson Hamiltonian and are used here to describe the BS that forms in the swept QPC. As is typical in discussions of the Anderson model, ε_σ is the energy of the resonant BS, n_σ is the operator that describes the occupation of this state, and U is its on-site Coulomb energy. The third and fourth terms of equation (1) represent the occupation of electron states in the detector QPC, and the quantum dot, respectively, while the last two terms represent the *coupling* between the different components of the device. The first of these terms represents the coupling between the swept QPC and the quantum dot, while the second describes the coupling from the detector QPC to the dot.

Starting from the Hamiltonian of equation (1), we have previously calculated the correction to the conductance of the detector QPC due to its coupling to a bound spin in the swept QPC. The details of this approach are described in [42], but the basic idea involves expressing the conductance of the detector QPC in terms of its density of states [46, 47]. By making use of standard Green's function techniques, the latter quantity may be computed for the explicit Hamiltonian of equation (1). The key result is that the coupling of the detector QPC, to a localized electron spin on the swept QPC, results in a correction to its density of states ($\rho_\sigma(\varepsilon)$), which may be expressed approximately as:

$$\rho_\sigma(\varepsilon) \approx \bar{\rho}_\sigma(\varepsilon) - \frac{d\bar{\rho}_\sigma(\varepsilon)}{d\varepsilon} \frac{|T|^2(\varepsilon - \varepsilon_\sigma - U\langle n_{\bar{\sigma}}\rangle)}{(\varepsilon - \varepsilon_\sigma - U\langle n_{\bar{\sigma}}\rangle)^2 + \gamma_\sigma^2}. \quad (2)$$

The first term on the right-hand side of equation (2) is the unperturbed (free-electron) density of states of the detector QPC at energy ε. γ_σ is the broadening of the levels in the detector QPC due to their coupling to the quantum dot and swept wire. The matrix element (T) that appears in equation (2) accounts for the transfer of electrons between the two wires:

$$T = \sum_k \frac{v^*_{kq\sigma} V_{k\sigma}}{\varepsilon - E_{k\sigma}}. \quad (3)$$

The separate matrix elements $v_{kq\sigma}$ and $V_{kq\sigma}$ here describe the transfer of electrons between the detector QPC and the quantum dot, and the swept QPC and the quantum dot, respectively. Finally, the density of states of the detector QPC can be connected to its conductance via the generalized Landauer formula [47]:

$$g = \frac{e^2}{h} \sum_\sigma \int -f'(\varepsilon)\Gamma_\sigma \rho_\sigma(\varepsilon)\, d\varepsilon. \quad (4)$$

The broadening that appears in this equation, Γ_σ, is due to the coupling of the detector QPC to its leads. Equation (2) shows

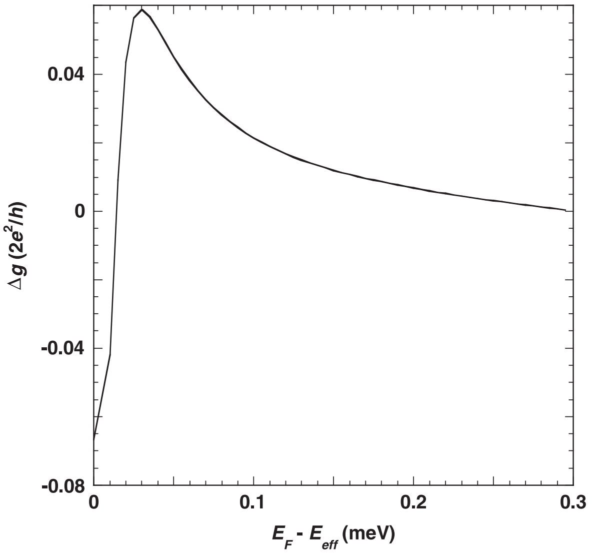

Figure 2. Calculated correction to the conductance of the detector wire as a function of the separation between the Fermi energy and the energy of the resonant state formed in the swept wire.

that the coupling between the QPCs yields an enhancement of the density of states of the detector QPC that is reflected in turn as a peak in its conductance. This is since the derivative of the one-dimensional density of states, which appears in the correction in equation (2), has a negative sign.

For a quantitative comparison with experiment, in [42] we performed numerical calculations based upon the model of equations (1)–(4). In these calculations, we assumed realistic values for the model parameters (γ_σ, Γ_σ, U, and T), and in figure 2 we show the conductance correction arising from the second term of equation (2) as a function of the separation between the Fermi energy (E_{F}) and the energy of the resonant state ($E_{\mathrm{eff}} = \varepsilon_{\mathrm{s}} + U\langle n_{\bar{\sigma}}\rangle$). Moving from right to left along the horizontal axis of this figure corresponds to driving the BS through the Fermi level, and is therefore equivalent to the process of gradually pinching off the swept wire. The conductance correction peaks at a positive value when the separation between the resonant state and the Fermi energy is roughly equal to γ_σ, which is taken to be 0.02 meV in this calculation. The correction becomes negative as the energy of the resonant state passes through the Fermi energy and this resonant state disappears thereafter. The calculation clearly reproduces the character of the peak seen in experiment (figure 1(b)), such as its absolute magnitude, the relatively slow growth on the right-hand side of the curve, and the much sharper drop to a negative value on the other side.

The success of our theoretical model in accounting for the experimentally observed resonance between coupled QPC provides strong independent support for the idea that a self-consistently formed BS is able to localized single spins on QPCs. In the remainder of this paper, we discuss the results of further experiments that have been performed to investigate the microscopic properties of bound spins on QPCs.

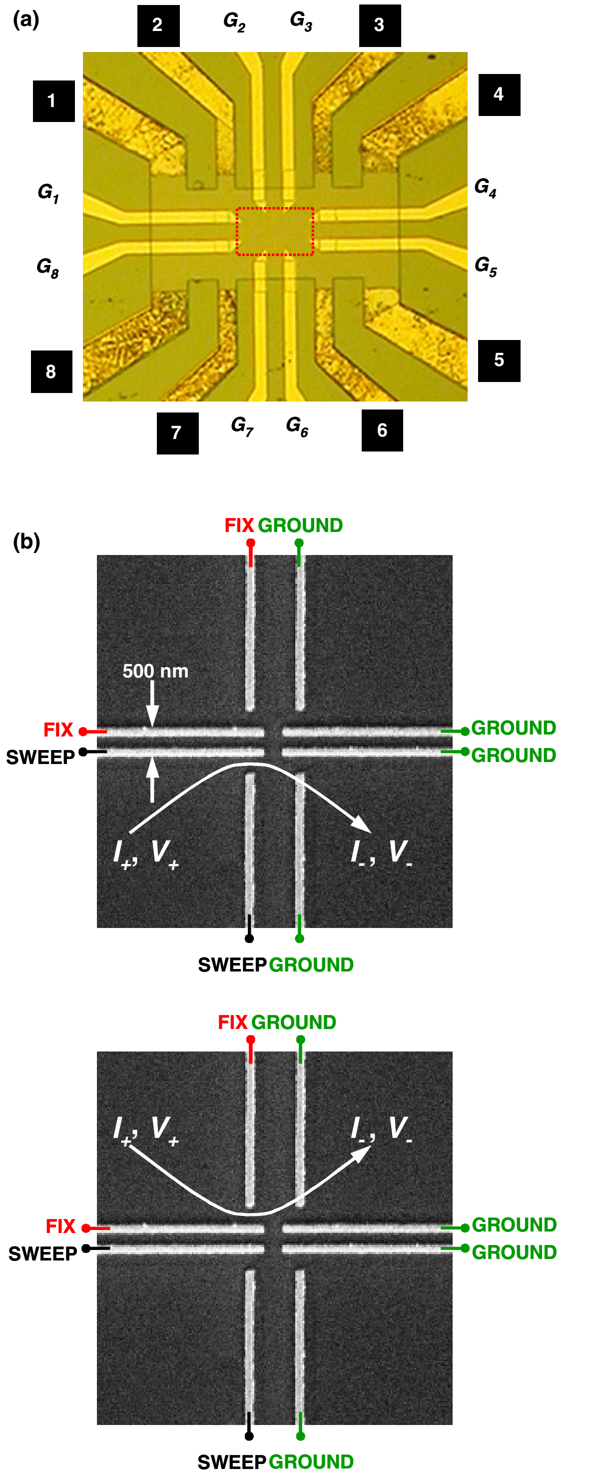

Figure 3. (a) An optical micrograph of the device, with its gates ($G_1 - G_8$) and Ohmic contacts (1–8) indicated. (b) An electron micrograph of the critical region of the device (enclosed by the dotted line in (a)), indicating the conductance measurement schemes for the swept (top) and the detector (bottom) QPCs.

3. Probing bound spins on QPCs

Subsequent to our original work [41], we have performed further experiments [45] using the improved device geometry of figure 3 to probe the microscopic properties of the naturally formed BS on QPCs. Similar to the earlier experiments, this device was fabricated in the high-quality 2DEG (with carrier density 2.3×10^{11} cm^{-2}, mobility 4×10^6 cm^2 V^{-1} s^{-1}, and mean free path 32 μm, at 4.2 K, Sandia sample EA750) of a GaAs/AlGaAs heterojunction. The particular advantage of the gate design of this device is that it allows a variety of swept–detector QPC combinations to be implemented, simply through appropriate choice of particular sets of gates. In figure 3, for example, we show how the different Ohmic contacts may be used to measure the swept and detector QPCs, when these are realized using the four gates on the left-hand side of the device. It should be emphasized, however, that this represents just one possible measurement configuration.

In [45], we showed the results of conductance measurements that were obtained by using different combinations of gates to form the swept and detector QPCs. In all of these measurements, we observed in the detector conductance (G_d) as the conductance of the swept QPC (G_s) pinched off. The resonance showed quantitatively similar behavior in all cases, ruling out the possibility that it is related to the formation of an *unintentional* quantum dot due to the presence of random impurities. In particular, it was pointed out in these studies that the resonance systematically occurs *after* the QPC pinches off, a characteristic that is also apparent in the results of figure 4. This shows the result of a set of experiments in which, as indicated in the inset to figure 4(a), the swept QPC gates were varied while maintaining a fixed voltage difference (ΔV_g) between them. In this way, we were able to modify the pinch off voltage of the swept QPC, but in all cases we found that the detector resonance occurred immediately after the pinch off. (Note that at 4.2 K, the 1D conductance quantization is washed out in our device, although the 0.7 feature remains.) This can be seen very clearly in the color contours of figures 4(b) and (c), in which the correlation of the resonant enhancement of the detector QPC to the pinch off of the swept QPC is indicated by the white dotted line (which is the same in both panels). It is also interesting to note that, while the swept QPC does not show such a prominent 0.7 feature in the measurement, the detector nonetheless show a resonant peak as the swept QPC pinches off. Asymmetric gate biasing has been used in previous studies of the 0.7 feature [4, 7], as a means to demonstrate that this feature does not result from anomalous transmission through some impurity-defined artifact in the self-consistent potential. Similarly, we take the systematic correlation of the resonant peak to the pinch off condition in figure 4 as a further demonstration that this resonance in a generic, predominantly geometry-related, effect.

In figure 5, we compare the temperature dependence of the detector resonance and the swept QPC 0.7 feature. The 0.7 feature can be clearly seen at 4.2 K (the frontmost curve in figure 5(b)), but becomes less prominent with increasing temperature. By ~17 K (indicated by the red dotted line), it has vanished completely and the conductance instead varies as a monotonic function of gate voltage. The detector peak, on the other hand, exhibits very different behavior (figure 5(a)). It persists weakly even at 35 K, gradually shifting to more negative gate voltage with increasing temperature. This remarkably robust temperature-dependent evolution suggests

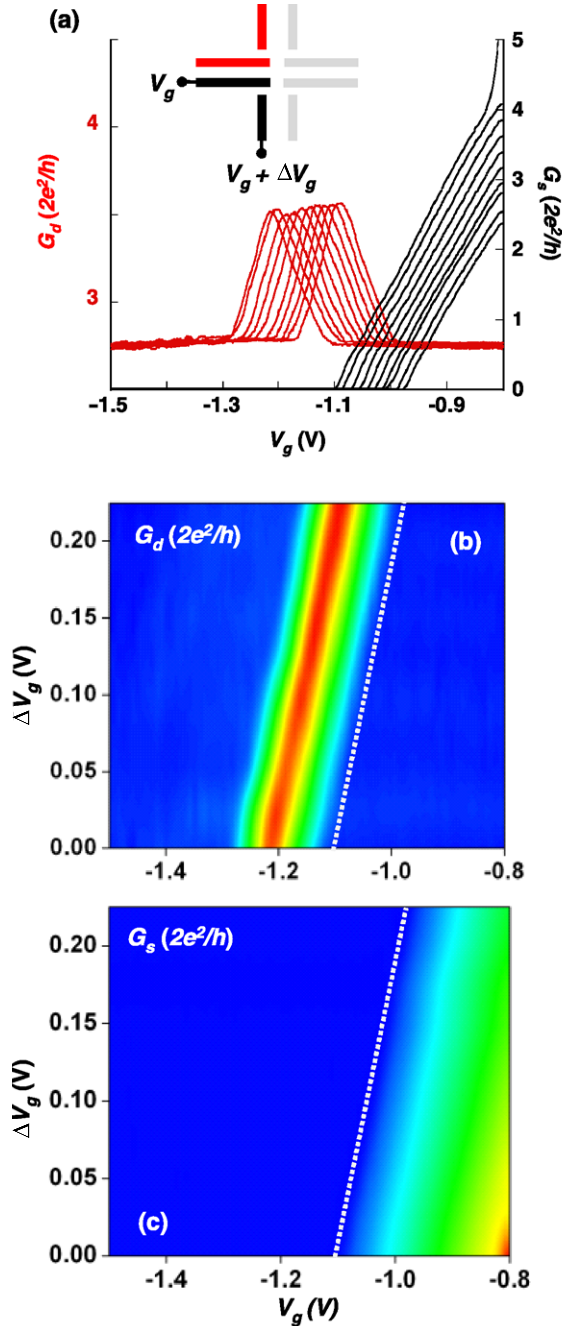

Figure 4. (a) Resonant interaction of coupled QPCs at 4.2 K. The detector (dark gray: G_1 and G_2) and swept (black: G_7 and G_8) QPCs are indicated in the inset, in which the light gray regions indicate grounded gates. Black curves: variation of the swept QPC conductance obtained by applying voltage V_g to G_8 and $V_\mathrm{g} + \Delta V_\mathrm{g}$ to G_7. ΔV_g varies from 0 mV to +225 mV, in 25 mV steps, from the left to the right curves. Dark-gray curves: $G_\mathrm{d}(V_\mathrm{g})$, with the fixed voltage applied to the detector gates. (b) Contour of G_d in (a). (c) Contour of G_s in (a).

that the effective confinement associated with the BS of the QPC state is at least on the order of a few millielectronvolts (from the thermal energy available at 35 K). The shifting of the peak with increasing temperature suggests that stronger gate confinement is needed to form the self-consistent BS in the swept QPC at higher temperatures. It is also consistent

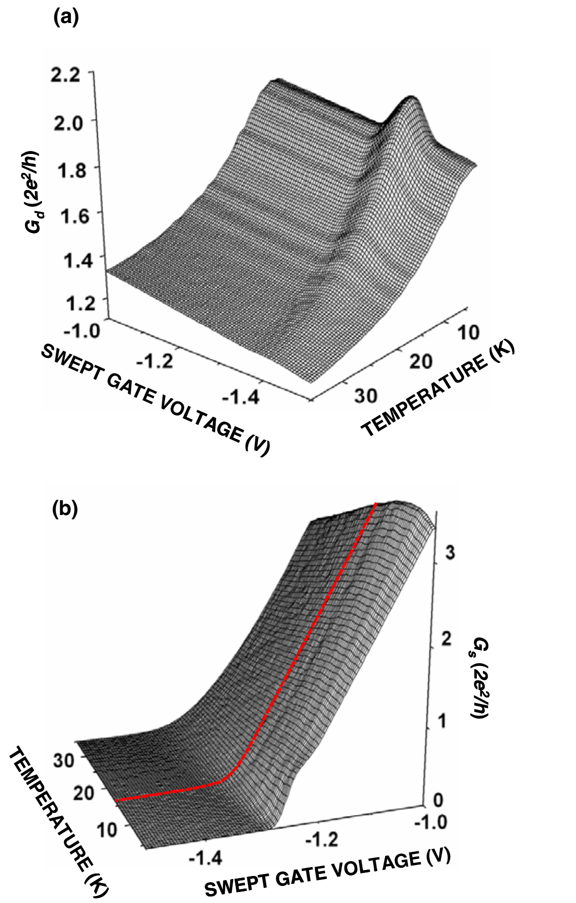

Figure 5. Temperature dependence of the detector peak (a) and the 0.7 feature (b). The washout temperature of the 0.7 feature is indicated by the thick dotted line in (b). Detector QPC: G_7 and G_8. Swept QPC: G_1 and G_2.

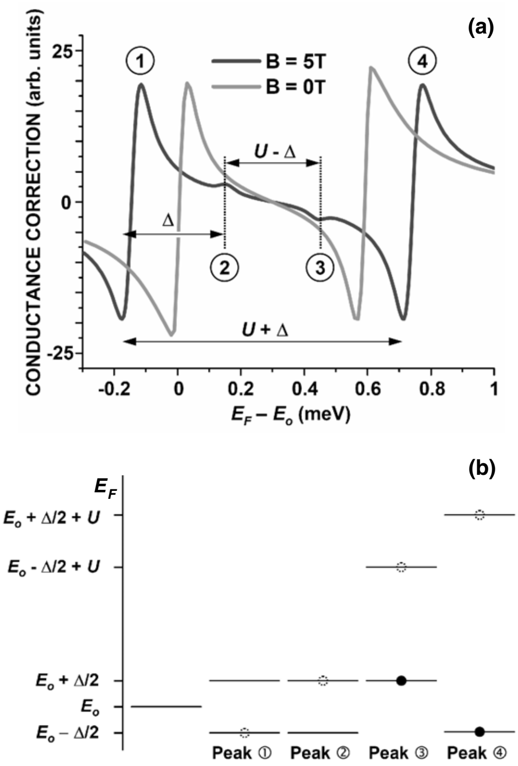

Figure 6. (a) The correction to the conductance of the detector QPC due to the Zeeman splitting of the BS. The calculations are performed for a temperature of 0.1 K and an on-site Coulomb energy $U = 0.6$ meV. E_0 is the energy of the BS at zero magnetic field, and the Zeeman splitting at 5 T is $\Delta = 0.3$ meV (assuming an electron g-factor of 2 and zero-spin splitting at zero magnetic field).

with the results of figure 1(b), which were obtained at much lower temperatures, where the conductance quantization is well defined. In this figure, the detector resonance clearly occurs much closer to the pinch off the swept QPC than in our measurements performed at 4.2 K and above.

An important comment that should be made on the basis of the results of figures 4 and 5 is that the 0.7 feature and the detector peak need to be viewed as *separate* manifestation of spin polarization in QPCs. In particular, the detector resonance does *not* indicate detection of the 0.7 feature *per se*, since it is observed for stronger gate confinement (more negative V_g) than the 0.7 feature. As we expand upon below, we believe that a fully consistent analysis of these two conductance signatures should involve a discussion in which the self-consistent potential of the QPC undergoes as dynamic evolution [14, 28, 29, 31, 35, 39] as V_g is varied from open conduction to pinch off.

Another valuable means to probe for the formation of a BS in the swept QPC is to apply an in-plane magnetic field. Theoretically, this problem was investigated in [44], in which, for computational convenience, the related problem of a detector QPC coupled to a BS on a *quantum dot* was investigated. (The quantum dot took the place of the swept QPC in this work; conceptually, at least, this problem should be similar to that which we study.) The calculations make use of a modified version of equation (1), in which the coupling of the detector QPC to its reservoirs is treated explicitly. The correction to the detector conductance calculated in this way is shown in figure 6(a), for magnetic fields of 0 and 5 T. These results show that the conductance of the detector QPC can serve as a sensitive probe of the energy levels of the BS. To understand this, we recall that the conductance peak in the detector QPC arises when its Fermi level is resonant with the BS. This yields a Fano resonance in the detector conductance, as is clear from the results of figure 6(a). In the presence of a magnetic field, the BS should split into two distinct Zeeman levels, the energy of each of which depends on the occupancy of the other. This situation is illustrated in figure 6(b), where we show the position of the two Zeeman levels for various occupancies of the quantum dot. This figure shows that when the two Zeeman levels are unoccupied their energy separation is simply equal to Δ. When the lower (or higher) Zeeman level is occupied, however, the resulting separation is $U + \Delta$ (or $U - \Delta$), as indicated in the figure. According to this picture, peak ① in figure 6(b) denotes the situation where the BS is unoccupied and the incoming electron in the detector QPC interacts with the lowest Zeeman level of this state. Peak ② corresponds to the case where the BS is unoccupied and the incoming electron in the detector QPC interacts with the upper Zeeman level of this state. This is therefore shifted by Δ with respect to peak ①. Furthermore, since peak ② represents an excited state for the single spin, it has a smaller probability of occupation than the state responsible for peak ①, and it is this property that causes the amplitude of peak ② to be much smaller than that of peak ① (figure 6(a)). Peak ③ indicates the situation where the detector electron interacts with the lower Zeeman level of the BS, when its upper Zeeman level is already occupied. Consequently, this feature is shifted in energy by an amount U with respect to peak ①. Finally, peak ④ corresponds to the situation where the lower Zeeman level is already occupied so that the incoming electron interacts with the upper Zeeman level. This peak is therefore shifted in energy by $U + \Delta$ with respect to peak ①.

The results of figure 6 suggest that it should be possible to clearly distinguish the occupation of the different spin branches of the BS in a magnetic field (note the very different amplitudes of peaks ① and ②). It must also be pointed out that the calculations of figure 6(a) were performed for a BS defined by a *deliberate* quantum dot, which meant that the various levels shown in figure 6(b) could implicitly be assumed to exist over the *entire* range of energy considered. Consequently, as energy is varied, it becomes possible to populate a second electron on the dot. For the BS on a QPC, however, the potential profile may (as we have mentioned) evolve with gate voltage. Consequently, the BS may only be able to bind a single electron to the QPC, after which its conductance onsets as the gate confinement is weakened. Such a scenario is certainly consistent with the results of our experiment at zero magnetic field, where we only ever observe a *single* detector resonance in experiment. If we associate this resonance with the first peak in the zero-field data of figure 6(a), then we should only expect to observe peaks ① and ② in a magnetic field.

Turning now to our experiment, in figure 7 we present results that show evidence for the Zeeman splitting predicted in [44]. To understand the results of this experiment, we need to consider how the Zeeman splitting of the BS should influence the gate voltage position of the detector resonance. The upper (lower) Zeeman branch of the BS should shift to lower (higher) energy with increasing magnetic field, as a result of which more negative (less negative) gate voltage should be needed to bring this branch into resonance with the Fermi level. In terms of the results of figure 6, we expect that peak ①, which represents the lower Zeeman (ground) state, should shift to more negative gate voltage, while peak ②, which corresponds to the excited upper Zeeman branch should shift to less negative gate voltage, with increasing magnetic field. Behavior very reminiscent of this is shown in figure 7. Figure 7(a) shows a linear shift of the main detector peak to more negative V_g with increasing in-plane magnetic field (black symbols). As the magnetic field is increased, however, an additional weak feature develops on the high-energy (less negative V_g) side of the detector peak, as indicated by the arrows in figure 7(b). Moreover, this shoulder shifts in the opposite direction to the main peak in the magnetic field, as indicated by the red symbols in figure 7(a).

The data of figure 7 are clearly consistent with the Zeeman splitting predicted in figure 6, and the close correspondence of the observed peak amplitudes to those predicted for peaks ① and ② moreover provide strong evidence that the BS formed in the QPC is indeed occupied by a single electron. Indeed, while it might be suggested that the weak shoulder that appears in figure 7 denotes the population of the BS by a *second* electron, the results of our calculations suggest that in this case a resonance of similar amplitude to that associated with the first electron should be observed (compare peaks ① and ④ in figure 6).

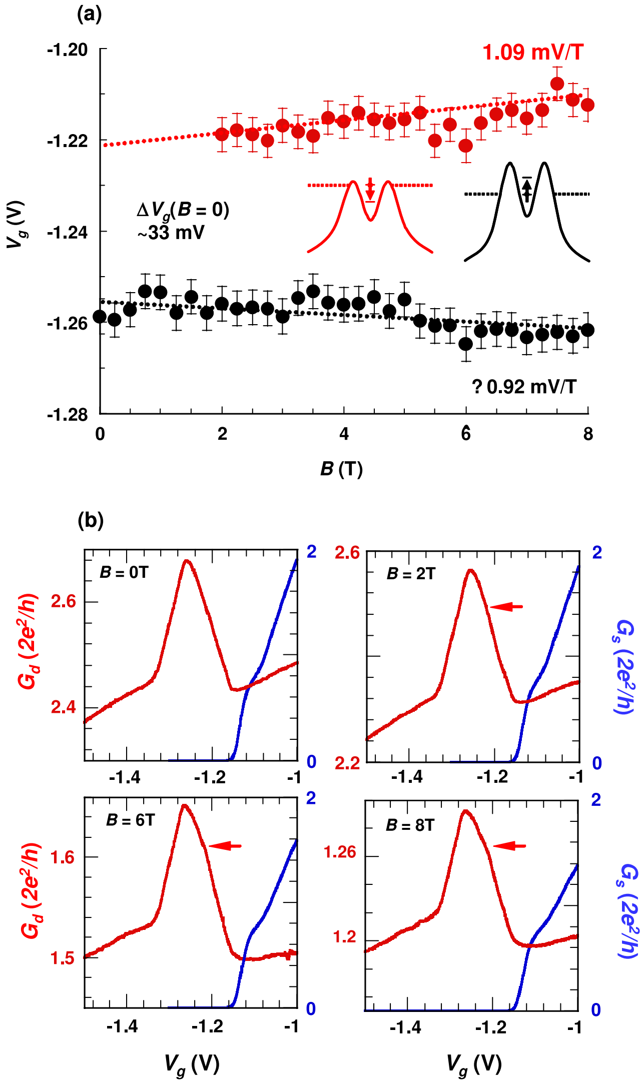

Figure 7. (a) In-plane magnetic-field dependence of the gate voltage position of the main peak (black circles) and the weak shoulder (gray circles). Dotted lines are linear fits. Detector: G_7 and G_8. Swept QPC: G_1 and G_2. Insets: population of the upper and lower Zeeman branches of the BS, corresponding to gray and black data sets. The BS is shown with weaker confinement in the gray schematic, since it corresponds to less negative V_g than the main peak. Dotted lines: E_F in the 2DEG. (b) $G_d(V_g)$ and $G_s(V_g)$ at several different values of the in-plane magnetic field. The weak shoulder is indicated by gray arrows.

An interesting feature of the results of figure 7(a) is that the two data sets extrapolate to a non-zero splitting at zero magnetic field ($\Delta V_g(B = 0) \sim 33$ mV), suggesting that the spin degeneracy of the BS is actually spontaneously broken at zero magnetic field. By assuming a g-factor of 0.4, we can

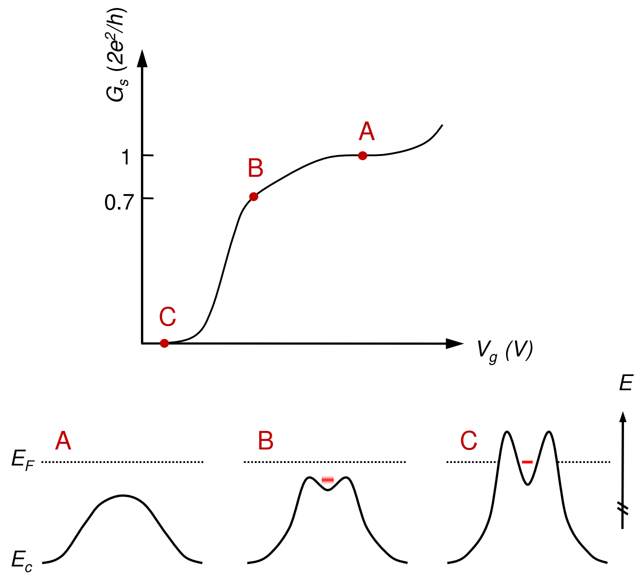

Figure 8. A possible model for the evolution of the self-consistent potential profile of QPCs near pinch off. The upper panel schematically shows the variation of G_s. Three possible scenarios are shown in the lower panels, as indicated by points A, B, and C on the conductance curves.

convert the slopes in figure 7(a) to an energy scale and relate the non-zero separation of peaks ① and ② to a spin splitting of ∼0.8 meV at zero magnetic field. Enhanced g-factor (∼1.5) have been reported [4, 7] for QPCs near pinch off, however, so that the actual the value of the spin splitting may be much larger than this (consistent with the washout temperature of the detector peak).

4. Connection to the 0.7 feature

The results of our experimental and theoretical work provide what we believe is a consistent body of evidence, demonstrating that self-consistently generated BS may form in QPCs near pinch off. By using coupled QPCs to probe the behavior in the pinch off regime inaccessible to usual experiments, we have moreover been able to provide strong evidence that the BS formation is a generic phenomenon, which results in the binding of just a single electron to the QPC. The idea that QPCs may be used as a naturally formed single-spin system with electrical readout, has the potential to open up new applications, in particular in the area of scalable quantum computing.

One of the outstanding issues related to this research concerns what it can tell us about the microscopic feature responsible for the 0.7 feature. Obviously, the demonstration that bound spins may be realized on QPCs should provide strong support for models that invoke a Kondo mechanism to account for the 0.7 feature [29, 31]. Since the 0.7 feature and the resonant peak do not occur at the same gate voltage, however, we believe that it should be necessary to consider how the self-consistent potential of the QPC evolves with the gate confinement. A simplistic analysis of this problem is suggested in figure 8, which considers the form of the QPC potential in three very different regimes of conductance. When the conductance is comparable to, or larger than, the quantized value at G_0, it seems reasonable to that the potential profile of the QPC should not exhibit any spin-dependent features, and should instead resemble the simple saddle form that has been widely studied in the literature [48] (point A in figure 8). At the other extreme, with the swept QPC pinched off we have presented strong evidence here for the formation of a robustly confined BS that should be supported by some dramatic modification of the QPC potential (as shown in point C in figure 8). On the basis of our temperature-dependent studies (figure 5), we have seen that the potential barriers that confine this BS should rise several millielectronvolts above the Fermi level.

The important observation that follows from the discussion immediately above is that the 0.7 feature occurs in a regime of intermediate confinement, where the gate potential is weakened away from the detector resonance and the swept QPC begins to transmit carriers (point B in figure 8). As such, its self-consistent potential in this regime may correspond to some hybrid version of the quantum dot and saddle forms, with a much more weakly confined BS that is strongly coupled to the reservoirs. Since the effective confinement generated by the BS should be weakened enough in this regime to allow for significant electron transmission, it is therefore not surprising that the 0.7 feature should exhibit a more rapid decay with increasing temperature than the detector peak. Furthermore, we note that in the Kondo model of [29, 31] the 0.7 feature occurs when the reservoir Fermi energy is *above* the BS level, consistent with the appearance of the 0.7 feature at less negative V_g than the detector peak.

Finally, since the resonant interaction between the swept and detector QPCs corresponds to a novel Fano effect, involving the coupling of propagating and bound states, there is a strong connection to recent work on such resonances in the conductance of quantum dots [49–53]. In future, it will therefore be of interest to explore the use of QPCs as a tunable Fano system, much as has been done for quantum dots.

5. Conclusions

In this paper, we have reviewed our recent work in which we make use of coupled QPCs to probe the properties of transport very close to pinch off. We observe a resonant interaction between the QPCs whenever one of them pinches off, which we believe is associated with the binding of a single spin to the QPC that is pinching off. A phenomenological theoretical model, based on the ideas of the Anderson Hamiltonian, provides further support for these conclusions, and relates the observed resonance to a tunnel-induced correlation that arises from the interaction between a bound spin on one QPC and conducting states in the detector. Building on these ideas, we have used this measurement technique to probe the microscopic properties of the bound spin, finding it to be robustly confined and to show a Zeeman splitting in a magnetic field. The spin binding occurs for stronger gate confinement than the 0.7 feature, and we have therefore suggested an alternative scenario for understanding the formation of this feature. In this, one considers the evolution of the self-consistent BS as the gate potential is weakened from pinch off to allow for electron transmission through the QPC. The suggestion of this work is that a QPC may serve as a naturally formed single-spin system with electrical readout. The robust character of this spin binding, combined with the structural simplicity of QPCs, may eventually lead to new applications of these devices (spin filter or spin pump, driven Rabi oscillator [44]) in single-spin electronics.

Acknowledgments

This work was supported by the Department of Energy (DE-FG03-01ER45920) and was performed, in part, at the Center for Integrated Nanotechnologies, a US DOE, Office of Basic Energy Sciences nanoscale science research center. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the US Department of Energy under Contract No DE-AC04-94AL85000.

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