

# Nonlocal bias spectroscopy of the self-consistent bound state in quantum point contacts near pinch off

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We perform nonlocal bias spectroscopy of the self-consistent bound state (BS) in quantum point contacts (QPCs), determining the lever arm ( $\gamma$ ) that governs the gate-voltage induced shift in its energy. The value of  $\gamma$  allows us to infer an enhanced  $g$  factor, and large remnant spin splitting, for the BS. Our results show many similarities with bias spectroscopy of quantum dots and are reproduced by calculations that assume a discrete BS coupled to a reservoir. This study therefore provides independent evidence in support of the notion of BS formation in QPCs. © 2009 American Institute of Physics. [DOI: 10.1063/1.3142418]

A powerful tool for exploring the states of quantum dots is *bias spectroscopy*, in which one detects different electronic configurations in tunneling, using the source bias as an effective energy probe.<sup>1–4</sup> This technique is also used in quantum point contacts (QPCs) to study the “0.7 feature” (see Ref. 5 for an overview and Refs. 6–8 for more recent works), which has been connected to some form of spin-dependent transport near pinch off. The origins of this effect remain subject to debate, and one idea is that, close to pinch off where the density in the QPC is very small, scattering from its barrier induces Friedel oscillations, which define a quantum-dot-like bound state (BS) for a single spin.<sup>9–11</sup> Recent work suggests the driving force for this effect is a Rashba mechanism, in which the gate generates a spatially nonuniform electric field normal to the transport plane, inducing a self-consistent potential with a local minimum at the QPC center that grows pronounced at pinch off.<sup>12</sup> Our understanding of this problem is far from complete, however, and there is a critical need for experiments that *quantify* the energy scales associated with the BS—something provided here.

Recently, we used coupled QPCs [Fig. 1(a)] to achieve BS detection by forming the BS in a “swept QPC” and using the other as a nonlocal detector.<sup>13–17</sup> A peak [Fig. 1(b)] is observed in the detector conductance once that ( $G_s$ ) of the swept QPC vanishes, and has been explained as a Fano resonance due to the mutual overlap of the BS and detector wave functions.<sup>14</sup> In this effect, variation in the swept QPC gate voltage ( $V_s$ ) near pinch off is thought to drive the BS through the Fermi level. The detector resonance then arises from a tunnel correlation, in which electron partial waves transmitted from the detector to the drain interfere with those [indicated by the dotted line in Fig. 1(a)] scattered by the BS.<sup>14</sup> Consistent with this we have shown an additional gate may

be used to cut off the wave function overlap of the QPCs, suppressing the detector resonance.<sup>17</sup> The resonance occurs at *more-negative*  $V_s$  than the 0.7 feature (which we also typically observe in our measurements).<sup>16</sup> This has led us to suggest<sup>16</sup> a picture in which the BS evolves dynamically as the gate voltage is varied near pinch off, with the detector resonance occurring when the BS is strongly confined and

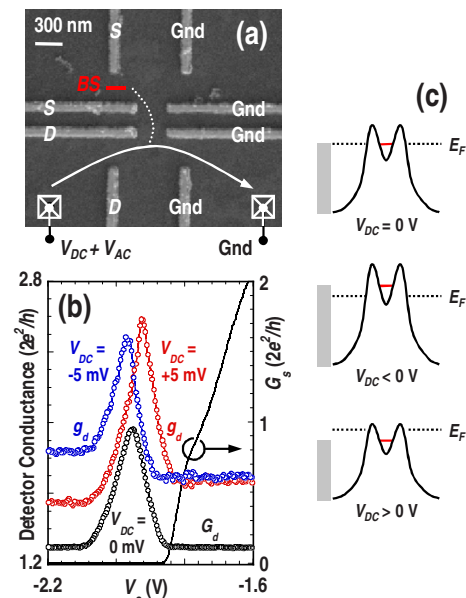


FIG. 1. (Color online) (a) Electron micrograph of the device and measurement scheme. The device consists of detector ( $D$ ) and swept ( $S$ ) QPCs, and grounded gates ( $Gnd$ ). A dc voltage ( $V_{dc}$ ), superimposed on a small ac voltage ( $V_{ac}$ ), is applied across the detector, while the drain is kept grounded. White dotted line indicates schematically the coupling of the BS and detector. (b) Linear ( $G_d$ ,  $V_{dc}=0$ ) and nonlinear ( $g_d$ ,  $V_{dc}=\pm 5$  mV) conductance variation with  $V_s$ . The variation in the swept QPC conductance ( $G_s$ ,  $V_{dc}=0$ ) is also shown. (c) Energy diagrams for different  $V_{dc}$ .  $E_F$  denotes the Fermi level of the unbiased 2DEG, and the gray region indicates the detector quasi-Fermi level. The red line denotes the BS in the swept QPC.

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the transmission through it is small (i.e.,  $G_s \approx 0$ ). The 0.7 feature should then correspond to the regime where  $V_s$  is weakened to allow transmission through the BS, an idea consistent with the Kondo scenario<sup>9–11</sup> for this feature. In this sense, our work provides an alternative way to think about the formation of the 0.7 feature, starting from a strongly confined BS with the QPC pinched off.

While our studies of the detector resonance have focused on its manifestations in *linear* transport, we show here how bias spectroscopy of this feature may yield quantitative information on the microscopic structure of the BS. By applying dc bias ( $V_{dc}$ ) across the *detector*, we modify its quasi-Fermi level and induce a linear shift in the  $V_s$  position of its resonance. This allows us to infer the BS lever arm (its shift in energy as a function of  $V_s$ ), and to thereby determine a significant enhancement in the BS  $g$  factor ( $g^* \sim 2-3$ ), as well as a remnant splitting of its Zeeman branches (of  $\sim 4$  meV) at zero magnetic field. Our results are reproduced by a model that treats coupling of the detector to a discrete state, and are reminiscent of those in a spectroscopy study of *deliberately formed* quantum dots.<sup>18</sup>

We report on the GaAs multi-QPC device of Ref. 16 [Fig. 1(a), Sandia sample EA750], whose two-dimensional electron gas (2DEG) (of density  $2.3 \times 10^{11}$  cm<sup>-2</sup> and mobility  $4 \times 10^6$  cm<sup>2</sup>/V s at 4.2 K) had a mean free path (31  $\mu$ m) much longer than the QPC separation. While this device could be used to implement coupled QPCs in various geometries,<sup>16,17</sup> for a systematic discussion we present representative results obtained for the configuration of Fig. 1(a). In these measurements, the detector was defined with a voltage of  $-0.73$  V applied to the gates marked *D*, while a *variable* voltage  $V_s$  was applied to the gates marked *S* to define the swept QPC. Although not shown, the gates were formed on a Hall bar with eight Ohmic contacts along its upper and lower edges, allowing four-probe measurements of the conductance of the QPCs. When the upper contacts were used to measure the detector conductance ( $G_d$ ) in Fig. 1, the lower ones on the swept QPC were left floating. To measure  $G_s$ , this scheme was reversed (see Ref. 16 for details). In our measurements of the detector, a dc bias ( $V_{dc}$ ) was superimposed upon the small ac signal ( $V_{ac}$ , 27  $\mu$ V, and 30 Hz) normally used in our linear-conductance measurements, to determine its differential conductance ( $g_d$ ). All data were obtained using lock-in techniques at 1.7 K and zero magnetic field.

Figure 1(b) shows the influence of  $V_{dc}$  on the detector resonance, whose amplitude appears unchanged at  $V_{dc} = \pm 5$  mV, consistent with the idea it arises from a phenomenon (BS formation) that takes place in the *swept* QPC. The weak asymmetry of the resonances, which appear almost triangular, was explained in Ref. 17 in terms of the wave function overlap of the QPCs. Another feature is a clear shift in the  $V_s$  position of the resonance. Relative to its position at  $V_{dc}=0$ , negative/positive  $V_{dc}$  shifts the detector peak to more-/less-negative  $V_s$ . This shift is consistent with our idea<sup>14</sup> that the resonance arises from the alignment of the Fermi level in the detector and a well-defined BS in the swept QPC. Specifically, application of  $V_{dc}$  should result in a nonequilibrium energy distribution, in which the quasi-Fermi level in the detector is shifted by  $-q\beta V_{dc}$ , where the electron charge is  $-q$ , and  $\beta$  is a factor that expresses the symmetry of the voltage drop across the detector (for a symmetric QPC,

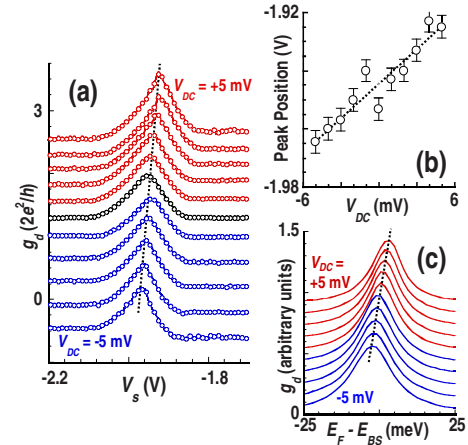


FIG. 2. (Color online) (a)  $g_d(V_s)|_{V_{dc}}$  with  $V_{dc}$  incremented in the range  $-5 \leq V_{dc} \leq +5$  mV in 1 mV steps. The curves are offset (in units of  $2e^2/h$ ) by  $+1.0, +0.8, +0.6, +0.4, +0.2, 0, -0.3, -0.8, -1.3, -1.8,$  and  $-2.3$ , from  $+5$  to  $-5$  mV, respectively. The dotted line indicates the movement of the resonance as  $V_{dc}$  is varied. (b)  $V_s$  position of the detector resonance as a function of  $V_{dc}$ . The dotted line is a best fit to the data. (c) Calculated detector resonance for different  $V_{dc}$ . Successive curves are shifted vertically in increments of 0.1.

$\beta = 1/2$ ).<sup>19</sup> In Fig. 1(c), we plot energy diagrams that explain the shift in the detector peak. With  $V_{dc}=0$ ,  $G_d$  exhibits its resonance immediately after the swept QPC pinches off,<sup>16,17</sup> where the BS should be aligned with the 2DEG Fermi level ( $E_F$ , we ignore the small  $V_{ac}$  across the detector).<sup>14</sup> Application of positive/negative  $V_{dc}$  lowers/raises the quasi-Fermi level in the detector, so that less-/more-negative  $V_g$  is needed to bring the BS into resonance with the detector.

Figure 2(a) shows the influence of  $V_{dc}$  on the detector resonance in greater detail. The  $V_s$  position of the resonance shifts systematically with  $V_{dc}$ , and Fig. 2(b) shows that this follows a linear dependence. Similar behavior is found in Fig. 2(c), which shows calculations (based on a modified model of Ref. 15) of the resonance exhibited by a QPC, coupled to a discrete state [see Eq. (2) of Ref. 15]. A temperature of 4.2 K is assumed [the resonance saturates in experiment below  $\sim 10$  K],<sup>16</sup> and  $V_{dc}$  is accounted for by modifying the Fermi function for electrons in one of the two 2DEG regions, to which the detector is coupled.  $g_d|_{V_{dc}}$  is determined qualitatively as a function of the separation between the BS energy and the equilibrium Fermi level of the detector. Accordingly, moving from right to left along the axis corresponds to increasing of the BS energy, or, in other words, to making the gate voltage more negative. These calculations reproduce the shift in the resonance in experiment, with the 10 mV swing of  $V_{dc}$  shifting the peak by 5 meV, consistent with  $\beta = 1/2$  for a symmetric QPC. The shift in the resonance in experiment, therefore, provides a means to calibrate the energy shift in the BS induced by  $V_s$ . To obtain this lever arm ( $\gamma$ ) we assume that, if the resonance position shifts by  $\Delta V_s$  in response to an applied dc bias  $V_{dc}$ , the associated energy shift in the BS is  $\Delta E = -\gamma \Delta V_s = -q\beta V_{dc}$ . From the slope of the straight line in Fig. 2(b), we infer a lever arm  $\gamma = 0.13$  meV/mV. To obtain this value we assumed  $\beta = \frac{1}{2}$ , which should be reasonable since  $G_d > 2e^2/h$ .<sup>19</sup>  $\gamma$  is within the range reported in experiments on quantum dots formed by electrostatic gating.<sup>18,20</sup>

In Fig. 3 we plot the differential conductance [ $g_d(V_s, V_{dc})$ ] obtained by scanning  $V_{dc}$  continuously, and in-

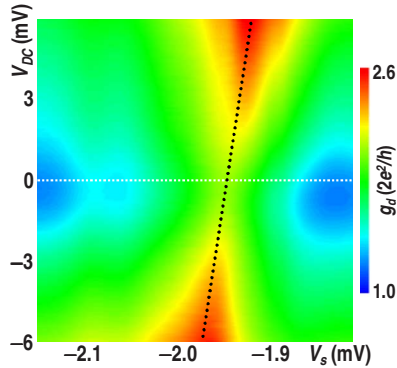


FIG. 3. (Color online)  $g_d$  plotted on a color scale in the  $(V_s, V_{dc})$  plane. The black dotted line indicates the movement of the detector resonance as  $V_{dc}$  is varied.

creasing  $V_s$  over the region near pinch off. Consistent with Fig. 2, the resonance (indicated by the black dotted line) again tracks linearly across the contour. From the slope of this line we obtain  $\gamma=0.12$  meV/mV, very close to the value inferred in Fig. 2. In measurements in which  $\gamma$  was determined by setting  $G_d$  in the range of  $1-5 \times 2e^2/h$  its value did not change in any systematic way, consistent with the notion this parameter is associated with the swept QPC. Although we have focused on the results of measurements of a particular QPC configuration, we have observed a similar linear shift in the resonance in measurements of three different coupled QPC combinations. By averaging these measurements, we finally obtain  $\gamma=0.14 \pm 0.02$  meV/mV.

The linear shift in the resonance in Figs. 2 and 3 closely resembles the results of Otsuka *et al.*,<sup>18</sup> who studied Coulomb oscillations in a dot coupled to a *single* wire. A  $V_{dc}$  across this wire induced distinct quasi-Fermi levels in its reservoirs, splitting the tunneling resonances into two unequal peaks, the largest of which shifted linearly as  $V_{dc}$  was varied. While we observe a single peak in our experiment, which we attribute to the fact that this resonance is due to alignment of the BS with the detector quasi-Fermi level, the results of Ref. 18 resemble ours. As such, the response of the detector resonance to the bias appears to provide further support of the formation of a BS in QPCs.

In Ref. 16, we observed Zeeman splitting of the detector resonance in an in-plane magnetic field, with a *gate voltage* shift of  $\pm 1$  mV/T. Using the value of  $\gamma$  found above, we infer an effective  $g$  factor,  $g^*=2.0-2.7$ . This exceeds the  $g$  factor for bulk GaAs ( $g^*=-0.44$ ), but is consistent with reports of a  $g$  factor enhancement in QPCs near pinch off.<sup>8,21-23</sup> These experiments also indicate that a remnant spin splitting, around a meV, persists at zero magnetic field,<sup>21,23</sup> and in Ref. 16 we also found such splitting. From our value for  $\gamma$ , we estimate this splitting is  $\sim 4$  meV, a large value but one consistent with the stronger confinement associated with the BS resonance compared to the 0.7 feature, and the fact that the detector resonance survives to temperatures approaching 50 K.<sup>16,17</sup>

In conclusion, we performed nonlocal bias spectroscopy of the self-consistent BS in QPCs, determining the lever arm that governs its energy shift. The lever arm allowed us to extract estimates for the  $g$  factor of the BS, and its zero-field spin splitting. The observed shift in the detector resonance is reproduced by a model, based on an *a priori* assumption of a BS coupled to a reservoir. The similarity of our results with

this theory, as well as with those obtained in bias spectroscopy of deliberately formed quantum dots, provides further evidence for BS formation in QPCs. The fact that the 0.7 feature is also commonly found in the QPCs we study<sup>16</sup> suggests BS formation is a required precursor for the observation of this feature, consistent with the ideas of the Kondo model.<sup>9-11</sup> The inferred remnant spin splitting at zero magnetic field is *inconsistent* with a Kondo model, however, and appears in agreement, instead, with models that predict a static spin polarization in the QPC.<sup>24,25</sup>

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