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Cavity assisted spin reconfiguration in a quantum wire

C. Yan[1,2]**, S. Kumar**[1,2]**, M. Pepper**[1,2]**, P. See**[3]**, I. Farrer**[4]**, D. Ritchie**[5]**, J. Griffiths**[5]**, G. Jones**[5]

[1] London Centre for Nanotechnology, 17-19 Gordon Street, London WC1H 0AH, United Kingdom

[2] Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom

[3] National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, United Kingdom

[4] Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom

[5] Cavendish Laboratory, J.J. Thomson Avenue, Cambridge CB3 OHE, United Kingdom

E-mail: `uceeya3@ucl.ac.uk`

Abstract. In the present work, we investigate the source-drain bias spectrum of a hybrid quantum device consisting of a dot-like QPC coupled to an electronic cavity. A singlet-triplet transition manifested as finite-bias anomaly is observed when the cavity is switched on. Besides, we noticed that the 0.7 conductance anomaly is not affected by the cavity, which provides a valuable insight on the origin of the 0.7 conductance anomaly.

1. Introduction

Nanoscale quantum wire, also known as quantum point contact (QPC), defined by applying gate voltage to a pair of split gates[1] has led to some of celebrated results in condensed matter physics. In addition to the quantization of 1D conductance (G)[2, 3], arising from the single-particle picture, which occurs at $G = N \times \frac{2e^2}{h}$ (where N is an integer), QPC is also a versatile platform to investigate many body phenomena such as spontaneous spin polarization[4, 5, 6, 7, 8], the incipient Wigner crystallization[9, 10] and the Kondo effect[11].

The Kondo effect, arising from the coherent spin-flip scattering between the dynamic localized magnetic impurity and conduction electrons, allows an easily accessible approach in manipulating spin configuration[12]. The Kondo effect has led to a series of fascinating results in quantum dots (QD), ranging from the zero-bias conductance anomaly (ZBA) due to single impurity Kondo effect[13] to finite-bias anomaly (FBA) which is a direct manifestation of singlet-triplet transition[14, 15]. Compared its counterpart in QD, the observation and understanding of the Kondo effect especially the multi-impurity system[16, 17] is far from complete in the QPC.

Here we present an evidence on the singlet-triplet Kondo effect in a novel hybrid system consisting of a QPC coupled to an electronic cavity. We show that by carefully engineering the geometry of the QPC and tuning the coupling between the cavity and QPC, anomalous coexistence of ZBA and FBA can be observed.
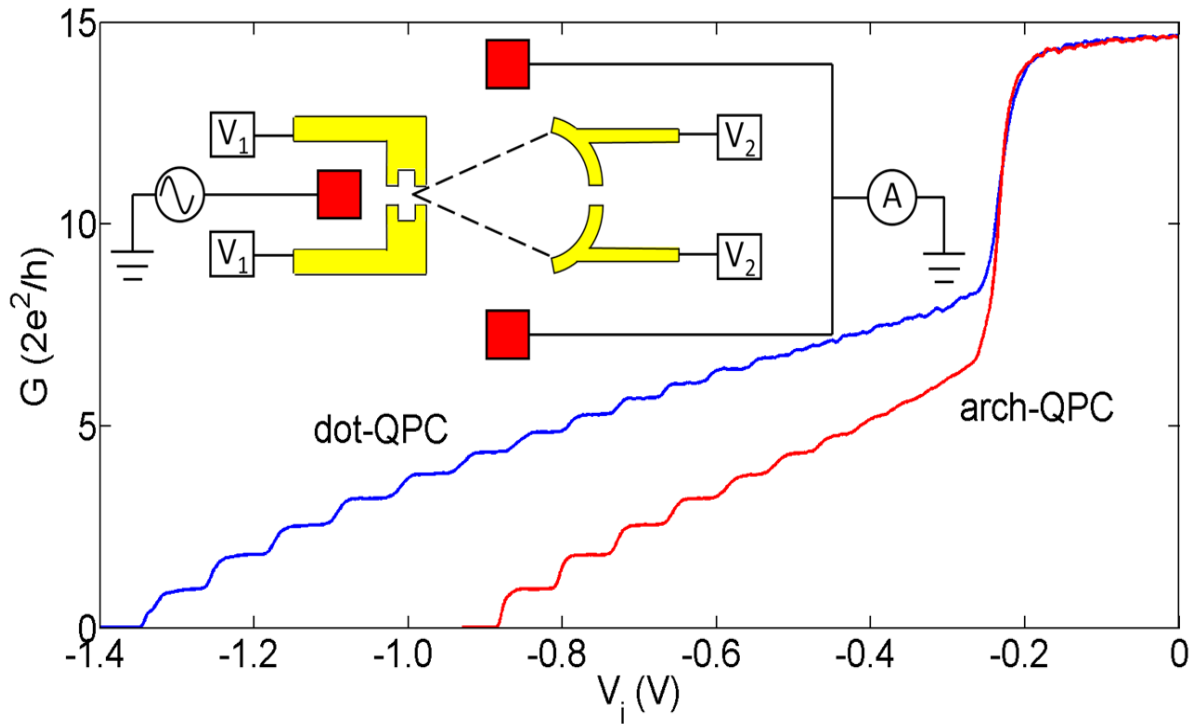
Figure 1. Characteristics of the device and the experiment setup. Main plot shows the conductance characteristics of the dot-QPC and arch-QPC with applied gate voltage V_i (i = 1,2). Inset, the yellow blocks are metallic gates and red squares are Ohmic contacts. The opening angle of the arch is 45° and the radius is 2.0 μm, both the length and width of the QPC embedded in the arch (hereafter referred as arch-QPC) are 200 nm; the length (width) of the injector QPC (named as dot-QPC) is 700 nm (500 nm). The measurement setup in the inset is for the main results, while the conductance characteristics of the individual components are investigated with the typical two-terminal measurement.

2. Experimental detail

The hybrid devices were fabricated on a high mobility two-dimensional electron gas (2DEG) formed at the interface of GaAs/Al$_{0.33}$Ga$_{0.67}$As heterostructure. The metallic gates are deposited on the surface which is 90 nm away from the 2DEG. The electron density (mobility) measured at 1.5 K was 1.80×10^{11}cm^{-2} (2.1×10^6cm^{2}V^{-1}s^{-1}) therefore the mean free path was over 10 μm which is much larger than the distance between the QPC and reflector (2.0 μm). All the measurements were performed with the standard two-terminal lock-in technique, using an ac voltage of 10 μV at 77 Hz, in a cryofree dilution refrigerator with a lattice temperature of 20 mK (the electron temperature was around 70 mK estimated from the temperature dependence of the Shubnikov-de Haas oscillations).

3. Results and discussion

Both the dot-QPC and arch-QPC show well defined conductance plateaus when measured individually as shown in Fig. 1. It has been carefully examined that the dot-QPC does not show a quantum-dot like behaviour. However, the rectangular grooves of the dot-QPC affect the results significantly in two aspects: first, the reflection from the edge of the split gates could result in the Friedel oscillations which in turn contribute to the formation of an emergent
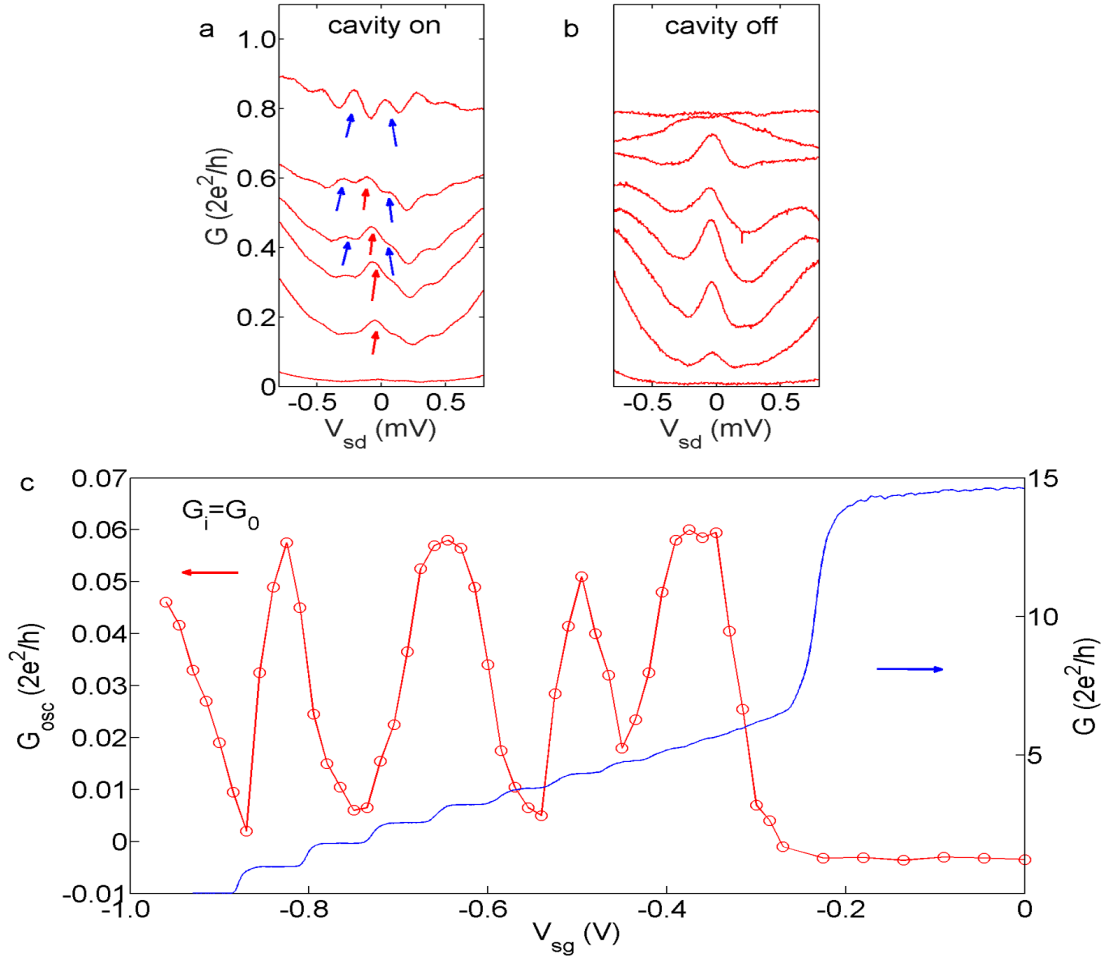
Figure 2. Zero-bias spectrum as a function of the dot-QPC conductance. **a** and **b** show the result with cavity switched on and off, respectively. **c**, conductance oscillation as a function of arch-QPC gate voltage with dot-QPC fixed at G_0.

localized state within the quasi-1D channel; second, coupling between the dot-QPC and the electronic cavity can be tuned in a similar manner to that between a QD and a cavity[19].

The source-drain bias spectroscopy shows dramatic difference when the cavity is switched on and off as shown in Fig. 2. A standard sharp ZBA is observed with the cavity switched off. The ZBA has been studied extensively in QPCs and has been shown to arise from the Kondo effect[11]. Interestingly, more features are observed when the cavity is switched on. In the low conductance regime, the ZBA still dominates the spectrum. With further increasing the conductance of the dot-QPC, FBA peaks occur at ± 0.2 mV in additional to the ZBA (see Fig. 2(b)), which is similar to that observed in a QD[15]. In the large conductance regime (G $\geq 0.8G_0$), only the FBA survives while the ZBA alters into a dip; the FBA-only behaviour, a signature of singlet-triplet transition, is similar to that reported previously[16, 17]. In the presence of in-plane magnetic field, it was found that the ZBA gradually split into two peaks whereas the FBA initially shift towards larger V_{sd} and then smeared out (results not shown here).

Also, it is interesting to notice that, as shown in Fig. 2(c), the oscillatory part of the total conductance G_{osc} arising from the quantum correction due to the cavity (equals to the total
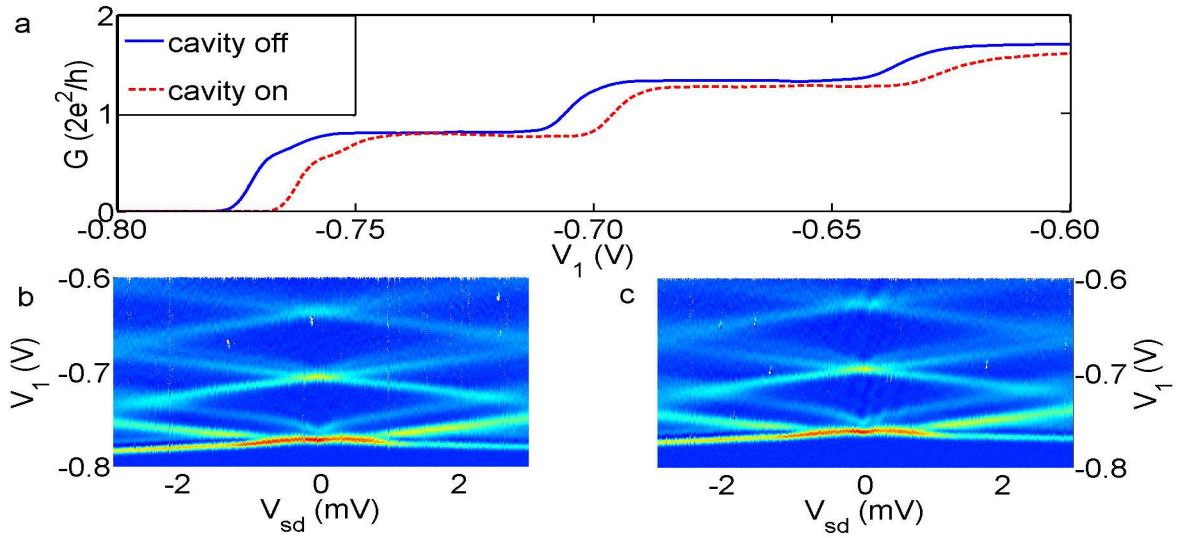
Figure 3. Comparison of the 0.7 anomaly when cavity is switched on and off in sample B. a, injector conductance measured with cavity switched on (red dotted trace) and off (blue solid trace). **b** and **c**, transconductance $\frac{dG}{dV_1}$ with cavity off and on, respectively.

conductance measured with the setup in Fig. 1 minus the dot-QPC conductance; in the plot, dot-QPC was set to G_0) was triggered when the cavity was switched on ($V_{sg} \leq$ -0.25 V, where the electrons underneath the arch-shaped gate were depleted and a quasi-1D channel started to form within the arch-QPC). The oscillatory conductance was still observed even after the arch-QPC was fully pinched-off ($V_{sg} \leq$ -0.85 V) which a signature of coupling between the dot-QPC and cavity[18].

In the previous reports, it was suggested that the occurrence of FBA is correlated with the 0.7 conductance anomaly[16, 17], in other words, the 0.7 anomaly is related to the localized state in the QPC. However, we found no signature of such correlation as shown in Fig. 3(a). It is seen that despite a change in the pinched-off voltage there is no appreciable change in the dot-QPC conductance (including the subband spacing) especially the shape of the 0.7 anomaly. Fig. 3(b) and (c) show the transconductance $\frac{dG}{dV_1}$ with the cavity being switched off and on, respectively, and further indicate that the occurrence of FBA is not related to the 0.7 conductance anomaly. Due to a weak coupling between the dot-QPC and electronic cavity at zero source-drain bias, the states within the 1D channel are not affected significantly. We note that a recent scanning gate microscopy experiment also indicated that the 0.7 anomaly is not correlated with the localized state[21].

In conclusion we have demonstrated a singlet-triplet transition with the assistance of an electronic cavity coupled to a QPC. The singlet-triplet transition manifests itself as a pair of finite bias peaks. Besides, our experiments also reveal that the occurrence of 0.7 conductance anomaly is not correlated with FBA. The hybrid device presented here provides an easily accessible route to spintronics and related quantum schemes.

References

[1] Thornton T. J., Pepper M., Ahmed H., Andrews D., Davies G. J. 1986 *Phys. Rev. Lett.* **56** 1198-1201

[2] Wharam D. A., Thornton T. J., Newbury R., Pepper M., Ahmed H., Frost J. E. F., Hasko D. G., Peacock D. C., Ritchie D. A. and Jones G. A. C. 1988 *Journal of Physics C: Solid State Physics* **21** L209-L214

[3] van Wees B. J., van Houten H., Beenakker C. W. J., Williamson, J. G., Kouwenhoven L. P., van der Marel D. and Foxon C. T. C. 1988 *Phys. Rev. Lett.* **60** 848–850

[4] Thomas K. J., Nicholls J. T., Simmons M. Y., Pepper M., Mace D. R. and Ritchie D. A.1996 *Phys. Rev. Lett.* **77** 135–138

[5] Yan C., Kumar S., Thomas K., Pepper M., See P., Farrer I., Ritchie D., Griffiths J. P. and Jones G. A. C. 2017 *Appl. Phys. Lett.* **111** 042107

[6] Yan C., Kumar S., Pepper M., See P., Farrer I., Ritchie D., Griffiths J. P. and Jones G. A. C. 2017 *Phys. Rev. B* **95** 041407

[7] Yan C., Kumar S., Pepper M., See P., Farrer I., Ritchie D., Griffiths J. P. and Jones G. A. C. 2017 *Phys. Rev. Applied* **8** 024009

[8] Yan C., Kumar S., Pepper M., See P., Farrer I., Ritchie D., Griffiths J. P. and Jones G. A. C. 2017 *Nanoscale Research Letters* **12**:553

[9] Hew W. K., Thomas, K. J., Pepper M., Farrer I., Anderson D., Jones G. A. C. and Ritchie D. A. 2009 *Phys. Rev. Lett.* **102** 056804

[10] Kumar S., Thomas K. J., Smith L. W., Pepper M., Creeth G. L., Farrer I., Ritchie D., Jones G. and Griffiths J. 2014 *Phys. Rev. B* **90** 201304

[11] Cronenwett S. M., Lynch H. J., Goldhaber-Gordon D., Kouwenhoven L. P., Marcus C. M., Hirose, K., Wingreen N. S. and Umansky V. 2002 *Phys. Rev. Lett.* **88** 226805

[12] Kondo J. 1964 *Progress of theoretical physics* **32** 37–49

[13] Cronenwett S. M., Oosterkamp T. H. and Kouwenhoven L. P 1998 *Science* **281** 540–544

[14] Paaske J., Rosch A., Wölfle P., Mason N., Marcus C. M. and Nygård J. 2006 *Nature Physics* **2** 460–464

[15] Roch N., Florens S., Bouchiat V., Wernsdorfer W. and Balestro F. 2008 *Nature* **453** 633–637

[16] Iqbal M. J., Levy R., Koop E. J., Dekker J. B., De Jong J. P., van der Velde J. H. M., Reuter D., Wieck A. D., Aguado, R., Meir Y. and van der Wal C. H. 2013 *Nature* **501** 79–83

[17] Brun B., Martins F., Faniel S., Hackens B., Bachelier G., Cavanna A., Ulysse C., Ouerghi A., Gennser U., Mailly D., Huant S., Bayot V., Sanquer M. and Sellier H. 2014 *Nature Communication* **5** 4290

[18] Saito M., Usuki T., Okada M., Futatsugi T., Kiehl R.A. and Yokoyama N. 1994 *Appl. Phys. Lett.* **65** 3087-3089

[19] Rössler C., Oehri D., Zilberberg O., Blatter G., Karalic M., Pijnenburg J., Hofmann. A., Ihn T., Ensslin K., Reichl C. and Wegscheider W. 2015 *Phys. Rev. Lett.* **115** 166603

[20] Jaksch P., Yakimenko I. and Berggren K. F. 2006 *Phys. Rev. B* **74** 235320

[21] Iagallo A., Paradiso N., Roddaro S., Reichl C., Wegscheider W., Biasiol G., Sorba L., Beltram F. and Heun S. 2015 *Nano Research* **8** 948–956