A Tunable Fano System Realized in a Quantum Dot in an Aharonov-Bohm Ring

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Abstract. We report a tunable Fano system realized in a quantum dot embedded in an Aharonov-Bohm interferometer on a two-dimensional electron gas. In the Coulomb oscillation, clear asymmetric line shapes were observed, which manifest the formation of the Fano state, i. e., a coherent mixture of localized-continuum states. The Fano interference can be tuned through the phase of electrons by the electrostatic gate and the magnetic flux piercing the ring. In addition, this effect was found to significantly affect the phase evolution of electrons.

1. Introduction

A system where coexist a discrete state and the continuum energy state possesses a characteristic transition probability around the discrete energy level [1]. This is the Fano effect, reflecting the quantum interference between the two configurations in the transition process into the final states with the same energy: one directly through the continuum and the other through the resonance level arising around the discrete state, as sketched in Fig. 1 (a). This “configuration interaction” yields the peculiar asymmetric line shape in the transition probability T from an arbitrary initial state, which is expressed as

$$T(\tilde{\epsilon}) \propto \frac{(\tilde{\epsilon}+q)^2}{\tilde{\epsilon}^2+1}, \quad \tilde{\epsilon} = \frac{\epsilon-\epsilon_0}{\Gamma/2}, \tag{1}$$

where ϵ_0 is the energy level of the resonance state and Γ is its width. The parameter q, which is the ratio of the matrix elements linking the initial state to the discrete and continuum parts of the final state, serves as a measure of the degree of coupling between them. When $q \to \infty$, Eqn. (1) falls into a Lorentzian corresponding to an ordinary Breit-Wigner-type resonance. For a finite q, Eqn. (1) gives various line shapes as shown in Fig. 1 (b).

The Fano effect is a ubiquitous phenomenon observed in wide-ranging spectroscopy including neutron scattering [2], atomic photoionization [3], Raman scattering [4], and optical absorption [5]. It can be viewed as a theory describing how a localized state embedded in the continuum acquires itinerancy over the system [6]. An experiment on a single site, therefore, would reveal this fundamental process in a more transparent way. While the single-site Fano effect has been reported in the scanning tunneling spectroscopy study of an atom on the surface [7, 8] or in transport through a quantum dot (QD) [9], it has been difficult to obtain a Fano system with variable parameters.

In the present work, we report a tunable Fano experiment performed in a QD embedded in an Aharonov-Bohm (AB) interferometer [10]. Especially, we focus on the result of the electrostatic and magnetic tuning of the Fano interference.

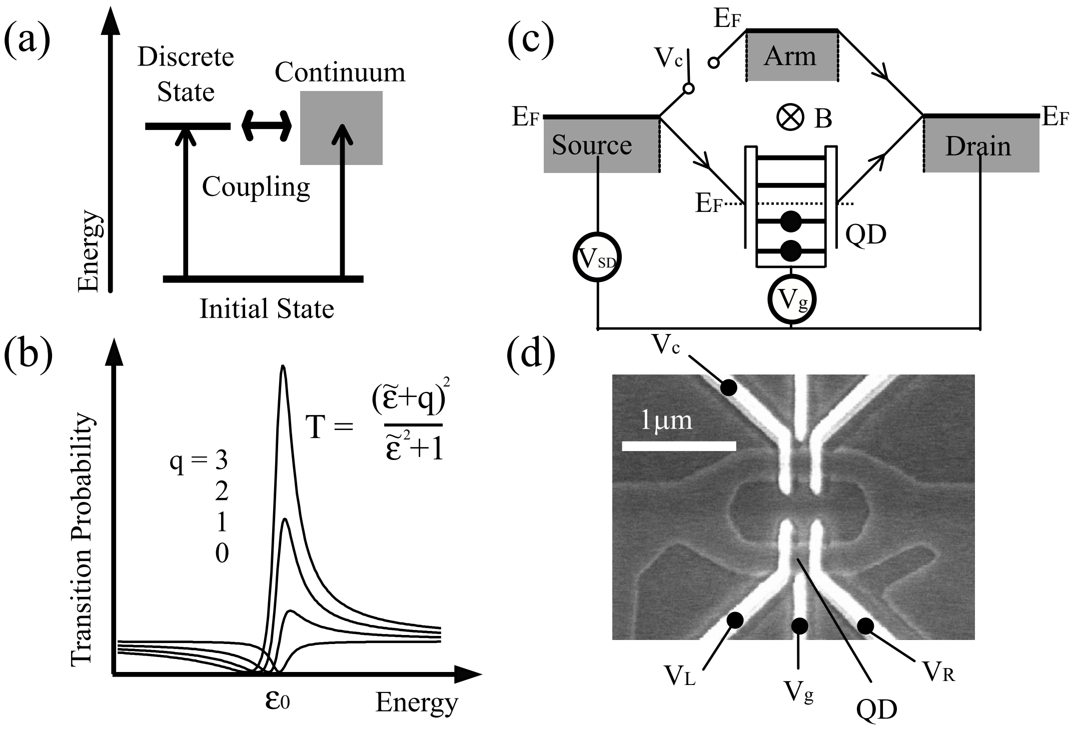

Figure 1. (a) Principle of the Fano effect. (b) Fano's line shapes for several q parameters. (c) Schematic representation of the experimental setup. An electron injected from the source traverses the ring along two different paths through the continuum in the arm and the discrete level inside the QD and interferes before the drain. This corresponds to an artificial single-site Fano system. (d) Scanning electron micrograph of the correspondent device fabricated by wet-etching the 2DEG at an AlGaAs/GaAs heterostructure. The white regions indicate the Au/Ti metallic gates. The three gates (V_R, V_L, and V_g) at the lower arm are used for controlling the QD and the gate at the upper arm is for V_C.

2. Experiments

To realize a well-defined Fano system, a localized state is necessary to be embedded in the energy continuum. We designed an AB ring with a QD in one of its arms as seen in Fig. 1 (c). The QD is an "artificial atom" [11] connected to the leads with tunneling barriers, whose single-particle level can be controlled electrostatically by the gate voltage (V_g). Thus, an electron injected from the source traverses our "modified" AB interferometer along two different paths through the continuum in the arm and the discrete level inside the QD and interferes before the drain. If the coherence of the electrons is fully maintained during the traverse over the system, this interferometer is exactly a realization of the Fano system [12–15]. Unlike the other Fano systems it is unique in that it is controllable through several parameters; V_g (the position of the discrete level inside the QD), the control gate voltage V_C (the coupling between the continuum and the discrete levels), and the magnetic field B piercing the ring (the phase difference between two paths).

Figure 1 (d) shows the Fano system fabricated on a two-dimensional electron gas (2DEG) system at an AlGaAs/GaAs heterostructure (mobility $= 9 \times 10^5$ cm^2/Vs, sheet carrier density $= 3.8 \times 10^{11}$ cm^{-2}, and Fermi wavelength $\lambda_F \sim 40$ nm). This sample geometry is similar to those in the previous studies [16–19]. The ring-shaped conductive region was formed by wet-etching the 2DEG. The white regions in Fig. 1 (d) indicate the Au/Ti metallic gates deposited to control the device. The QD can be defined in the lower arm by tuning the side-gate voltages

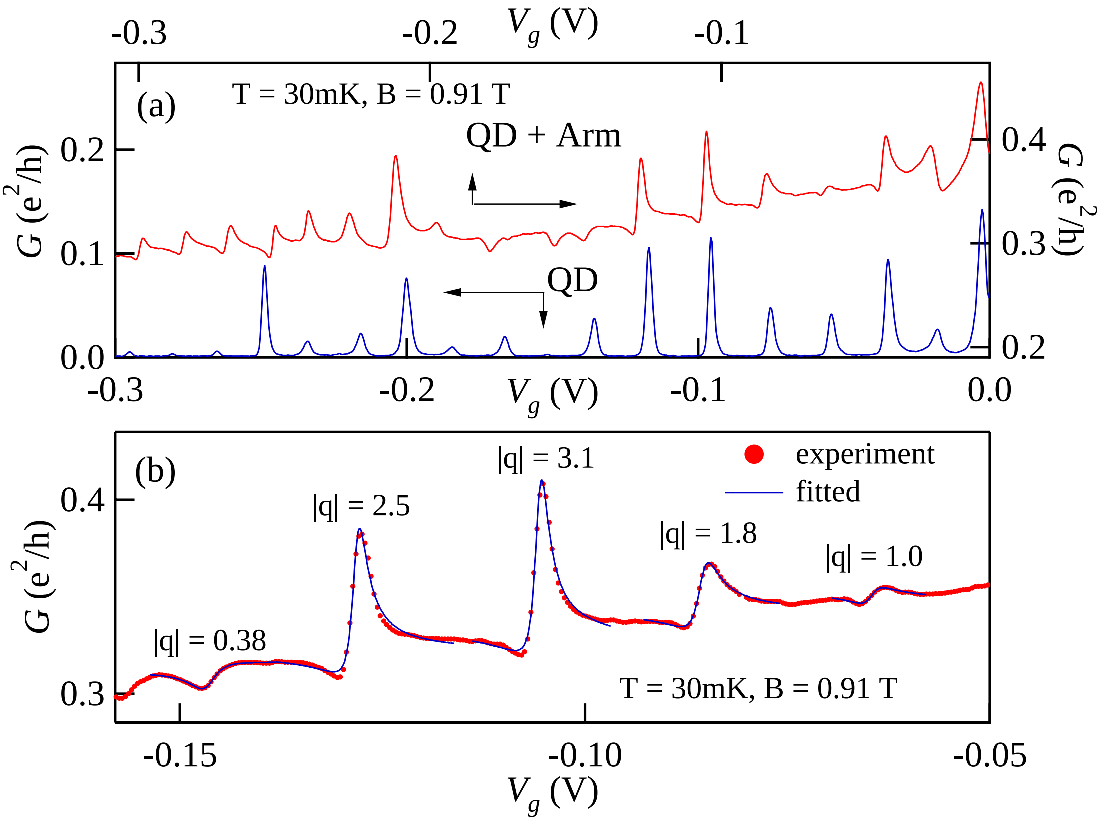

Figure 2. (a) Typical Coulomb oscillation at $V_C = -0.12$ V with the arm pinched off, and asymmetric Coulomb oscillation at $V_C = -0.086$ V with the arm transmissible. The latter shows a clear Fano effect. Both of them were obtained at $T = 30$ mK and $B = 0.91$ T. (b) Typical results of the fitting to the Fano line shape with various q's.

(V_L and V_R) and its single-particle level can be tuned by V_g. The gate in the upper arm is V_C for switching the transition through the continuum state on and off. Measurements were performed in a dilution refrigerator by a standard lock-in technique in the two-terminal setup with an excitation voltage of 10 μV (80 Hz) between the source and the drain.

3. Results and Discussions

3.1. Fano Effect in the Coulomb Oscillation

First, we pinched off the upper arm by applying large negative voltage on V_C. The QD was defined in the lower arm by tuning the side-gate voltages (V_L and V_R). The lower panel of Fig. 2 (a) shows the pronounced peaks in the conductance G through the QD as sweeping V_g, namely, a typical Coulomb oscillation expected for QDs in the CB regime. The small irregularity of the peak positions reflects that of the addition energy and supports the occurrence of transport through each single level inside the QD.

Next, we made the upper arm conductive. Because the control gate and the QD are well separated electrostatically, a clear one-to-one correspondence is observed between the two results in Fig. 2 (a), ensuring that the discreteness of the energy levels in the QD is maintained. It is noteworthy that the line shapes of the oscillation become very asymmetric and show even dip structures. The asymmetric line shape observed above is a clear sign of the

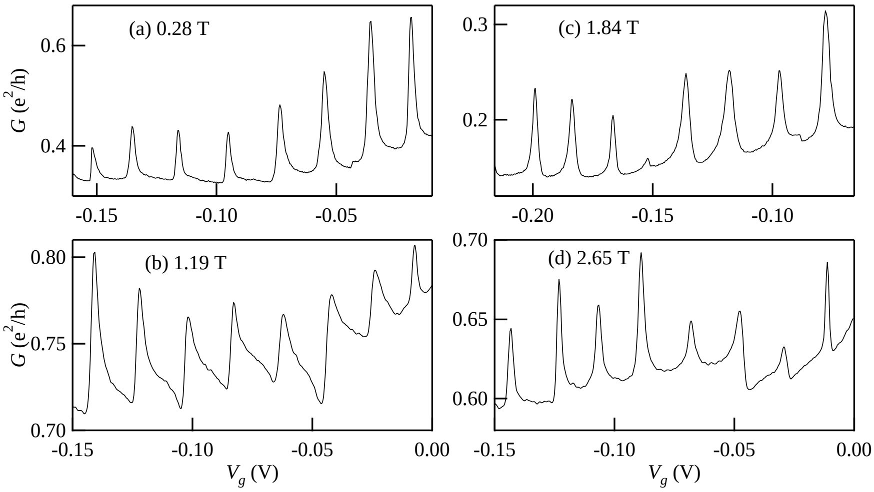

Figure 3. Fano's line shapes taken at (a) 0.28 T, (b) 1.19 T, (c) 1.84 T, and (d) 2.65 T.

Fano effect. Actually, as seen in Fig. 2 (b) each peak was found to be well fitted by Eqn. (1). The dip structure, which corresponds to $|q| < 1$, indicates a strong destructive interference, supporting that the electron passing the QD retains sufficient coherency to interfere with the one passing the arm in spite of the significant charging effect inside and around the QD. This is in contrast with the previous reports [16–19], where the coherence was limited to a fraction of the transmission through the QD.

The above Fano line shapes were obtained at $B \sim 0.92$ T. We found the Fano effect prominent within several specific magnetic field ranges as shown in Figs. 3 (a)-(d) besides $B \sim 0.92$ T, while it was less pronounced in other ranges. This implies that the coherence of the transport through the QD strongly depends on B. A similar role of B is reported in the Kondo effect in a QD [18], where the Kondo effect appeared at the specific magnetic field other but not at $B \sim 0$ T. Such phenomena arise from the change of the electronic states caused by B in a QD. It is also possible that the magnetic field affects the coherent transport in a mesoscopic sample such as in a quantum wire, due to the reduction of boundary roughness scattering by the magnetic field as theoretically treated in Ref. [20]. An example of the experimental indications was seen in Ref. [21]. At the present moment, these problems are left to be clarified in future. Henceforth, we will focus on the Fano effect observed at $B \sim 0.92$ T.

3.2. Electrostatic and Magnetic Control of the Fano Interference

The present system is much larger in size than the others such as an atom that shows the Fano effect. Its largest advantage over them lies in the spatial separation between the discrete level and the continuum, which allows us to control Fano interference both electrostatically and magnetically.

First, we discuss the electrostatic control by the control gate voltage V_C. Figure 4 shows the Coulomb oscillation curves at $V_C = -0.081$ V and -0.092 V. It is clear that the direction of asymmetric tail of the Fano effect is opposite between the two, which means the change of the sign of q in Eqn. (1). This can be qualitatively explained as follows. The variation of the electrostatic potential energy by V_C results in that of the kinetic energy, and hence the wave number of the electrons which traverse the region underneath the gate electrode. According to a simple capacitance model between the gate and the 2DEG [22], this effect yields the phase

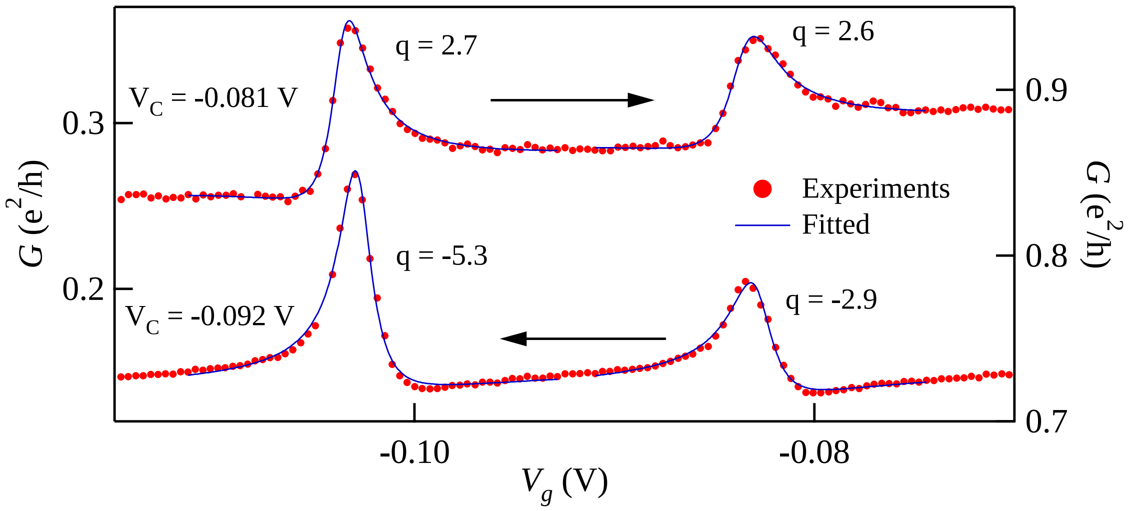

Figure 4. Coulomb oscillations at $V_C = -0.081$ V and -0.092 V. The results of the fitting to Eqn (1) indicate that the sign of q is different between the two results.

difference $\Delta\theta$ between the two paths as follows;

$$\Delta\theta(V_C) = 2\pi \frac{W}{\lambda_F}\left(1 - \sqrt{1 - \frac{V_C}{V_{dep}}}\right), \quad (2)$$

where W and V_{dep} are the width of the gate and its pinch-off voltage (-0.10 V for the present case), respectively. Now, if we take the effective width $W \sim 120$ nm, $|\Delta\theta(V_C = -0.081) - \Delta\theta(V_C = -0.092)| \sim 0.92\pi \sim \pi$. Therefore, the change of the sign of q is attributed as due to the phase shift by $\sim \pi$ electrostatically caused by V_C.

We have shown that the electrostatic phase control is possible by using the gate electrode, while the variation of V_C also greatly affects the conductance of the system as seen in Fig. 4. On the other hand, the magnetic field is more suitable to control only the phase between the localized state and the continuum. Indeed, the line shape changed periodically with the AB period of ~ 3.8 mT, which agrees with that expected from the ring dimension. Typical results are presented in Fig. 5. As B is swept, an asymmetric line shape with negative q continuously changes to a symmetric one and then to an asymmetric one with positive q; the sign of interference can be controlled by the AB effect. It is interesting to note that the Fano effect is usually characterized by an asymmetric line shape, while an almost symmetric line shape is obtained at a specific magnetic field, for example, as seen in the conductance at $B = 0.9151$ T in Fig. 5.

Such behavior is most likely explained systematically by introducing a complex number q whose argument is a function of B or the AB flux, although an expression of such q applicable to our case is not known at present. Here, Eqn. (1) is generalized as follows:

$$T(\tilde{\epsilon}) \propto \frac{|\tilde{\epsilon} + q|^2}{\tilde{\epsilon}^2 + 1} = \frac{(\tilde{\epsilon} + \mathrm{Re}q)^2 + (\mathrm{Im}q)^2}{\tilde{\epsilon}^2 + 1}. \quad (3)$$

Qualitatively, even when the coupling strength $|q|$ is almost independent of B, the B-dependence of $\arg(q)$ yields asymmetric and symmetric line shapes of G for Re$q \gg$ Imq and Re$q \ll$ Imq, respectively. Hence, when the line shape is very asymmetric, the fitting with a real q is valid as seen in Figs 2 (a) and 4. While the expression of Eqn. (3) does not at all conflict with the Fano theory [1], the asymmetric parameter q has been implicitly treated as a real number in his original work and most of the subsequent studies. We would

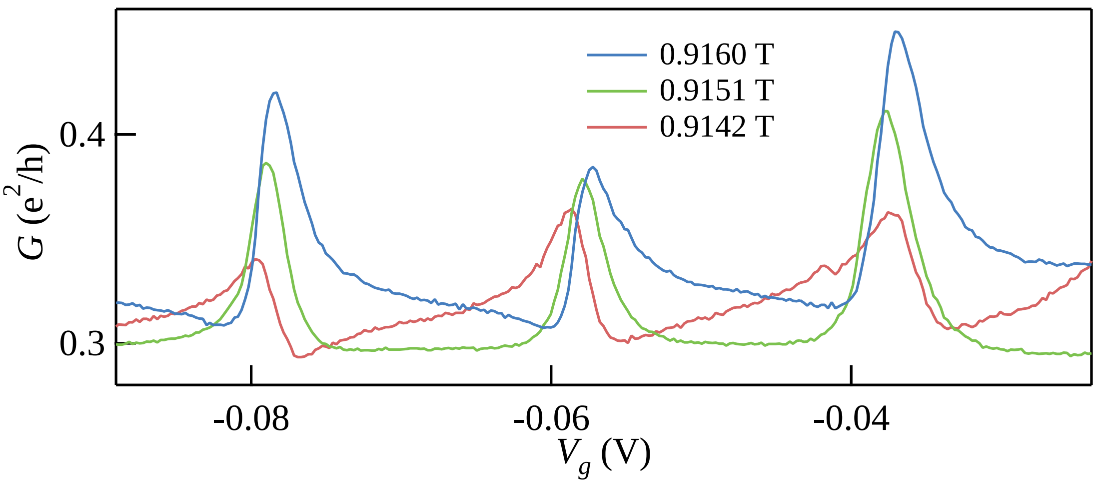

Figure 5. Conductance of the Fano peaks at $B = 0.9142$, 0.9151, and 0.9160 T. The direction of the asymmetric tail changes between $B = 0.9142$ and 0.9160 T and the symmetric shape appears in between.

like to emphasize that such a treatment is valid only when the system has the time-reversal symmetry and thus the matrix elements defining q can be taken as real. The influence of the breaking of the time reversal symmetry (TRS) to the Fano effect has been theoretically treated in Refs. [14, 15, 23]. Our result experimentally clarifies that when the TRS breaks under the magnetic field q should be a complex number.

3.3. AB Oscillation in the Fano State

Next we focus on the behavior of the AB oscillation across a single Coulomb peak to see how the Fano effect affects the phase evolution of electrons. In Fig. 6 (b), we plotted several AB oscillations taken at the points indicated in the top panel of Fig. 6 (a). Note that the amplitude of the AB oscillation is as large as the net intensity of the original Coulomb peak, supporting that the transport through this QD-AB-ring system occurs very coherently. We also note that clear AB oscillation is observed even at the conductance valley between the resonant peaks (see the curves a and f in Fig. 6 (b)). This provides an evidence that the state in the QD becomes delocalized with the aid of the continuum.

Not only the AB amplitude but also the phase of the AB oscillation is quite unique. From the curve a to c, the phase is gradually shifted. Between c and d across the resonance, the phase changes very rapidly by $\sim \pi$. Then, from d to f, the phase varies slowly again, and at last a and f become in phase. This behavior is plotted in the bottom panel of Fig. 6 (a). Thus, the adjacent Fano resonances are in phase, indicating that the resonance peaks are correlated to each other [24]. Since the measurement was performed in the two-terminal setup that allows only phase changes by multiples of π due to reasons of symmetry, the continuous behavior of the AB phase is unexpected, but may be attributed to the breaking of the time-reversal symmetry [24]. Several theoretical predictions on the behavior of the AB phase in the Fano system have been reported [12–15], still there are features left to be explained theoretically.

It is also worth comparing our result with those in previous two-terminal experiments for a normal QD [16] and a Kondo QD [18]. In the former case, it was found that the AB phase jumps by π at the resonant peak and that the adjacent Coulomb peaks are in phase. For a Kondo QD, no phase change is observed in the Kondo valley and only one of the two Coulomb peaks located at the side of the valley exhibits the π phase flip. Thus, the behavior of

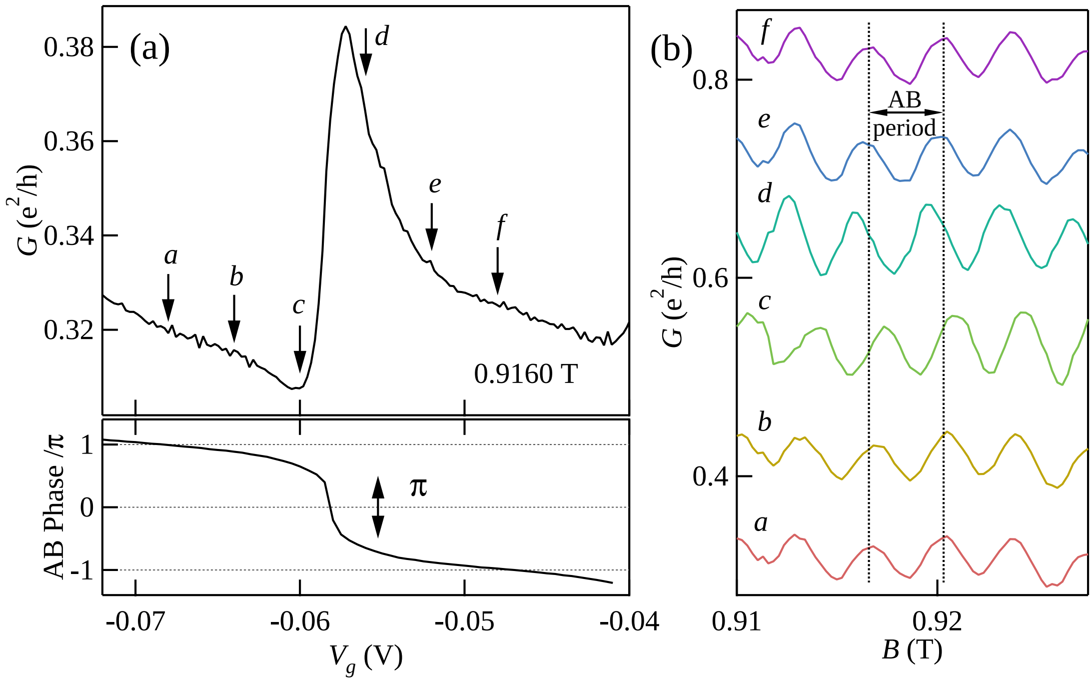

Figure 6. (a) Conductance at $B = 0.9160$ T (top). The phase of the AB oscillation (bottom). (b) AB oscillation taken at various points a-f indicated in (a). The curves are incrementally shifted upwards by $0.1e^2/h$ for clarity. The dotted vertical lines indicate that the curves a and f are in phase.

the AB phase in the present Fano system is qualitatively different from both. At this moment, the observed phase of electrons through a QD, especially through a Kondo QD [18, 19], remains open, where the Fano effect is recently predicted to play an important role [14, 25, 26]. Our result provides an important experimental indication that this effect critically affects the phase evolution of electrons through such a quantum system similar to ours, particularly when the coherence is highly preserved.

4. Conclusion

We report a tuning experiment of the Fano effect performed in the QD-AB-ring hybrid system. The electrostatic and magnetic controlling of the Fano line shape has been discussed and we found that the Fano parameter q should be a complex number when the TRS breaks. Delocalization of the discrete levels in the QD due to this effect shows up in the considerable AB amplitude in the CB. The behavior of the AB phase is found to be different from the previous results, indicating that the Fano effect intrinsically affects the phase evolution of electrons.

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References

[1] U. Fano, Phys. Rev. **124,** 1866 (1961).
[2] R. K. Adair, C. K. Bockelman, and R. E. Peterson, Phys. Rev. **76,** 308 (1949).
[3] U. Fano, A. R. P. Rau, in *Atomic Collisions and Spectra* (Academic Press, Orland, 1986).
[4] F. Cerdeira, T. A. Fjeldly, and M. Cardona, Phys. Rev. B **8,** 4734 (1973).
[5] J. Faist, F. Capasso, C. Sirtori, K. W. West, and L. N. Pfeiffer, Nature **390,** 589 (1997).
[6] G. D. Mahan, *Many-Particle Physics* (Plenum Press, New York, 1990).
[7] V. Madhavan, W. Chen, T. Jamneala, M. F. Crommie, and N. S. Wingreen, Science **280,** 567 (1998).
[8] J. Li, W. D. Schneider, R. Berndt, and B. Delley, Phys. Rev. Lett. **80,** 2893 (1998).
[9] J. Göres, D. Goldhaber-Gordon, S. Heemeyer, M. A. Kastner Hadas Shtrikman, D. Mahalu, and U. Meirav Phys. Rev. B **62,** 2188 (2000).
[10] K. Kobayashi, H. Aikawa, S. Katsumoto, and Y. Iye, Phys. Rev. Lett. **88,** 256806 (2002).
[11] M. Kastner, Phys. Today **46,** 24 (1993).
[12] C.-M. Ryu and S. Y. Cho, Phys. Rev. B **58,** 3572 (1998).
[13] K. Kang, Phys. Rev. B **59,** 4608 (1999).
[14] O. Entin-Wohlman, A. Aharony, Y. Imry, and Y. Levinson, cond-mat/0109328 (2001).
[15] T.-S. Kim, S.-Y. Cho, C.-K. Kim, and C.-M. Ryu, cond-mat/0110395, Phys. Rev. B **65,** 245307 (2002).
[16] A. Yacoby, M. Heiblum, D. Mahalu, and H. Shtrikman, Phys. Rev. Lett. **74,** 4047 (1995).
[17] R. Schuster, E. Buks, M. Heiblum, D. Mahalu, V. Umansky, and H. Shtrikman, Nature **385,** 417 (1997).
[18] W. G. van der Wiel, S. De Franceschi, T. Fujisawa, J.M. Elzerman, S. Tarucha, and L.P. Kouwenhoven, Science **289,** 2105 (2000).
[19] Yang Ji, M. Heiblum, D. Sprinzak, D. Mahalu, and Hadas Shtrikman, Science **290,** 779 (2000).
[20] H. Akera and T. Ando, Phys. Rev B **43,** 11676 (1991).
[21] L. P. Kouwenhoven, F. W. J. Hekking, B. J. van Wees, C. J. P. M. Harmans C. E. Timmering, and C. T. Foxon, Phys. Rev. Lett. **65,** 361 (1990).
[22] A. Yacoby, U. Sivan, C. P. Umbach, and J. M. Hong, Phys. Rev. Lett. **66** (1991) 1938.
[23] A. A. Clerk, X. Waintal, and P. W. Brouwer, Phys. Rev. Lett. **86,** 4636 (2001).
[24] H.-W. Lee, Phys. Rev. Lett. **82,** 2358 (1999).
[25] B. R. Bulka and P. Stefanski, Phys. Rev. Lett. **86,** 5128 (2001).
[26] W. Hofstetter, J. Konig, and H. Schoeller, Phys. Rev. Lett. **87,** 156803 (2001).