Tuning of the Fano Effect through a Quantum Dot in an Aharonov-Bohm Interferometer

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The Fano effect, which arises from an interference between a localized state and the continuum, reveals a fundamental aspect of quantum mechanics. We have realized a tunable Fano system in a quantum dot (QD) in an Aharonov-Bohm interferometer, which is the first convincing demonstration of this effect in mesoscopic systems. With the aid of the continuum, the localized state inside the QD acquires itinerancy over the system even in the Coulomb blockade. Through tuning of the parameters, which is an advantage of the present system, unique properties of the Fano effect on the phase and coherence of electrons have been revealed.

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When a discrete energy level is embedded in a continuum energy state and there is coupling between these two states, a resonant state arises around the discrete level. In 1961, Fano proposed [1] that in such a system a transition from an arbitrary initial state occurs through the two interfering configurations—one directly through the continuum and the other through the resonance level—and that this quantum mechanical interference yields a characteristic asymmetric line shape in the transition probability. This is the Fano effect, a ubiquitous phenomenon observed in a large variety of experiments including neutron scattering [2], atomic photoionization [3], Raman scattering [4], and optical absorption [5]. While a statistically averaged nature of the system containing contributions from numerous sites is observed in these experiments, the Fano effect is essentially a single-impurity problem describing how a localized state embedded in the continuum acquires itinerancy over the system [6]. Therefore, an experiment on a single site 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], there is little, if any, controllability in either case since the coupling between the discrete level and the continuum is naturally formed.

In this Letter, we report the first tunable Fano experiment. We have clarified characteristic transport properties arising from this effect, such as the delocalization of the discrete level and the excitation spectra of the Fano system. External control of the relative phase between a localized state and the continuum indicates that the Fano parameter should be treated as a complex number.

To realize a well-defined Fano system, we designed an Aharonov-Bohm (AB) ring with a QD embedded in one of its arms as seen in Fig. 1(a), similar to those in previous studies [10–13]. The AB ring is essentially a double-slit interferometer of electrons. In contrast, the QD [14], a small electron droplet isolated from its leads by tunneling barriers, has discrete energy levels arising from the electron confinement and the charging energy that is much larger than the thermal energy k_BT (k_B is the Boltzmann constant, and T is the temperature). In the Coulomb blockade (CB) regime, the single-particle level in the QD can be controlled electrostatically by the gate voltage (V_g), and only when the level matches the chemical potential of the leads is conduction through the QD allowed. Thus, our "modified" AB interferometer has the continuum energy state in one arm and the discrete energy level in the QD in the other arm. If the coherence of the electron is fully maintained during tunneling through the QD and during propagation through the arm, interference of traversing electrons will occur through two different configurations. Physically, this situation is exactly a realization of the Fano system [15–18]. The present system is unique in that it is controllable through several parameters; the position of the discrete level inside the QD, the coupling between the continuum and the discrete levels, and the phase difference between two paths are controlled by V_g, the control gate voltage (V_C), and the magnetic field (B) penetrating the ring, respectively.

Figure 1(b) shows the fabricated Fano system on a two-dimensional electron gas (2DEG) system at an AlGaAs/GaAs heterostructure (mobility $= 9 \times 10^5$ cm^2/V s, sheet

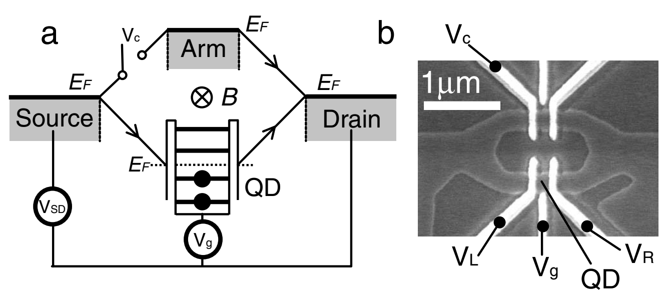

FIG. 1. (a) Schematic representation of the experimental setup. An electron injected from the source traverses the ring along two different paths through the continuum in the arm and the discrete level inside the QD and interferes before the drain. This corresponds to an artificial single-site Fano system. (b) 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.

carrier density = 3.8×10^{11} cm^{-2}, and electron mean free path $l_e \sim 8$ μm). The ring-shaped conductive region was formed by wet etching the 2DEG. The length of one arm of the ring is $L \sim 2$ μm. The Au/Ti metallic gates were deposited to control the device. The three in the lower arm were used for defining a QD (with ~80 electrons contained in its area about 0.15×0.15 μm^2) and the gate in the upper arm is V_C for switching the transition through the continuum state on and off. Measurements were performed between 30 and 800 mK 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. Noise filters were inserted into every lead at $T < 1$ K as well as at room temperature.

First, we pinched off the upper arm by applying a 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.

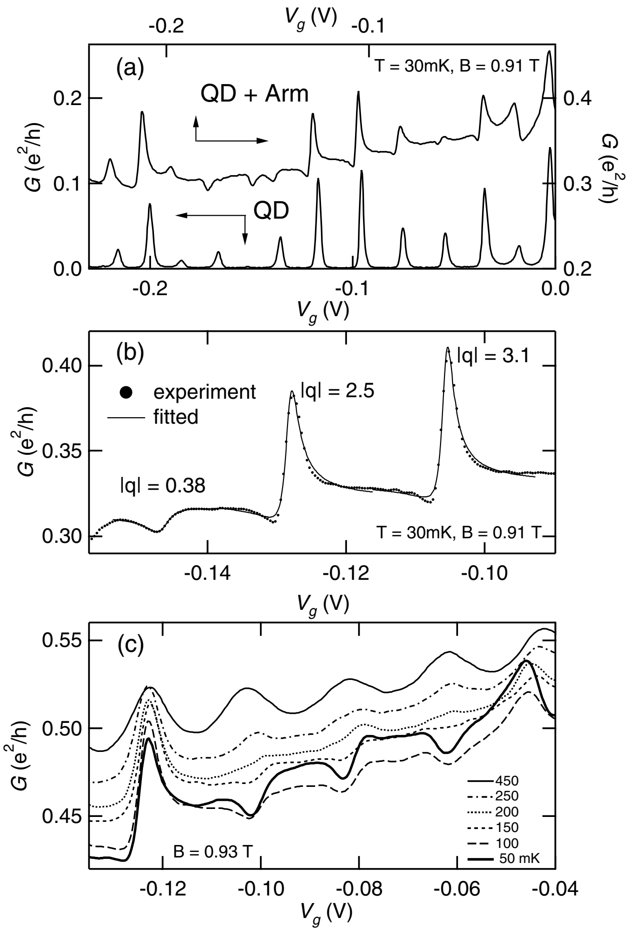

FIG. 2. (a) Typical Coulomb oscillation at $V_C = -0.12$ V with the arm pinched off, and asymmetric Coulomb oscillation at $V_C = -0.086$ V with the arm transmissible. The latter shows a clear Fano effect. Both of them were obtained at $T = 30$ mK and $B = 0.91$ T. (b) The typical results of the fitting to the Fano line shape with $|q| = 0.38$, 2.5, and 3.1. (c) The Fano effect measured at several temperatures at $B = 0.93$ T. It gradually disappears as the temperature increases.

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. This is a clear sign of the Fano effect. Indeed, each peak can be well fitted by the Fano line shape [1] $G(\epsilon)$ of the form

$$G(\epsilon) \propto \frac{(\epsilon + q)^2}{\epsilon^2 + 1}, \qquad \epsilon = \frac{V_g - V_0}{\Gamma/2}, \tag{1}$$

where V_0 is the energy of the resonance position, and Γ is the width of the resonance. The real 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 both. The line shape analysis for several resonance levels gives $|q| = 0.2$–7 with $\Gamma \sim 3$ meV as the typical results of the fitting are shown in Fig. 2(b). The observed $|q|$ values are correlated with the values of the conductance of the original Coulomb peak in that a large peak tends to have a large $|q|$. The dip structure with $|q| < 1$ 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 [10–13], where the coherence was limited to a fraction of the transmission through the QD.

The Fano effect was found to be prominent within several specific magnetic field ranges such as around $B \sim 0.3$, 0.9, and 1.2 T, while it was less pronounced in the 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 [12]. Such phenomena arise from the change of the electronic states caused by B in each mesoscopic system, while this remains to be clarified theoretically.

When the temperature increased, decoherence increased and the asymmetric Fano line shapes gradually evolved into an ordinary Lorentzian line shape corresponding to $|q| \to \infty$ as clearly seen in Fig. 2(c). Because of the loss of coherence over the interferometer at $T \geq 450$ mK, the system is simply a classical parallel circuit of the QD and the arm, being no longer in the Fano state.

We measured the differential conductance at the lowest temperature as a function of both source-drain bias (V_{sd}) and V_g. Figure 3 depicts that the resonating conductance peak of the width ~70 μeV (colored white) stretches along the line of $V_{sd} = 0$ V with the Coulomb diamond superimposed. The appearance of the zero-bias conductance

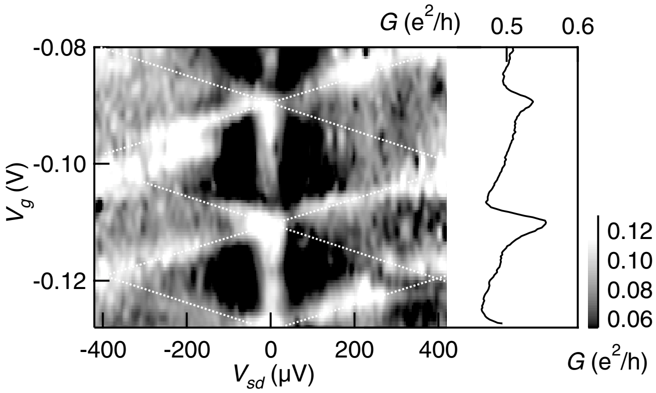

FIG. 3. Differential conductance obtained as a function of V_g at $T = 30$ mK and $B = 0.92$ T. The corresponding Fano line shape is also shown in the right panel. The zero-bias conductance peak exists in the CB region with a Coulomb diamond superimposed. The edge of the CB region is emphasized with white dashed lines. Incoherent contribution from the differential conductance of the upper arm, which shows slight non-Ohmic behavior at finite V_{sd}, has been subtracted from the data.

peak even in the CB region indicates that the transmission through the QD is now allowed due to the aid of the continuum in the opposite arm. Such delocalization of the electron in the CB region is highly analogous with that observed in the QD in the Kondo regime [19–21], although the mechanism is different. Delocalization in the Kondo dot occurs through resonating spin singlet formation, while resonance due to the configuration interaction between the discrete state and the continuum is the cause in the Fano regime [6].

In our system, the discrete level and the continuum are spatially separated, allowing us to control Fano interference via the magnetic field piercing the ring as shown in Figs. 4(a), 4(b), and 4(c). The line shape changes periodically with the AB period of ~3.8 mT, which agrees with that expected from the ring dimension. Figure 4(b) illustrates that the oscillation amplitude at the conductance maximum is of the same order as the net peak height, again ensuring that the transmission through the QD occurs coherently. 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. Typical results are presented in Fig. 4(a). The Fano effect is usually characterized by an asymmetric line shape, while a perfect symmetric line shape is obtained at a specific magnetic field here. Since the magnetic field mainly affects the phase difference between the two paths through the resonant state and the continuum, the aforementioned periodic 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 Eq. (1) is generalized to $G(\epsilon) \propto |\epsilon + q|^2/(\epsilon^2 + 1) = [(\epsilon + \text{Re}q)^2 + (\text{Im}q)^2]/(\epsilon^2 + 1)$. Qualitatively, even when the coupling

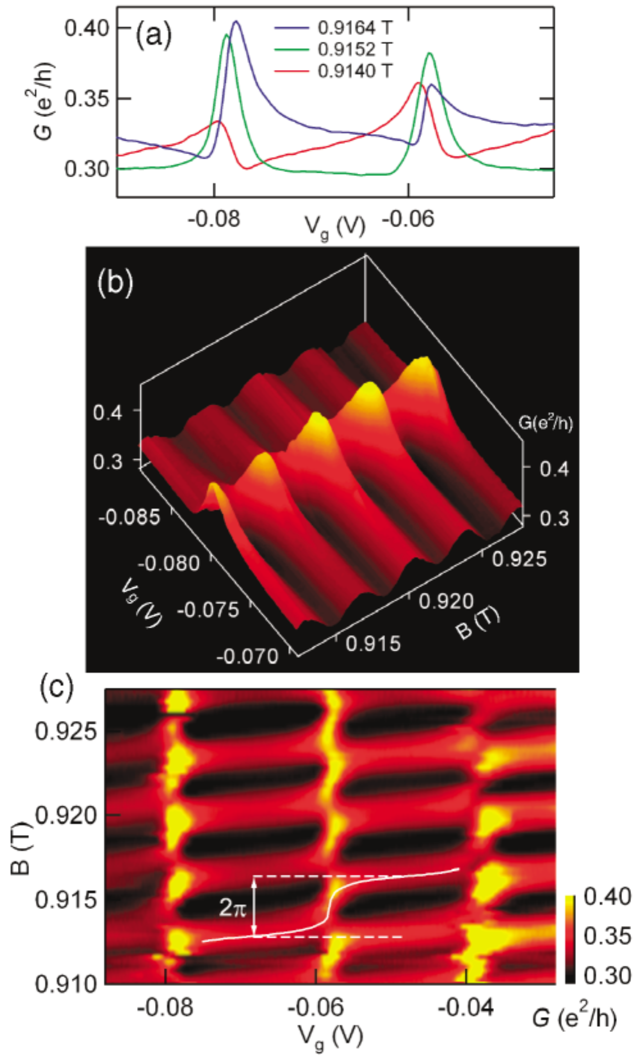

FIG. 4 (color). (a) Conductance of two Fano peaks at 30 mK at the selected magnetic fields. The direction of the asymmetric tail changes between $B = 0.9140$ and 0.9164 T and the symmetric shape appears in between. (b) Conductance of one Fano peak as a function of V_g and B at 30 mK. Note the large AB oscillation of the same order as the resonance peak. (c) Conductance of the Fano peaks as a function of V_g and B at 30 mK. AB oscillation exists even at the midpoint of the resonances. The white line represents the AB phase as a function of V_g. Note that the AB phase changes by 2π through the resonance, and all the resonances are in phase.

strength $|q|$ is almost independent of B, the B dependence of $\arg(q)$ yields asymmetric and symmetric line shapes of G for $\text{Re}q \gg \text{Im}q$ and $\text{Re}q \ll \text{Im}q$, respectively. In the original work by Fano [1] and most of the subsequent studies based on his theory, the asymmetric parameter q has been implicitly treated as a real number, while this is valid only when the system has the time-reversal symmetry, and thus the matrix elements defining q can be taken as real. Our experiment indicates that when this condition is broken, for example, by applying the magnetic field, q should be a complex number, which has not been explicitly recognized.

Figure 4(c) represents the result over three Fano resonances in the V_g-B plane. Clear AB oscillation is observed even at the conductance valley between the resonant peaks. This provides another evidence that the state in the QD becomes delocalized with the aid of the continuum. In Fig. 4(c) we also plot the conductance maximum as a function of V_g, where the phase is observed to change by 2π rapidly but continuously across the resonance. 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 [22,23]. The AB phase changes only slightly at the conductance valley and, therefore, all the adjacent Fano resonances are in phase, indicating that the resonance peaks are correlated to each other [22]. Several theoretical predictions on the behavior of the AB phase in the Fano system have been reported [15–18], while none of them perfectly reproduces the overall behavior discussed above. Further study is needed to fully understand the behavior of the AB phase coexistent with the Fano effect.

It is also worth comparing our result with those in previous two-terminal experiments for a normal QD [10] and a Kondo QD [12]. 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 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 [12,13], remains open, where the Fano effect is recently predicted to play an important role [17,24,25]. 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.

In conclusion, we have clarified a peculiar quantum transport through the QD-AB-ring hybrid system, which is caused by the Fano effect due to the sufficiently coherent transport through the QD and the ring. While this effect has been observed in a variety of physical systems, the present system is the first convincing realization of a Fano system that can be tuned. Delocalization of the discrete levels in the QD due to this effect shows up both in the resonating zero-bias peak in the differential conductance and in the considerable AB amplitude in the CB. Controlling the Fano line shape by the magnetic field has revealed that the Fano parameter q will be extended to a complex number. The behavior of the AB phase is found to be very different from the previous results, indicating that our system is not simply a QD with an adjective reference arm but should be regarded as a novel quantum system.

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