Phase Information from Two-Terminal Conductance of Quantum Dot Systems

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Abstract. Two-terminal devices generally work as "leaky resonators" in coherent transport, which mixes up the quantum phase information from all parts of the devices, e.g., quantum dots (QDs) embedded in them. With the aids of appropriate theoretical modeling, however, we can extract important information on the phase from the total conductance. As typical examples, we here present experiments in a side-coupled QD, and a QD embedded in an Aharonov-Bohm (AB) ring. In the former, kinetic freedoms transverse and longitudinal to a quantum wire give rise to dramatic change in the interference effect. In the latter, "phase shift locking to $\pi/2$" appears as a plateau structure in the conductance. Specialized theoretical models give reasonable explanations to these effects, bringing important information on the phase of the electron wavefunctions in the QDs.

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The phase of a wavefunction is a most important concept in wave-mechanics. Various interference effects in mesoscopic physics are direct consequences of phase difference. A sharp contrast between mesoscopic conductors and ordinal wave interferometers lies in the constraint of unitarity in two-terminal devices. In other words, the two-terminal devices usually work as "leaky resonators" than simple interferometers. This situation makes the output complicated and gives significant distortion on the phase information. On the other hand, the two-terminal devices have apparent advantage in the amplitude of interference signals.

In this article, we show that we can extract important undistorted phase information from two-terminal conductance with the aid of appropriate theoretical models. Especially the phase shifts through quantum dots (QDs) are of interest because they carry essential knowledge of electronic states in them and many body effects, which arise from indirect interaction between conduction electrons via QDs.

The quantum interference circuits and the QDs used in the present study were made from two-dimensional electron system at AlGaAs/GaAs heterointerface. The circuits and the dots were defined by wet-etching or lithography-made metallic gates.

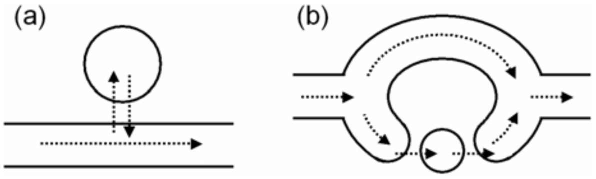

FIGURE.1 Schematic diagrams of interference circuits used in the present experiments. (a) T-shaped stab resonator. (b) AB ring with a quantum dot in one of the arms.

In Fig.1, we show two types of interferometers adopted in the experiments. In the side-coupled geometry (Fig.1(a)), the size of the dot can be extremely small by applying negative voltage to the plunger gate with keeping a finite coupling to the quantum wire. This feature makes it possible to explore the interference effect in few-electron QD regime. However because the interference and the resonance occur in very narrow region, the control of the parameters of the interferometer is inevitably associated with variation of other parameters. On the other hand in an Aharonov-Bohm (AB) ring structure shown in Fig.1(b), the phase difference between the two arms can be easily tuned by the flux piercing the ring without changing other parameters though it is hard to measure the transport in few-electron regime.

In the side coupled geometry (Fig.1(a)), we measured the conductance (G_w) through the quantum wire as a function of the plunger gate voltage (V_p) of the QD and the gate voltage of the wire (V_w), which determines the width of the constriction. Roughly G_w varies stepwise in V_w and the effect of interference appears as an additional variance, which responds to V_p. Fig.2 shows such variance ΔG_w as a function of V_p and V_w. The peak structures in the oscillation of ΔG_w versus V_p show the charging-Fano mixed effect and the steep decrease in the amplitude of such structure around $V_p = -1$V indicates that the electrons in the dot are depleted for V_p lower than -1V.

From the interval of the Fano peaks, we estimate the addition-energy of an electron, which is apparently larger for electron number 2 and 6. They are the numbers to form the first and the second shell structure of the two-dimentional harmonic oscillator, indicating circular confining potential. An interesting feature appeared in Fig.2 is abrupt inversion in the lineshape of the Fano peaks in the middle of the first plateau, to which we give a convincing theoretical explanation based on a tight binding model. The detail will be given elsewhere.

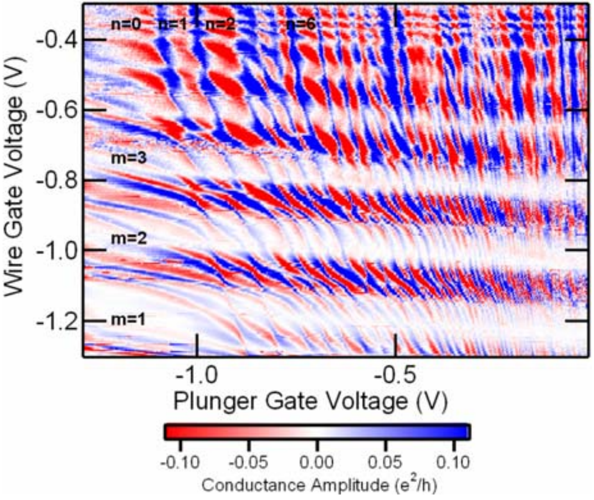

FIGURE 2. Color plot of ΔG_w as a function of V_p and V_w. The electron number in the dot and the conductance plateau number are indicated by *n* and *m* respectively. The temperature is 30mK.

Next we report the Fano-Kondo effect in a QD embedded in an AB ring. We first optimize the QD gate voltage to form the Kondo state in the lower arm. Then we opened the upper reference path to observe the Fano-Konndo effect. To get the coherent portion in the conductance, we subtracted the mid-line of the AB oscillation from the bare conductance. Fig.3(a) shows the results around 0.5T, in which clear mixed lineshape of the Fano-Kondo effect appeared. The theories for perfect one-dimentional electron paths predict "frequency doubling" in the middle of the valley due to the Onsager reciprocity for two terminal devices. However the experimental result seems to be free from the constraint and is similar to that predicted for four terminal devices. Clear sign of $\pi/2$ phase shift locking is observed in the middle.

In order to explain the result, we have considered a minimal model of two-channel AB ring with a QD with a single electron level (Fig.3(b)). The main feature of this model is the existence of the two interacting channels with different enclosing area and this causes the breaking of the "phase rigidity" in appearance. We have adopted a finite-U slave boson mean-field approximation for the Kondo effect and calculated the conductance at zero temperature. The calculated lineshape (Fig.3(c)) is in good agreement with the experiment in (a), manifesting that the model grabs the essence of the phenomenon. The result also certificates that the anomaly in the middle is due to the $\pi/2$ phase shift locking. The successful analysis demonstrates that the conductance through two-terminal interferometers can provides useful information on the quantum phase.

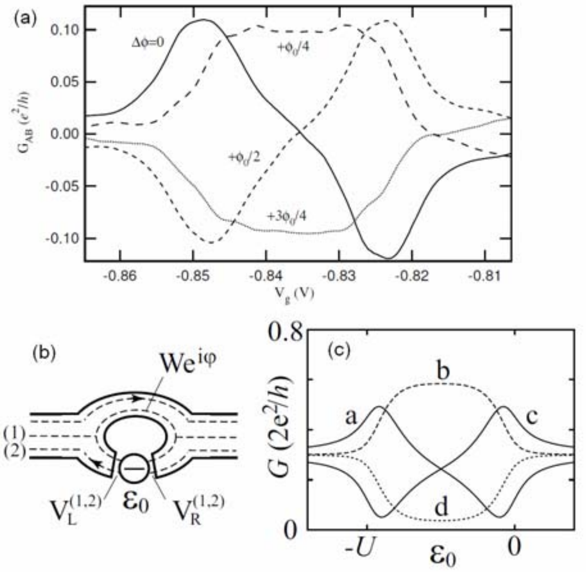

FIGURE 3. (a): Coherent part of conductance, which responds to the AB flux in the interferometer in Fig.1(b). The temperature is 45mK. The base magnetic field is 0.49T and ϕ_0 is the flux quantum *h*/*e*. (b): Theoretical model for calculation. To take account of the finite medium magnetic field, we consider edge channels and a direct channel. (c): Calculated conductance for the model shown in (b). The parameters are taken to imitate the results in (a).