Coherence and Phase Sensitive Measurements in a Quantum Dot

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Via a novel interference experiment, which measures magnitude and *phase* of the transmission coefficient through a quantum dot in the Coulomb regime, we prove directly, for the first time, that transport through the dot has a coherent component. We find the same phase of the transmission coefficient at successive Coulomb peaks, each representing a different number of electrons in the dot; however, as we scan through a single Coulomb peak we find an *abrupt* phase change of π. The observed behavior of the phase cannot be understood in the single particle framework.

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Almost 40 years ago Landauer showed [1] that current transport can be considered as a scattering experiment. In the case of a single plane wave impinging on a system the conductance is simply proportional to the absolute value squared of the transmission coefficient of the system. It is therefore evident that the relative phase between incoming and outgoing electronic waves cannot be measured in a simple transport experiment. In coherent processes, where the phase is deterministic, the phase of the transmission coefficient might contain complementary information to the conductance. Of particular interest are the coherency and the transmission phase of a *resonant tunneling* (RT) process through a quasibound state, be it in a resonant tunneling *diode* in 3D and 2D [2] or in a *quantum dot* (QD) in 0D [3]. The phase is expected to change by π as the energy of the impinging electron is being scanned through a resonant level [4]. Evidently, the conductance of these structures cannot reveal such phase information; moreover, as was shown theoretically [5], conductance measurements cannot even distinguish between *sequential* (where carriers scatter in the well and their phase is randomized) and *coherent* resonant tunneling. Hence, contrary to many unsubstantiated claims, the nature of transport in RT devices still remains ambiguous.

In general, *coherency* or *dephasing,* but not the actual phase of the transmission coefficient, can be studied via indirect interference experiments such as weak localization and conductance fluctuations. The phase factor, in turn, can be obtained by exploiting the *Aharonov-Bohm* (AB) effect or via a newly developed *double slit* interference experiment [6,7]; both directly probe the coherency and the phase of the transmission. Here we utilize a novel interference device that makes use of the AB effect for studying the *magnitude* and *phase* of transmission through a QD in the *Coulomb blockade* regime—an *a priori* RT device.

The QD can be viewed as a large atom [8], a few hundred nm in size, containing up to a few hundred electrons. Because of its small capacitance the addition of an extra electron requires a relatively large potential energy, called *charging energy,* leading to an energy gap (the so-called Coulomb blockade regime). Currently, most theories describing transport through a QD in the Coulomb regime do not predict the phase behavior of the transmitted wave through the dot [3,9]. Experimentally, aside from a couple of recent works studying dephasing in large chaotic dots [10,11], no direct studies of the coherency, let along the phase, of QD's had been published. We tackle this problem by constructing a *modified AB* interference experiment, utilizing a bare AB ring with a QD embedded within one of the ring's arms (see Fig. 1) [12]. In general, an AB ring's conductance is known to oscillate when a variable magnetic field penetrates its inner core, with a periodicity of a flux quantum h/e. One would thus expect these oscillations to persist also in our modified AB ring if transport through the QD has a coherent component. Performing such an experiment we find that (a) transport through the dot contains a coherent component; (b) the phase of the dot's transmission coefficient changes abruptly by $\approx\pi$ at some energy in the resonance peak; and (c) the phase is identical both qualitatively and in magnitude in all resonances.

Our experiments were performed with a selectively doped GaAs-AlGaAs heterostructure supporting a two-dimensional electron gas (2DEG) residing some 70 nm from the surface. The 4.2 K electron concentration and mobility are 2.2×10^{11} cm^{-2} ($E_F \cong 8$ meV) and 1.5×10^6 cm^2/V sec, respectively, leading to an elastic mean free path of order 10 μm. The modified AB ring was formed by depositing submicron metal gates on the surface of the heterostructure and subsequently biasing them negatively in order to deplete the electrons underneath. Figure 1(a) describes the schematics of the circuit, and Fig. 1(b) is a SEM micrograph of the surface. Note that a special lithographic process, invoking a metallic air bridge, had been developed in order to contact the center metal gate (that depletes the ring's center). The QD (0.4 μm wide and 0.5 μm long) is inserted in the left side arm, and its area, and hence the number of electrons in it, is controlled by biasing the *plunger* gate P. The coupling

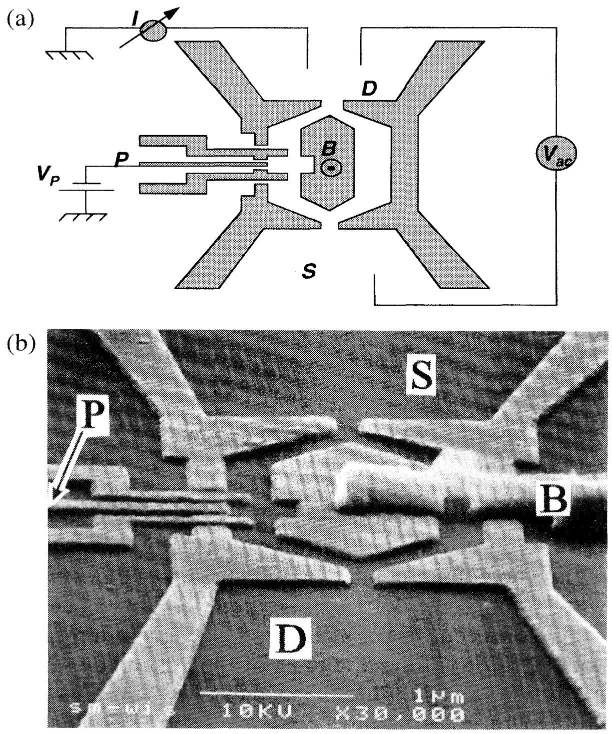

FIG. 1. (a) A schematic description of the modified Aharonov-Bohm ring's circuit. The shaded regions are metallic gates. (b) A SEM micrograph of the structure. The white regions are the metal gates. The central metallic island is biased via an air bridge (B) extending to the right.

of the QD to the ring's arm is controlled by the two gates surrounding the plunger gate, making the QD's resistance considerably larger than the resistance of each arm. The AB ring, in turn, is coupled to the large 2DEG reservoir via two point contacts with resistance larger than that of the arms. This configuration enables a continuous variation of the QD's resistance without affecting the two-terminal resistance of the modified ring. Since each of the ring's arms usually contains a few 1D channels and the estimated thermal smearing length is comparable to the ring's size, the AB interference contrast of the bare ring (without an embedded QD) is typically around 10% at 100 mK.

We first study the behavior of the conductance of the QD and its effect on the coherency of the transport through the dot. Before describing the experimental results it might be instructive to consider a simple model of noninteracting electrons confined within the QD. The energy spectrum of a QD can be viewed as a ladder of single particle eigenstates, each being broadened due to tunneling into (and out of) the QD and by inelastic scattering. As electrons are being added to (or depleted from) the QD this ladder sweeps down (or up) through the Fermi level. If $k_BT \ll \Gamma$, Γ being the width of a resonant level, the conductance of the dot as a function of V_P has the form of a sequence of peaks, each having a Lorentzian line shape [13] (Breit-Wigner type resonance [14]), representing the absolute value squared of the transmission coefficient of the QD. When $k_BT > \Gamma$, the line shape of each conductance peak takes the form of the derivative of the Fermi-Dirac distribution (with width $\sim 4k_BT$) [15]. Since our QD has a very small capacitance ($C \approx 160$ aF), each additional electron that occupies the QD charges the dot and changes its energy by $E_C = e^2/2C \cong 0.5$ meV. Thus an additional energy E_C is needed, on top of the single particle energy spacing, in order to add a single electron to the QD.

What is the nature of transport through the QD? Our QD contains about 200 electrons, and its resistance is being varied in the range of 10^5 to 10^6 Ω while the resistance of each arm of the ring is ~ 5 kΩ. Measurements are done at an electron temperature of 80 mK, estimated from the peaks' width, and with a 10 μV ac excitation voltage applied across the ring. The QD was set to conduct by tuning the plunger gate voltage ($V_p = V_m$ in Fig. 2) with the total dot's resistance controlled by adjusting both point contacts of the dot (trying to keep the dot symmetric). An AB flux was then applied, and the measured current oscillations are plotted in Fig. 2 (on top of a subtracted out large background due to the right arm) in the same scale as that of the Coulomb peak. The period of the oscillating signal is ≈ 20 G, in very good agreement with the expected AB period, providing a direct indication that transport has a coherent component. As the resistance of the dot is being changed the oscillations contrast, defined as peak to peak over the average dot's current, does not vary much and hovers in the range 0.2 to 0.4 (inset of Fig. 2).

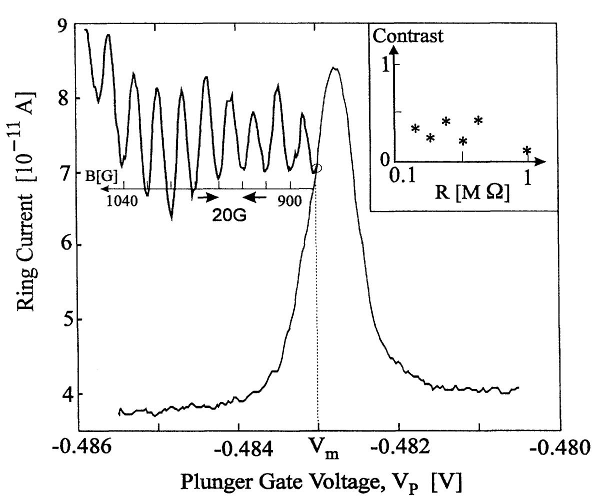

FIG. 2. One of the ring's current (conductance) peaks as a function of the plunger gate voltage. At the top left the current is plotted as a function of magnetic field (the magnetic field increases to the left) at $V_p = V_m$ showing Aharonov-Bohm oscillations. In the inset the oscillation contrast (peak-to-peak versus average current through the dot) as a function of the dot's resistance is shown. The large current of the right arm is subtracted.

Intuitively, a QD strongly coupled to the ring's arm will dephase insignificantly. As the coupling strength is being reduced (by pinching the two point contacts of the dot) the *classical dwell* time of the electrons in the QD becomes longer, possibly eventually allowing dephasing to take place. In order to consider the interference experiment more quantitatively it is convenient to work in the framework presented by Büttiker [16] for the problem of resonant tunneling. We model the QD as having *single particle* resonant states, and for a fully coherent transport the transmission amplitude can be described by the Breit-Wigner formula $t_D(E) = \Gamma_e/(E + i\Gamma_e)$, where the homogeneous broadening of the resonant level at $E = 0$ is Γ_e and the tunneling rates in and out of the dot are assumed equal (named the *symmetric* case). For a single conducting channel in the right arm with transmission t_R we find the peak current through the ring, for the resonance located at the Fermi energy, to depend on flux via

$$I_{DS} = V_{DS}\frac{e^2}{h}\int_{-\infty}^{\infty}|e^{i2\pi\phi/\phi_0}t_R + t_D(E)|^2\left(-\frac{\partial f}{\partial E}\right)dE\,.$$

Assuming $k_BT \gg \Gamma_e$, we find

$$I_{DS} = V_{DS}\frac{e^2}{h}\left[|t_R|^2 + \frac{\pi\Gamma_e}{4k_BT}\left\{2t_R\sin\left(\frac{2\pi\phi}{\phi_0}\right) + 1\right\}\right],$$

leading to an oscillating conductance as a function of ϕ with an average conductance of the modified ring $g_R + g_D$ with $g_D = (e^2(\pi\Gamma_e/h)/k_BT)$ being the average conductance of the dot. This simple model predicts that the interference contrast is independent of Γ_e and is given by $4t_R$. This result is valid in the general case where the peak transmission is independent of Γ_e (when the ratio between in and out dot's resistances is constant). Note that changing the dot's in and out resistances in a manner different than specified above will affect the contrast. If, however, the transport has an incoherent component, with an inelastic width Γ_i, it is intuitively expected that as long as $\Gamma_i < \Gamma_e$ the contrast will be independent of Γ_e as above. However, when $\Gamma_i > \Gamma_e$ the contrast will diminish upon decreasing the coupling of the dot to the arm. We use the coherent expression to estimate the width of the resonance level [17]. For dot resistance of 1 MΩ and $k_BT = 100$ mK we find $\Gamma_e \approx 0.2$ μeV and a corresponding dwell time $\tau_D \approx 3.2$ ns. As seen in Fig. 2 coherency is preserved even at this long dwell time.

After showing that transport is (at least) partly coherent we move on to study the dependence of the accumulated phase through the QD on its occupation. How should the phase behave on the basis of the single particle model discussed above? Considering only the coherent part and $k_BT \ll \Gamma_e$, the phase of the transmission coefficient deduced from the Breit-Wigner formula is expected to be almost constant away from the resonance and to undergo a smooth change of π as the energy scans a resonant peak [4]. Similarly, for $k_BT > \Gamma_e$, it can be easily shown that the phase is expected to change smoothly over a scale of k_BT rather than Γ_e. An exact solution of a simple 1D RT model suggests that the phase of each resonance (or every other one when spin degeneracy is lifted) is out of phase with its predecessor. However, this might not be necessarily the case in other dimensions where it is not even clear theoretically whether a systematic behavior of the phase of the transmission coefficient with the number of electrons is expected. Note that since the number of electrons in the QD is around 200, the bare level average spacing is $\approx E_F/200 = 40$ μeV (also estimated from the conductance of the dot as function of V_P at finite applied dc V_{DS}), which is evidently larger than k_BT (≈ 9 μeV). This suggests that each Coulomb peak results from tunneling through a single resonant level.

Experimentally we follow the phase evolution of the transmission coefficient through the QD by comparing AB interference patterns measured along a single Coulomb peak as well as at different Coulomb peaks. Figure 3(b) shows the AB oscillations for three typical *successive* peaks [shown in Fig. 3(a)], chosen out of a series of 12 measured successive peaks, with all oscillations taken at similar locations on the peaks (denoted by A, B, and C). It is clearly seen that the oscillations have the *same* phase at the three peaks, suggesting the same absolute phase of the transmission coefficient at each peak. However, the behavior of the phase along a *single* Coulomb peak is quite striking. Figure 4(a) presents the expected line shapes for $k_BT \ll \Gamma$, for $k_BT > \Gamma$, and that of a measured Coulomb peak. Four different interference patterns, taken at the specified points on the Coulomb peak shown in Fig. 4(a), are represented in Fig. 4(b). The patterns indeed show a π phase change which takes place rather *abruptly* between points 2 and 3. This change can be seen more clearly in Fig. 4(c) where we summarize the phase behavior along a single Coulomb peak (for two different peaks). Note that the phase change occurs on a scale of $\approx k_BT/10$, in

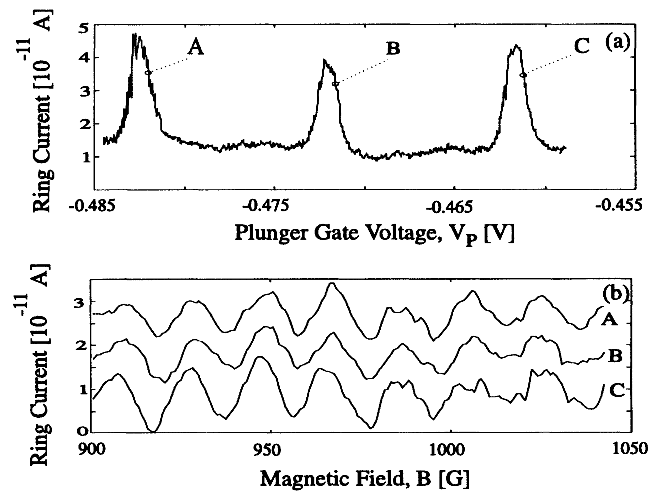

FIG. 3. (a) A series of Coulomb peaks and (b) the corresponding interference current oscillations taken at the marked points A, B, and C in successive peaks of the ring's current. All oscillations are seen to be in phase. The large current of the right arm is subtracted.

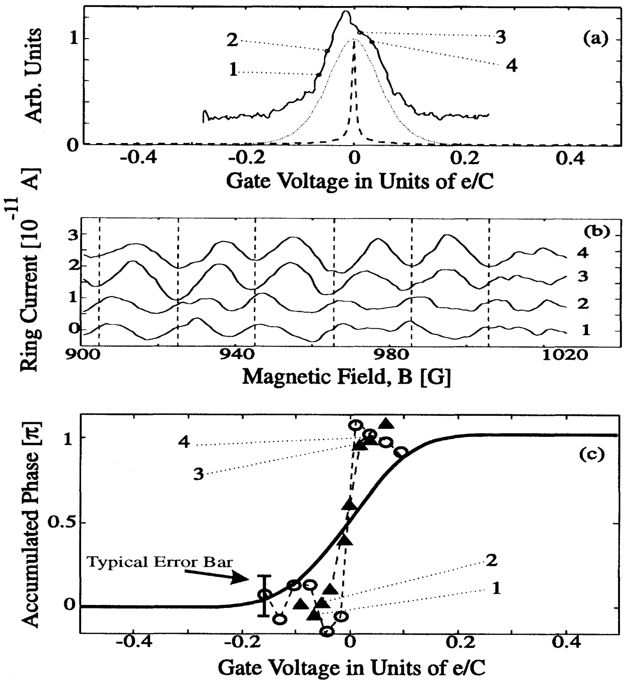

FIG. 4. The evolution of the phase along one conductance peak. (a) Level broadening, Γ, at $T = 0$ (broken line) and for $k_BT > \Gamma$ (dotted line), and the experimentally measured peak (shifted up solid line). (b) A series of interference patterns taken at the specified points on a peak. Note the phase jump between patterns 2 and 3. (c) Summary of the experimentally measured phases within two peaks (o and ▲; the broken lines are only guides to the eye). The expected behavior of the phase in a 1D resonant tunneling model is shown by the solid line.

direct contradiction with the expected change on the scale of the temperature. It is important to mention that the conductance in the region where the phase change occurs is accompanied by severe noise in the measured ring's current. It is not clear at the moment if that noise results from the AB interference in the presence of the phase switching in the dot or a *conductance fluctuation* of the QD itself.

The coherent properties and consequently the phase behavior of the quantum dot, which are first being measured here, provide new insight into the state of current transport in the dot with its full complexity. Coherent transport is observed even though the estimated dwell time in the dot is about 10 ns. The measured phase behavior of the coherent component is striking. It deviates altogether from the noninteracting, single particle, model of interference between an amplitude transmitted through the dot and a reference amplitude. Though the *identical phases* of successive conductance (or Coulomb) peaks belong effectively to different dots (each with a different number of electrons) and thus not obvious (see also the argument of dimensionality before), the *abrupt* π change in phase on a scale much smaller than k_BT, as the occupation of the dot changes, is totally unexpected. It might be associated with a coupling between the dot and the Aharonov-Bohm ring, affecting, via magnetic flux penetration, the eigenstates of the whole system (ring plus dot) and thereby the transmission through it [18].

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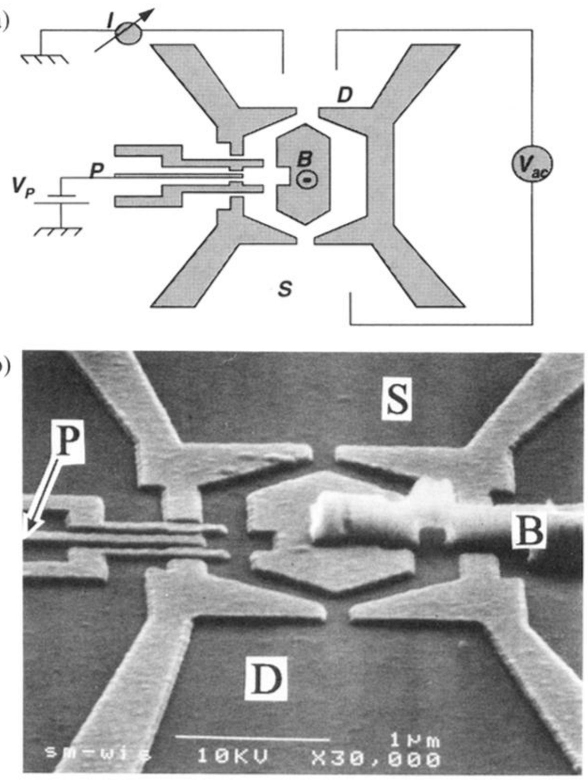
(a)

(b)



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