Transmission Phase Through Two Quantum Dots Embedded in a Four-Terminal Quantum Ring

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Two-teminal double-slit measurements in nanostructures do not allow the determination of the relative transmission phase due to the generalized Onsager relations. Recently it has been demonstrated [1,2] that in a multi-terminal geometry the transmission phase can be directly observed. A phase-lapse for the transmission through a Coulomb blockaded quantum dot was found in these experiments. The explanation of this observation is still controversially discussed and other experiments are lacking so far.

We have realized a four-terminal Aharonov-Bohm (AB) ring on a shallow Ga[Al]As heterostructure by AFM-lithography (Fig. 1a)). Two or more quantum dots can be electrostatically induced by appropriate plunger gate voltages. While clear Coulomb oscillations are observed (Fig. 1b)), the precise location of the charged islands is not well defined along one of the arms of the ring. For the measurements presented here, two quantum dots were induced in the ring by the plunger gates pg1 and pg3 (see Fig. 1a)). The phase of Aharonov-Bohm oscillations as a function of magnetic field was measured at temperatures around 50 mK in a dilution refrigerator. A bias voltage V_{bias} was applied to the left contact while the contacts at the top and the bottom (I_1 and I_3) were grounded via two current-voltage converters. The relative transmission phase was determined from the non-local voltage V_{nl} measured at the right probe.

Phase shifts of the AB oscillations in V_{nl} could be detected in a regime in which the quantum dots forming in segment 1 and 3 are close to the Coulomb blockade regime and pronounced conductance peaks exist. Fig. 2 shows an example of the transmission phase evolution across a conductance peak of dot 3. Dot 1 was kept on a conductance resonance during this measurement. The left part of Fig. 2 shows the current measured in the current voltage converters showing a conductance peak in dot 3 (I_3) while the current through dot 1 (I_1) is almost constant. The central figure is a greyscale image of V_{nl} showing the AB-oscillations in the non-local voltage. The phase shift can be directly followed on this image. The right plot shows cross-sections through the center image exhibiting the phase shift by π explicitly. Typically, a phase of about π accumulates by sweeping through a well isolated conductance peak, similar to Ref. [1]. Smaller or larger phase shifts are occasionally observed if neighboring conductance peaks overlap strongly. Adding an electron to both of the dots results in a negligible phase shift as expected. If the dots are operated in a regime, where the coupling to source and drain is minimized, we can no longer detect AB-oscillations since the relative noise in the non-local voltage becomes too large. In the regime presented here, the conductance between Coulomb blockade maxima is large enough to allow for the observation of clear AB-oscillations. For a gate sweep of dot 3 over several Coulomb peaks (not shown) the tendency in our data is towards a stepwise increase of the phase with increasing gate voltage.

In the open regime of the dots and at high magnetic fields (about 5 T) a continuous phase increase can be found with increasing gate voltage as observed in other experiments [3].

References:
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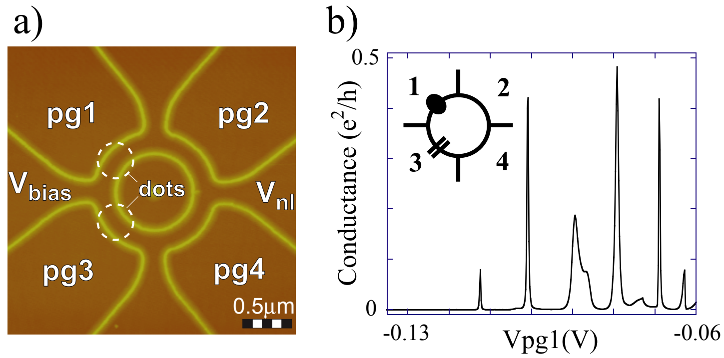

Figure 1: a) Ring sample defined by AFM-lithography. Two dots are formed in arm 1 and 3 for negative plunger gate voltages pg1 and pg3. b) Coulomb blockade oscillations in the conductance through dot 1 when the other arms of the ring are pinched off.

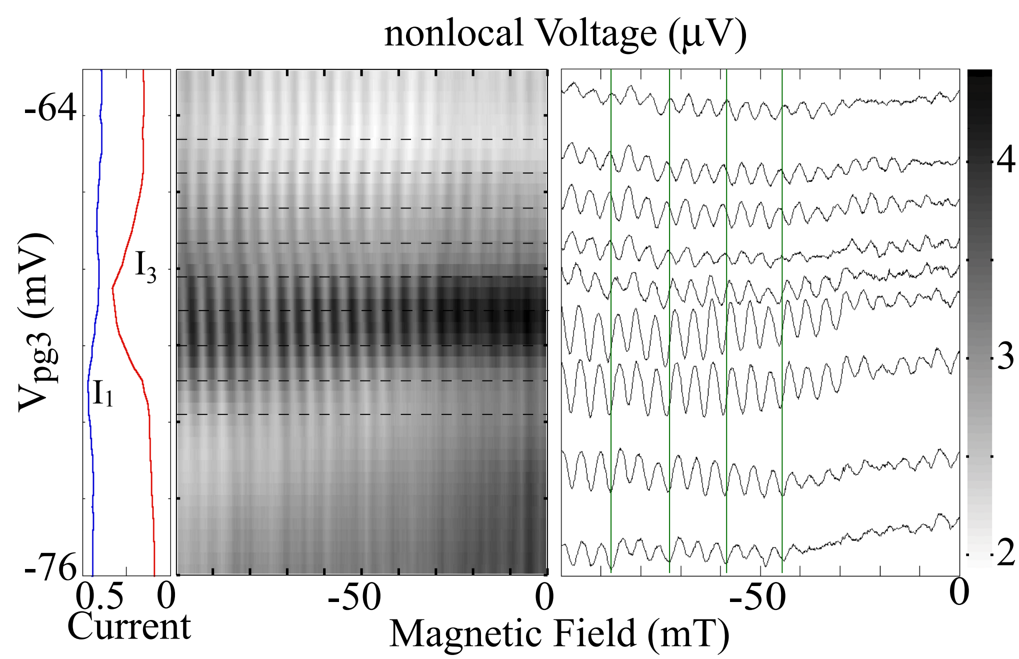

Figure 2: Measurement of the phase shift in the nonlocal voltage Vnl as a function of magnetic field as the gate voltage pg3 is stepped across a conductance peak in dot 3. The phase shift of π is directly visible in the greyscale plot and can be seen more clearly in the cross-sections to the right for fixed gate voltages.