Controlled Dephasing of Electrons *via* a Phase Sensitive Detector

D. Sprinzak, E. Buks,* M. Heiblum, and H. Shtrikman

Braun Center for Submicron Research, Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel

(Received 21 January 2000)

We demonstrate a controlled dephasing experiment via exploiting a unique entangled interferometer-detector system, realized in an electronic mesoscopic structure. We study the dephasing process both from the *which path* information available in the detector and, alternatively, from the direct effect of the detector on the interferometer. Detection is possible only due to an induced phase change in the detector. Even though this phase change cannot actually be measured, strong dephasing of the interferometer took place. The intricate role of detector's noise and coherency are investigated.

PACS numbers: 73.23.–b, 03.65.Bz, 73.40.Hm, 85.30.St

An electronic mesoscopic system, where electrons maintain their wave properties, may serve as an excellent playground for demonstrating quantum mechanical interference. In turn, the Coulomb interaction among the electrons can strongly affect this interference, facilitating *entanglement* between coupled coherent systems. Such coupled coherent systems are the basis for the realization of quantum computers. Recently, a mesoscopic *which path* (WP) type experiment was performed by Buks *et al.* [1]. There, a WP detector, in the form of a quantum point contact (QPC), was placed in close proximity to one path of a two-path electron interferometer [2]. Electrons traversing this path affected the current in the detector, and even though the actual current was not measured partial dephasing took place. The loss of coherence can be understood also from another, equivalent [3], point of view: via looking at the direct effect of the charge fluctuations in the detector on the interferometer. Although theoretical analysis, based on the two approaches, resulted with similar predictions [4–9], the exact role of charge fluctuations in the detector is difficult to ascertain. In this work a novel *detector-interferometer* system was constructed, with detection being provided *only* via an induced quantum mechanical phase in the detector's current. We show that, even though the induced phase could not be extracted in our setup, strong dephasing of the interferometer took place. Moreover, this result was independent of the detector's coherency.

The visibility of an interferometer, in an entangled detector-interferometer system, can be expressed in terms of a *dephasing rate* induced by the detector times an *effective time of interaction.* We choose to estimate the dephasing rate by relating it to the information supplied by the detector [1,4,6], namely, to the overlap of detector states: $\langle \chi_w | \chi_{wo} \rangle$, with $|\chi_w\rangle$ and $|\chi_{wo}\rangle$ the states of the detector with and without an electron in the trajectory it is coupled to, respectively. A small overlap indicates nearly orthogonal detector states, hence, clear determination of the chosen trajectory leading to strong dephasing of the interferometer.

The overlap of the QPC detector states, with current flowing through it, can be expressed in terms of the single electron states in the QPC. These states are of the form $t_d|t\rangle + r_d|r\rangle$, where t_d and r_d are the complex transmission and reflection amplitudes, and $|t\rangle$ and $|r\rangle$ are the quantum states of the transmitted and reflected electrons. For a weak interaction between detector and interferometer (as is usually the case) the dephasing rate, $1/\tau_\varphi$, can be shown to have the form [1,4,6]

$$\frac{1}{\tau_\varphi} = \frac{eV_d}{8\pi h} \frac{(\Delta T_d)^2}{T_d(1 - T_d)} + \frac{eV_d}{2h} T_d(1 - T_d)\gamma^2, \quad (1)$$

where $T_d = |t_d|^2$ and ΔT_d are the transmission probability through the QPC and the change in it induced by the interferometer, V_d is the applied voltage to the QPC, and $\gamma = \Delta\theta_t - \Delta\theta_r$ is a phase factor, with $\Delta\theta_t$ and $\Delta\theta_r$ the respective phase changes induced by the interaction with the interferometer in the transmitted and reflected waves. Our experiment is designed to study only the second term (namely, $\Delta T_d = 0$). Note that, while ΔT_d can be determined directly via conductance measurement of the QPC, the phase change γ can be measured *only* by constructing an interference loop *within the detector* between the transmitted and reflected waves (see box in Fig. 1). Such an interference signal, if it were to be measured, is proportional to the product of the amplitudes of the transmitted and reflected waves $\sqrt{T_d(1 - T_d)}$, and vanishes for $T_d = 0$ and 1. In the alternative approach of understanding the dephasing process, charge fluctuations in the detector, resulting from *partitioning* of the incoming current by the QPC (related to *shot noise,* which is proportional to $T_d(1 - T_d)$ [10]), interact Coulombically with the electrons in the interferometer and lead to dephasing [8,9]. We have, though, difficulties with the physical interpretation combining both approaches. For example, while the second term in Eq. (1) seems to be intuitively correct, namely, a noisy detector leads to strong dephasing, the first term is inversely proportional to the shot noise (proved to be experimentally correct [1]).

 0031-9007/00/84(25)/5820(4)$15.00

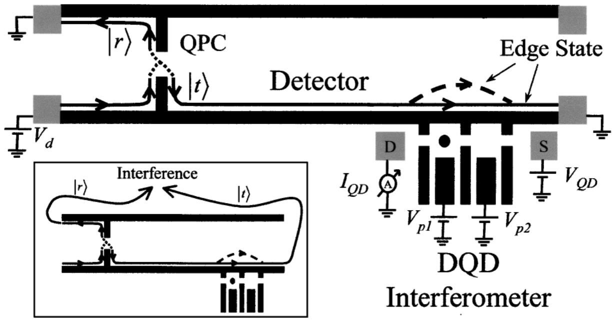

FIG. 1. A schematic of the DQD interferometer and a QPC detector. The QPC, the DQD, and the trajectories of the edge states were defined by depositing metal gates on the surface of the structure (heavy block lines) and biasing them negatively. The DQD, with each dot lithographically patterned to $0.4 \times 0.4\ \mu\text{m}^2$, is placed some 30 μm away from the QPC. The magnetic field is tuned so that one or two edge states coexist near the boundary ($\nu = 1, 2$, respectively). The edge states emanating from an Ohmic contact on the left are partly transmitted ($|t\rangle$) and partly reflected ($|r\rangle$) by the QPC. The transmitted edge state is Coulombically coupled to the near by DQD interferometer, which is in turn connected to its own circuit (with source S and drain D). The DQD is tuned to resonance via voltages on the two plunger gates, V_{p1} and V_{p2}. Whenever an extra electron is added to the DQD, the nearby edge state is slightly diverted (dashed line) thus acquiring additional phase, $\Delta\theta_t$. Inset: A schematic of the interference experiment that can measure the phase change $\Delta\theta_t$ hence providing "trajectory information." We do not actually perform such an interference experiment.

Experimentally, the device is fabricated in a high mobility two-dimensional electron gas (2DEG), embedded in a GaAs-AlGaAs heterostructure, with electron mobility $5 \times 10^5\ \text{cm}^2/\text{V sec}$ at ≈ 1 K (see Fig. 1). The condition $\Delta T_d = 0$, $\gamma \neq 0$ can be realized when the detector's current flows in *edge states*, namely, in chiral trajectories along edges of the sample, formed under the application of strong perpendicular magnetic field. A QPC constriction, added to the path of the edge state, serves as an electron "beam splitter" (Fig. 1), leading to partitioning of the edge state (namely, to reflected and transmitted edge states). The interferometer, being located near the transmitted edge state, but far from the QPC, induces *only* a phase change $\Delta\theta_t$ via spatially deflecting the edge state but without affecting the transmission through the QPC. We note schematically in the box in Fig. 1 how $\Delta\theta_t$ can be measured via interfering $|t\rangle$ and $|r\rangle$.

A standard two-path interferometer, like the one employed in Ref. [1], is ineffective in the presence of a high magnetic field. Hence, we used instead a double *quantum dot* (QD) [11,12] as an interferometer. A QD can be regarded as an electronic version of the optical Fabry-Perot interferometer, where interference takes place between the many trajectories that bounce back and forth between the two barriers connecting the QD to its leads. The interference leads to sharp resonances in the transmission through the QD at certain energies, each resonance with an intrinsic energy width Γ_i. The model used in Ref. [1] can be expanded to this case [4]. An electron dwelling in the QD interferometer charges it and deflects the nearby edge state away from the QD. The deflected path accumulates an extra phase $\Delta\theta_t$ ($\gamma = \Delta\theta_t$), which is added to the transmission phase of the QPC. Longer time dwelling trajectories will affect a larger number of electrons in the nearby edge state, making these trajectories *distinguishable*. Such partial dephasing leads to the broadening of the resonance peaks to $\Gamma_i + \hbar/\tau_\varphi$ [4]. Alternatively, the charge fluctuations in the edge state will "shake" the resonant level, again leading to an effective level broadening. The broadening is expected to be accompanied by a reduction in transmission peak height and a small shift in peak energy.

In most cases the QD conductance peaks [generally known as Coulomb blockade (CB) peaks] are quite broad, reflecting the finite electron temperature in the leads (width $\sim 4k_B\theta$, where θ is the temperature), preventing an accurate determination of weak dephasing. We hence employed a *double quantum dot* (DQD) system, where degeneracy between the resonant levels in both QDs is necessary for conduction. Such degeneracy eliminates thermal broadening, leading to considerably narrower CB peaks (width $\sim 2\Gamma_i$) [12]. With such a DQD interferometer the dephasing process remains essentially the same; however, because of the more complicated set of trajectories in the DQD we have no quantitative theory to express the dependence of peak width (or peak height) on the induced dephasing rate.

The DQD in Fig. 1 is being tuned with its gates to form CB peaks "above" the plane spanned by the two *plunger gate* voltages, V_{p1} and V_{p2}. The CB peaks are located on a hexagonal lattice [Fig. 2(a)]—a well-known fingerprint of CB in a DQD [13]. A single magnified peak, with a contour at half maximum, is shown in Fig. 2(b). We use the area enclosed in this contour as a measure of the dephasing rate.

A strong magnetic field is applied perpendicularly to the plane of the 2DEG in order to get one or two edge states propagating in the detector (*filling factor* $\nu = 1$ or 2). We present here results for $\nu = 2$, hence a conductance $2e^2/h$ of the detector when $T_d = 1$. We employ a relatively high injection voltage V_d in the QPC (2 mV), and hence can treat the two edge states as single edge state [14]. Figure 3(a) shows the dependence of the "contour area" of a single CB peak on T_d of the QPC at a fixed V_d, namely, at a constant impinging rate of electrons on the QPC detector. It qualitatively follows the expression $T_d(1 - T_d)$ in Eq. (1). Similarly, the peak height, seen in Fig. 3(b), has an inverse dependence on that expression. Moreover, a nearly linear dependence of the dephasing rate on the applied voltage V_d, at a constant $T_d = 0.7$, is measured (inset of Fig. 3). We also observed a similar behavior of other CB peaks at $\nu = 2$ and at $\nu = 1$, as well as in a few different devices. Note that due to the multiterminal configuration of the device a change in T_d does not affect the dissipated power in the detector ruling out heating related

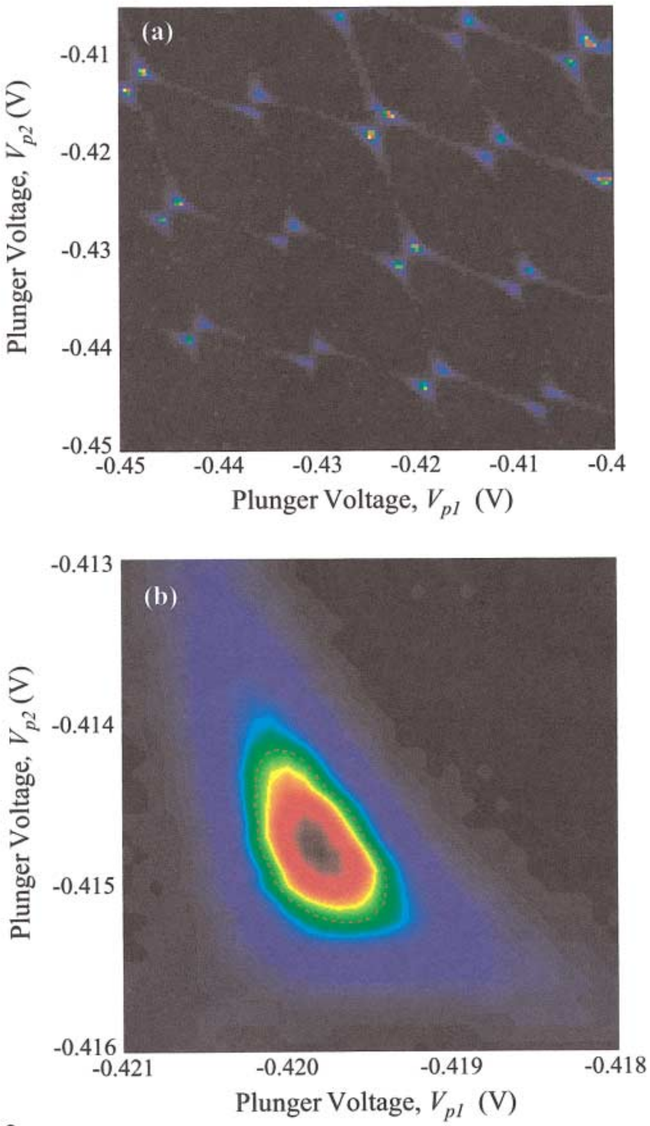

FIG. 2 (color). Coulomb blockade in a DQD. (a) Conductance of the DQD interferometer as a function of the two plunger gate voltages V_{p1} and V_{p2}. The bright spots correspond to CB peaks. The hexagonal ordering is a known property of a DQD system [9]. (b) Magnified view of one CB peak. The dashed line is a contour drawn at half maximum of the peak height. Because of the asymmetry of the peak shape we use the area enclosed by this contour as a measure of the peak width.

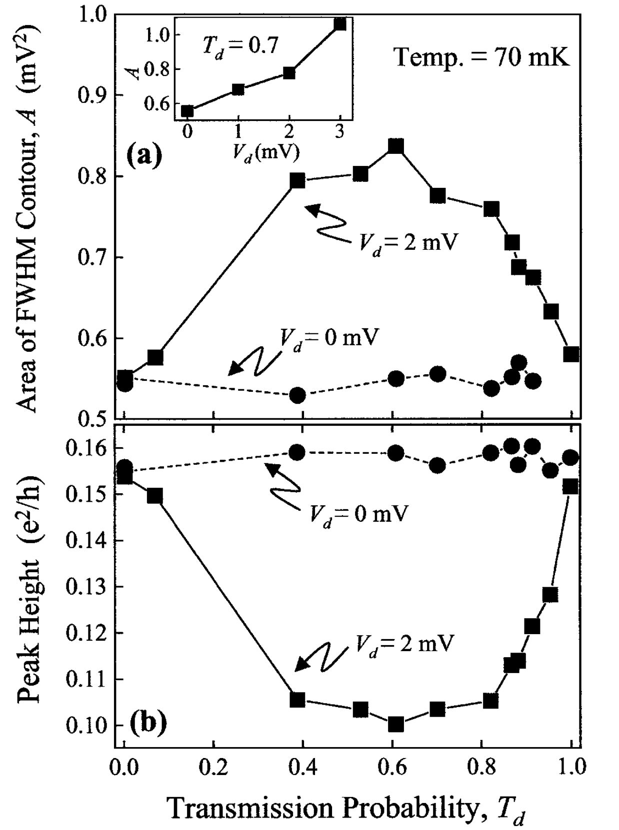

FIG. 3. Dependence of the CB peak shape on the QPC detector properties. (a) The area of the contour at half peak height as a function of the transmission probability, T_d, for two values of applied bias $V_d = 0$ and 2 mV. The dependence qualitatively agrees with the expected $T_d(1 - T_d)$. The measurement is done at a filling factor 2. Note that the large applied V_d does not allow resolving the splitting of the two edge states [14]. Inset: The dependence of the contour area on the applied voltage, V_d, for $T_d = 0.7$. (b) The dependence of the peak height (in units of quantum conductance) on the transmission probability, T_d, for two values $V_d = 0$ and 2 mV.

dephasing. Changing the coupling between the detector and the interferometer, in order to affect the induced phase γ, or alternatively, the effect of charge fluctuations in the QPC on the DQD, is difficult since it changes unrelated system properties.

Since the *extraction* of "trajectory information" from the detector requires an interference experiment between the transmitted and reflected edge states (box in Fig. 1), an important question naturally arises: must the detector be phase coherent in order to dephase the interferometer? The complementary approach, however, suggests that coherence is not necessary since the shot noise in the edge state is independent of detector's coherence. This apparent contradiction can be easily put to theoretical and experimental tests via adding an artificial *dephasor* in the path of the transmitted edge state before it reaches the DQD [15]. We utilize a *floating Ohmic contact* as a dephasor; serving as a thermal bath it emits the edge states that enter it totally dephased. Figure 4(a) describes the test system. A negatively biased gate in front of the floating Ohmic contact allows removing the contact from the path of the transmitted edge state. The experiment is repeated with Ohmic contact *in* and *out* the path of the edge state, with the dependence of contour area on T_d shown in Fig. 4(b). A small decrease in the dephasing rate in the presence of the Ohmic contact is observed; however, we attribute it to the finite (parasitic) capacitance of the Ohmic contact—"shorting to ground" high frequency components of the shot noise [16]. Indeed, by adding an external capacitor to the contact we were able to decrease the dephasing rate much further (not shown).

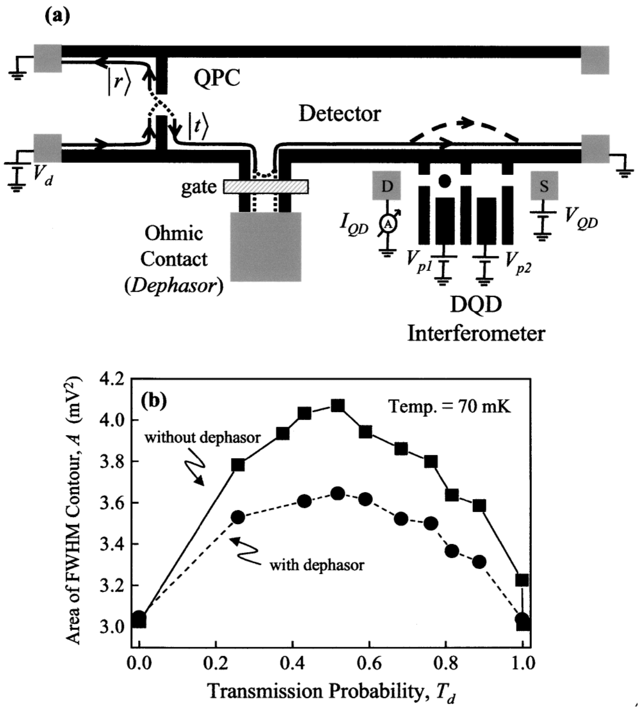

FIG. 4. Experimental results with an introduction of a dephasor to the detector. (a) A schematic of the experimental setup with a floating Ohmic contact introduced in the transmitted edge state. The Ohmic contact serves as a dephasor for the transmitted electrons. A gate in front of the Ohmic contact allows removing this contact from the electrons' path. (b) The area of the contour at half peak height as a function of the transmission probability, T_d, with and without the Ohmic contact in the electrons' path. The decrease in the dephasing rate is attributed to the nonnegligible capacitance of the Ohmic contact.

The apparent contradiction raised above can be settled within our model by including the dephasor (Ohmic contact) degrees of freedom in the detector. The single particle states of the "modified detector" (detector + dephasor) are $t_d|t\rangle|\pi_t\rangle + r_d|r\rangle|\pi_r\rangle$, where $|\pi_t\rangle$ and $|\pi_r\rangle$ are the states of the dephasor for an electron being transmitted or reflected by the QPC. The overlap factor $\langle\chi_w|\chi_{wo}\rangle$ now, and consequently the dephasing rate, remains unchanged. The interesting point to note is that with the dephasor the WP information cannot be extracted by the gedanken experiment proposed in Fig. 1. Only a rather more sophisticated measuring scheme that includes the dephasor degrees of freedom (experimentally unrealizable) might reveal the phase information.

With this experiment we demonstrated the realization of a *controlled dephasing* in an interfering mesoscopic system. This was achieved by creating an entangled system between a DQD interferometer and a phase sensitive QPC detector. The dephasing process is understood both from the *which path* information provided by the detector and from the effect of charge fluctuations in the detector on the interferometer. Although both approaches may provide the same results, some aspects can be better understood by utilizing one of them.

We thank D. Mahalu for valuable help in fabrication, and Ji Yang and H. Moritz for their help during all experiments. We thank S. Gurvitz and L. Stodolsky who introduced the problem to us, and Y. Aharonov who opened our eyes to see what is so obvious to him. We benefited from discussions with J. Imry, Y. Levinson, S. Levit, and A. Stern. One of us (E. B.) thanks M. Buttiker and Y. Meir for useful discussions. The work was partly supported by a MINERVA grant and by the Israeli Science Foundation.

*Present address: Condensed Matter Physics, California Institute of Technology, Pasadena, CA 91125.

[1] E. Buks *et al.,* Nature (London) **391**, 871 (1998).
[2] R. Schuster *et al.,* Nature (London) **385**, 417 (1997).
[3] A. Stern, Y. Aharonov, and Y. Imry, Phys. Rev. A **41**, 3436 (1990).
[4] E. Buks, Ph.D. thesis, Weizmann Institute of Science, 1998.
[5] I. L. Aleiner, N. S. Wingreen, and Y. Meir, Phys. Rev. Lett. **79**, 3740 (1997).
[6] L. Stodolsky, Phys. Lett. B **459**, 193 (1999).
[7] S. A. Gurvitz, Phys. Rev. B **56**, 15 215 (1997).
[8] (a) Y. Levinson, Europhys. Lett. **39**, 299 (1997). (b) Y. Levinson, Phys. Rev. B **61**, 4748 (2000).
[9] M. Buttiker and A. M. Martin, Phys. Rev. B **61**, 2737 (2000).
[10] A review on shot noise in mesoscopic systems: M. Reznikov, R. de Picciotto, M. Heiblum, D. C. Glattli, A. Kumar, and L. Saminadayar, Superlattices Microstruct. **23**, 901 (1998).
[11] H. Van Houten, C. W. J. Beenakker, and A. A. W. Staring, in *Single Charge Tunneling—Coulomb Blockade Phenomena in Nanostructures,* edited by H. Grabert and M. H. Devoret (Plenum Press, New York, 1992).
[12] C. Livermore *et al.,* Science **274**, 1332 (1996).
[13] N. C. van der Vaart *et al.,* Phys. Rev. Lett. **74**, 4702 (1995).
[14] The large applied voltage mixes edge states and prevents the observation of the e^2/h conductance plateau as the QPC is being slowly pinched off to reflect the second edge state.
[15] M. Buttiker, Phys. Rev. B **32**, 1846 (1985).
[16] We estimate the capacitance of the Ohmic contact shorts most of the fluctuations above some 10^7 Hz to ground; however, the remaining low frequency part of the spectrum is still effective in the dephasing process, due to the long dwell time in the DQD.