Dephasing and Measurement Efficiency via a Quantum Dot Detector

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Abstract. – We study charge detection and controlled dephasing of a mesoscopic system via a quantum dot detector (QDD), where the mesoscopic system and the QDD are capacitively coupled. The QDD is considered to have coherent resonant tunnelling via a single level. It is found that the dephasing rate is proportional to the square of the conductance of the QDD for the Breit-Wigner model, showing that the dephasing is completely different from the shot noise of the detector. The measurement rate, on the other hand, shows a dip near the resonance. Our findings are peculiar especially for a symmetric detector in the following aspect: The dephasing rate is maximum at resonance of the QDD where the detector conductance is insensitive to the charge state of the mesoscopic system. As a result, the efficiency of the detector shows a dip and vanishes at resonance, in contrast to the single-channel symmetric non-resonant detector that has always a maximum efficiency. We find that this difference originates from a very general property of the scattering matrix: The abrupt phase change exists in the scattering amplitudes in the presence of the symmetry, which is insensitive to the detector current but stores the information of the quantum state of the mesoscopic system.

Suppression of the quantum interference due to detection of a particle’s path is a fundamental issue for understanding the complementarity principle in quantum theory [1–3]. Recently, mesoscopic physics is evolving into a stage where understanding the measurement process becomes important. Of particular interest, controlled dephasing of resonant tunnelling through a quantum dot (QD) has been performed experimentally [4–6]. In the experiment, a quantum point contact (QPC) circuit electrostatically coupled to the QD enables detection of the charge state of the QD, and accordingly suppresses the coherent transmission of electrons through the QD. One may use another kind of sensitive charge detector composed of a single electron transistor (SET) [7,8]. There exists the trade-off between the measurement induced dephasing and the information acquisition by the detector [9,10]. The noise properties and efficiency of a detector composed of a resonant-level conductor has been investigated in Refs. [11,12].
Here we consider a fully phase-coherent ‘quantum dot detector’ (QDD) coupled to another quantum dot regarded as a ‘system’ (labelled as ‘QD-s’, see Fig. 1) with two possible charge states, namely ‘0’ and ‘1’. The detector is also composed of a quantum dot attached to two electrodes (labelled as ‘QD-d’) in the coherent resonant tunnelling limit. Two quantum dots (QD-s and QD-d) are capacitively coupled and electron transfer between the two dots are forbidden. For simplicity, we assume that the transmission of electron in the QDD takes place via a single resonant level, which can be realized in the GaAs-based two-dimensional electron gas (2DEG). Our major observation in this study is the peculiar role of the symmetry in the detector efficiency. We show that the detector efficiency is reduced near the resonance even in a detector with perfect time-reversal and mirror-reflection symmetry. This is in contrast with the case of the symmetric single-channel non-resonant detectors which have the maximum efficiency independent of its transparency [9, 10]. Based on a general symmetry argument for the scattering matrix, we show that the anomaly of a detector with resonance originates from the abrupt phase change of the scattering amplitudes. This anomaly of a resonant detector has not been taken into account previously [11, 12]. We also discuss the relation between the dephasing rate and the shot noise of the detector, and the detector properties in the presence of the Fano resonance.

The Hamiltonian of the system under consideration is given by $H = H_d + H_s + H_{int}$, where $H_d$, $H_s$, and $H_{int}$ represent the QDD, the ‘system’ containing QD-s, and the interaction between the two subsystems, respectively. The Hamiltonian for the QDD is expressed as

$$H_d = \sum_{\alpha=R,L} \sum_k \varepsilon_k c_{\alpha k}^\dagger c_{\alpha k} + \varepsilon_d d^\dagger d + \sum_{\alpha=R,L} \sum_k (V_d d^\dagger c_{\alpha k} + h.c.),$$

which consists of the two leads (1st term), single resonant QD level (2nd term), and tunnelling between QD-d and the leads (last term). The operator $c_{\alpha k}$ ($c_{\alpha k}^\dagger$) annihilates (creates) an electron with energy $\varepsilon_k$ of momentum $k$ on the lead $\alpha$. $d$ ($d^\dagger$) annihilates (creates) an electron in QD-d. QD-d is modelled as a single resonant level of its energy $\varepsilon_d$. A voltage $V_d$ is applied across the detector which gives the difference in the chemical potentials between the two leads by $eV_d$. The interaction between QD-d and QD-s is described by $H_{int} = Ud^\dagger d (\hat{n} - 1/2)$, where $\hat{n}$ and $U$ stand for the number operator for QD-s and the inter-QD Coulomb interaction, respectively. This interaction shifts the effective energy level of the QD-d, which implies that the information of the charge state of the QD-s is transferred to the QD-d. This transferred information enables detection of the charge state in the QD-s. For convenience we introduce the $n$-dependent energy level of the QD-d where $n$ denotes the charge state of the QD-s: $\varepsilon_n = \varepsilon_d + (n - 1/2)U$. Note that the Hamiltonian of the ‘system’ containing QD-s is not given explicitly since our main interest is to investigate the detector. The effect of the scattering at

Fig. 1 – Schematic diagram of the quantum dot detector (QDD) coupled to another quantum dot QD-s. The quantum dot QD-d of the QDD and QD-s are capacitively coupled.
the QDD is described by the $n$-dependent scattering matrix $S_n$:

$$S_n = \begin{pmatrix} r_n & t'_n \\ t_n & r'_n \end{pmatrix}.$$  (2)

Here we have assumed that the QDD provides only a single transverse channel. The unitarity of $S_n$ gives the constraints $|t_n|^2 + |r_n|^2 = |t'_n|^2 + |r'_n|^2 = 1$, and $r_n t'_n + r'_n t_n = 0$.

In the absence of the external magnetic field, time reversal symmetry (TRS) of the QDD is preserved, and thus $t_n = t'_n$. From the relation between the retarded Green’s function and the scattering matrix [13, 14], one can obtain the components of the scattering matrix given in the following form describing the Breit-Wigner resonance [15, 16]:

$$r_n = \frac{\varepsilon - \varepsilon_n + i(\Gamma_L - \Gamma_R)}{\varepsilon - \varepsilon_n + i\Gamma}, \quad r'_n = \frac{\varepsilon - \varepsilon_n - i(\Gamma_L - \Gamma_R)}{\varepsilon - \varepsilon_n + i\Gamma}, \quad t_n = t'_n = -\frac{i2\sqrt{\Gamma_L \Gamma_R}}{\varepsilon - \varepsilon_n + i\Gamma},$$  (3)

where $\varepsilon$ is the incident energy of an electron and $\Gamma = \Gamma_L + \Gamma_R$ with $\Gamma_{\alpha}$ ($\alpha = L, R$) being the coupling strength between the lead $\alpha$ and QD-$d$ given by $\Gamma_{\alpha} = \pi N_{\alpha}(0)|\langle \alpha | V | 0 \rangle|^2$, where $N_{\alpha}(0)$ denotes the density of states at the Fermi level of the lead $\alpha$.

The information of the charge state in QD-$s$ is transferred into the detector through the transmission probability $|t_n|^2$ and the relative scattering phase $\phi_n = \arg(t_n/r_n)$. The ‘measurement’ is performed by the transmission probability change of the detector due to an extra electron in the QD-$s$. The measurement rate is defined by [9, 17]

$$\Gamma_m = \frac{eV_d}{\hbar} \frac{(\Delta T)^2}{4T(1-T)},$$  (4)

where $T = ((|t_1|^2 + |t_0|^2)/2$ and $\Delta T = |t_1|^2 - |t_0|^2$. Concerning the phase information $\phi_n$, it is not actually measured. Therefore the phase does not affect the measurement rate. However it is related to dephasing because there is a possibility to measure the phase regardless of whether it is being measured or not [2, 3]. In a symmetric QDD ($\Gamma_L = \Gamma_R$), one can find that from Eq. (3) $\phi_n = -\pi/2$ for $\varepsilon < \varepsilon_n$ and $\phi_n = +\pi/2$ for $\varepsilon > \varepsilon_n$. In contrast to the non-resonant detector, there is a phase jump by $\pi$ at $\varepsilon = \varepsilon_n$. This phase jump contributes to the dephasing rate, and therefore distinguishes the dephasing from the measurement rate.

In order to describe the hybrid system, we adopt the density matrix formulation [18–20], combined with the scattering matrix. The effect of the capacitive interaction between the QDD and the QD-$s$ is described by a two-particle scattering matrix [19, 20] $S$ where its elements are given by

$$S_{nn'} = \delta_{nn'}(\delta_{n0}S_0 + \delta_{n1}S_1), \quad (n, n' \in \{0, 1\}).$$  (5)

In the case of a single scattering event in the QDD with the initial state of the total system $|\psi_{tot}^0\rangle = (a|0\rangle + b|1\rangle) \otimes |\chi_{in}\rangle$ where the initial state of QD-$s$ is coherent superposition of the $n = 0$ and $n = 1$ states denoted by $a|0\rangle + b|1\rangle$ with $|a|^2 + |b|^2 = 1$ and the initial state of the QDD is $|\chi_{in}\rangle$ with incident electron from the lead $L$, the state of QD-$s$ after the scattering is described by the reduced density matrix $\rho = \text{Tr}_{\text{QDD}}\{S|\psi_{tot}^0\rangle\langle\psi_{tot}^0|S^\dagger\}$. The reduced density matrix $\rho$ is given by $\rho = |a|^2|0\rangle\langle 0| + \lambda ab^*|0\rangle\langle 1| + \lambda^* a^*b|1\rangle\langle 0| + |b|^2|1\rangle\langle 1|$, where $\lambda = r_0 r_1^* + t_0 t_1^*$. One can find that the diagonal elements of $\rho$ do not change upon scattering, but the off-diagonal elements are modified by $\rho_{01} = \lambda^* r_0^* r_1$ and $\rho_{10} = \lambda r_0^* r_1$. We consider the limit where the scattering in the QDD occurs on a time scale much shorter than the relevant time scales in the QD-$s$. In the present case, $\Delta t \ll t_d$, where $\Delta t = h/2eV_d$ is the average time interval between two successive scatterings, and $t_d$ is the dephasing time of the charge state of the
QD-s induced by the QDD. In this limit, one can find that the time evolution of \( \rho_{01} \) is given as [20]

\[
\rho_{01}(t) = e^{-(\Gamma_d - i\nu)t} \rho_{01},
\]

where \( \nu = \arg(\lambda)/\Delta t \), and

\[
\Gamma_d = \frac{1}{t_d} = -\frac{\ln|\lambda|}{\Delta t} = -\frac{2eV_d}{\hbar} \ln|\lambda|.
\]

In the weak measurement limit (\( \lambda \approx 1 \)), the dephasing rate \( \Gamma_d \) can be expanded in terms of the change of the transparency \( \Delta T = |t_1|^2 - |t_0|^2 \) and the change of the relative scattering phase \( \Delta \phi = \arg(t_1/r_1) - \arg(t_0/r_0) \) as follows

\[
\Gamma_d = \Gamma_T + \Gamma_\phi \quad \text{with} \quad \Gamma_T = \frac{eV_d}{\hbar} (\Delta T)^2 / 4T(1 - T) \quad \text{and} \quad \Gamma_\phi = \frac{eV_d}{\hbar} T(1 - T)(\Delta \phi)^2.
\]

One can find that \( \Gamma_T = \Gamma_m \): That is, the current sensitive component of the dephasing rate is equivalent to the measurement rate in Eq. [21] [21].

The detector efficiency, namely \( \eta \), is defined by the ratio between the measurement rate (\( \Gamma_m \)) of the detector and the dephasing rate as [9, 10]

\[
\eta \equiv \Gamma_m/\Gamma_d.
\]

For a QPC detector that obeys the TRS and the mirror reflection symmetry (MRS), it has been shown that the phase-sensitive dephasing does not take place because the relative phase between the transmission and the reflection amplitudes remains constant (that is \( \Delta \phi = 0 \)) [9, 10]. Therefore the efficiency for a symmetric single-channel detector has its maximal value independent of the transparency of the detector. In the following, based on a symmetry argument for the scattering matrix, we show that the phases of the scattering amplitudes may play an important role in the detector efficiency in spite of the TRS and the MRS.

Concerning the relation between the dephasing and the symmetry of the detector, we reexamine the scattering matrix for the detector. In general, a scattering matrix for a single-channel transport can be written in the following form [22, 23]:

\[
S = \begin{pmatrix} r & t \\ t' & r' \end{pmatrix} = e^{i \theta} \begin{pmatrix} \sqrt{\Re e^{i \varphi_1}} & i \sqrt{\Re e^{i \varphi_2}} \\ i \sqrt{\Re e^{i \varphi_2}} & \sqrt{\Re e^{i \varphi_1}} \end{pmatrix},
\]

![Fig. 2](image_url) - (a) The measurement rate (\( \Gamma_m \)) and the dephasing rate (\( \Gamma_d \)), and (b) the detector efficiency, for a symmetric QDD (\( \Gamma_L = \Gamma_R = 0.5\Gamma \)). (c) The dephasing rates \( \Gamma_d, \Gamma_T, \Gamma_\phi \), and (d) the detector efficiency, for an asymmetric QDD (\( \Gamma_L = 0.4\Gamma, \Gamma_R = 0.6\Gamma \)). \( U = 0.05\Gamma \), \( \gamma_0 = 2eV_d/\hbar \).
with the constraint $R + T = 1$. In the presence of the TRS ($t = t'$) and the MRS ($r = r'$), the phase components $\varphi_1$ and $\varphi_2$ should satisfy $\varphi_1 = n_1\pi$ and $\varphi_2 = n_2\pi$, respectively, where $n_1$ and $n_2$ are integers. Therefore, the components of the scattering matrix can be written as follows:

$$r = r' = \sqrt{Re^{i\theta}} \text{ or } -\sqrt{Re^{i\theta}},$$

$$t = t' = i\sqrt{T}e^{i\theta} \text{ or } -i\sqrt{T}e^{i\theta}. \quad (11)$$

From these, one can find that $\arg(t/r) = \pm \pi/2$, implying $\Delta \phi = 0$ or $\Delta \phi = \pi$. The latter has not been noticed previously. Indeed we have shown in the previous section that the scattering matrix for a QDD (Eq. (2,4)) satisfies this condition for $\Gamma_L = \Gamma_R$ (symmetric QDD). For $\Gamma_L = \Gamma_R$, $\Delta \phi = 0$ except at resonance ($\varepsilon = \varepsilon_d$) where the abrupt change of the relative scattering phase ($\Delta \phi = \pi$) takes place due to the fact that $r = 0$. For this reason, the formula for a weak measurement limit of Eq. (5) is not valid for a symmetric detector since the phase-sensitive term cannot be well defined.

Fig. 2 shows (a) the dephasing rate $\Gamma_d$ (calculated from Eq. (7)) and the measurement rate $\Gamma_m$ (calculated from Eq. (4)), and (b) the efficiency $\eta$ for a symmetric QDD. In contrast to the single-channel non-resonant detector, the efficiency is not always at its maximum value of 1 even in the presence of the TRS and the MRS. Instead, it displays a dip around the resonance. This behavior originates from the abrupt phase change of scattering phase at resonance. According to Eq. (6), the phase of the reflection amplitude for a symmetric QDD ($\Gamma_L = \Gamma_R$) changes abruptly from $+\pi/2$ to $-\pi/2$. This abrupt phase change causes another source of dephasing insensitive to the detector current, and accordingly, lowers the efficiency of the detector. For an asymmetric detector ($\Gamma_L \neq \Gamma_R$), Eq. (6) can be used in the weak measurement limit since scattering phases do not have discontinuity. Fig. 2 shows (c) the dephasing rates $\Gamma_d, \Gamma_T, \Gamma_\phi$, and (d) the efficiency of the detector. Near the resonance the current-sensitive dephasing ($\Gamma_T$) shows a dip, which reduces the detector efficiency. On the other hand, the phase-sensitive dephasing has a peak around the resonance. As the asymmetry increases, the dip width of $\Gamma_T$ and the peak width of $\Gamma_\phi$ increase. In fact, these widths are proportional to the degree of the asymmetry, $|\Gamma_L - \Gamma_R|$.

In the weak measurement limit ($|\lambda| \sim 1$), from the relation $\ln|\lambda| \cong 1 - |\lambda|$, Eq. (8), and Eq. (7), we obtain

$$\Gamma_d = \frac{eV_d}{h} \frac{4\Gamma_L\Gamma_R U^2}{[(\varepsilon - \varepsilon_d)^2 + \Gamma^2]^2} = \frac{eV_d U^2}{4h\Gamma_L\Gamma_R} T^2. \quad (13)$$

This result is in very contrast with the non-resonant detector in the following aspects. First, the dephasing rate for a QDD increases as $T$ increases, while for a QPC detector, it has a maximum value in the intermediate value of $T \simeq 1/2$ and vanishes at the two extrema $T = 0$ and $T = 1$. One may understand that $\Gamma_d$ has its maximum at resonance, since a QDD is a detector based on the charge sensitivity of the resonant tunnelling. As we discussed above, although the current is insensitive to the charge state of the QD-s at resonance, discontinuity (for a symmetric QDD) or rapid change (for an asymmetric QDD) of the scattering phase stores the information of the quantum state of the QD-s, thereby induces strong dephasing. Second, Eq. (13) clearly shows that the dephasing rate has nothing to do with the shot noise of the detector. As pointed out before [24], the dephasing rate is formally different from the shot noise of the detector. The difference originates from the fact that the dephasing is caused by the charge fluctuations but the shot noise comes from the current fluctuations of the detector. However, QPC detectors mostly show that the dephasing rate is proportional to the shot noise of the detector (See Ref. [25] and references therein). An interesting point of our study is that the QDD dramatically shows that the two quantities are completely independent.
Next we consider the case where a QDD contains background transmission as well as resonant tunnelling. In this case transport through the QDD shows the Fano resonance. The QDD is assumed to have TRS and MRS. The Hamiltonian for the QDD is given by \( \hat{H}_d = \hat{H}_a + \sum_k (W_{LR} c_k^R c_{Lk} + h.c.) \), where the first term describes the resonant tunnelling (given by Eq. (1)) and the second term represents the direct (non-resonant) transmission between the two leads. Following the procedure of calculating the retarded Green’s function and the components of the scattering matrix [13, 14, 26], the transmission \((\tilde{t}_n, \tilde{r}_n)\) and the reflection \((\tilde{r}_n, \tilde{r}_n')\) coefficients can be calculated. For the symmetric case \( \Gamma_L = \Gamma_R = \Gamma \), we get

\[
\tilde{r}_n = \tilde{r}_n' = \frac{\sqrt{1 - T_b(\varepsilon - \tilde{\varepsilon}_n)^2}}{\varepsilon - \tilde{\varepsilon}_n - i\Gamma}, \quad \tilde{t}_n = \tilde{t}_n' = i\frac{\sqrt{T_b(\varepsilon - \tilde{\varepsilon}_n)^2}}{\varepsilon - \tilde{\varepsilon}_n - i\Gamma}.
\]

where \( T_b \) corresponds to the probability of the background transmission. The dot energy level and the resonance width are renormalized due to the background transmission as \( \tilde{\varepsilon}_n = \varepsilon_n - \kappa \tilde{\Gamma} \) (or \( \tilde{\varepsilon}_d = \varepsilon_d - \kappa \tilde{\Gamma} \)), and \( \tilde{\Gamma} = \Gamma/(1 + \kappa^2) \), respectively. Here the parameter \( \kappa \) is defined as \( \kappa = \pi N(0)|W_{LR}| \) where \( N(0) \) denotes the density of states of a lead. In terms of the parameter \( \kappa \), the background tunnelling probability is written as \( T_b = 4\kappa^2/(1 + \kappa^2)^2 \).

In the limit of \( T_b = 0 \) (that is, in the absence of the background transmission), Eq. (14) is equivalent to the result obtained in Eq. (3), as one can expect. Eq. (14) shows that the relative scattering phase \((\arg(\tilde{t}_n/\tilde{r}_n))\) changes abruptly by \( \pi \) both at the reflection zero and at the transmission zero, where the measurement rate \( \Gamma_m \) vanishes. On the other hand, the dephasing rate \( \tilde{\Gamma}_d \) via a QDD with Fano resonance is written as

\[
\tilde{\Gamma}_d = \frac{eV_d}{\hbar} \frac{\tilde{\Gamma}^2 U^2}{[(\varepsilon - \tilde{\varepsilon}_d)^2 + \tilde{\Gamma}^2]^2}.
\]

This shows that the dephasing rate is not modified by the presence of the background transmission (see Eq. (13)), except the renormalization of the energy level and the resonance width. Thus, one can conclude that the characteristics of the dephasing is not affected by the non-resonant transmission component, aside from the renormalization of the parameters, while the conductance (which is proportional to \( |\tilde{t}_n|^2 \)) is severely modified. Fig. 3 displays (a) the dephasing rate \( \tilde{\Gamma}_d \) and the measurement rate \( \Gamma_m \) together with the transmission probability \( T \), and (b) the detector efficiency, for a symmetric QDD with the background tunnelling probability \( T_b = 0.45 \). As one can see, \( \tilde{\Gamma}_d \) is equivalent to what is expected without the background transmission.
transmission. One peculiar feature is the two dips in $\Gamma_m$ (and also in the detector efficiency $\eta$): one from the transmission zero, the other from the reflection zero.

In conclusion, the dephasing rate of a mesoscopic system via a QDD is maximum at resonance of the QDD where the conductance is insensitive to the charge state of the mesoscopic system. As a result, the efficiency of the detector shows a dip structure and vanishes at resonance, in contrast to the symmetric non-resonant detector which retains a maximum detector efficiency. The anomaly of the QDD originates from the abrupt phase change of scattering amplitudes in the presence of resonance, which is insensitive to the detector current but stores the information of the quantum state of the mesoscopic system. If the QDD shows Fano resonance, there are two dips in the detector efficiency which correspond to the transmission and the reflection zeros.

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