Reduction of partial pure dephasing by a quantum-Zeno-like effect

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Partial pure dephasing resulting from the interaction with a super-Ohmic reservoir is qualitatively different than the decay which is typically countered by the quantum Zeno effect in, e. g., quantum optics. We show that a Zeno-like effect can be used to reduce partial pure dephasing relying on the impact of the inter-measurement evolution and of the measurements themselves on the reservoir state (instead of the state of the target system). Contrarily to Zeno, where fast measurements are favored, our effect is most pronounced at long delay times between the creation of the state and the measurements, when the system-reservoir-interaction-related dynamics are already steadied. Our observations are quantified by a study of a realistic quantum dot system interacting with a phonon reservoir and a gain of coherence of up to 10 % is found in the simplest single measurement scenario.

I. INTRODUCTION

Quantum dots (QDs) are zero-dimensional semiconductor nanostructures and constitute an example of textbook three-dimensional quantum wells, where trapped (electrons or holes) and excited (excitons) charge carriers display a discrete energy spectrum. As such, they were dubbed "artificial atoms" and since carrier states can be manipulated using ultrafast spectroscopy, QDs were declared good solid-state candidates for quantum computation[1]. A vast drawback for such applications is the carrier-phonon interaction which leads to partial pure dephasing on picosecond timescales[2–4]. To overcome this difficulty, a number of solutions were proposed, including qubits coded on spin states[5,6], hybrid spin-charge schemes[7?] , modification of the optical-pulse shape[8,9] or reservoir properties[10,11], and collective encoding[12,13]. Although some quite promising results have been shown, a substantial reduction of decoherence is accompanied by either amassing difficulties in coherent control of the qubit, or by making the ensemble more involved and resulting in fabrication problems.

The quantum Zeno paradox[14,15], which is studied in the context of inhibiting the decay of unstable quantum systems, states that a quantum system under continuous measurement cannot decay. The decay can still be substantially reduced or even prevented, if a discontinuous measurement is repeated frequently enough. Furthermore, the post-measurement unitary evolution is also affected and can be slowed[16–18] (Zeno effect) or accelerated[16,19] (anti-Zeno effect) depending on the parameters of the studied system. In QDs, excitation by a sequence of ultrashort pulses corresponding to the quantum Zeno effect was shown to yield a small reduction of decoherence[9].

We address the problem of inhibiting phonon-induced partial pure dephasing of an exciton confined in a QD and show that a quantum Zeno-like effect, consisting of a series of measurements performed on the dot, can be used to reduce the decoherence by affecting the environment. Contrarily to previous results, it is advantageous in our system, if the measurements are well separated in time from the initialization of the QD state and from each other. Although the measurements may cause both increase and loss of asymptotic coherence, displaying Zeno and anti-Zeno type behavior depending on the measurement times and outcomes, we show for the single measurement case that performing a measurement at any time after the initialization of the state is favorable, due to the interplay of given-outcome probabilities and corresponding dephasing values.

The paper is organized as follows. In Sec. II we describe the system and its Hamiltonian, and introduce the Weyl operator method for exact diagonalization of the exciton-phonon interaction. In Sec. III we describe the repeated measurement scenario and find a recursive scheme for calculating the reservoir state and subsequently the degree of coherence after the last measurement. Sec. IV is devoted to the results in the single measurement case and Sec. V concludes the paper.

II. THE SYSTEM AND THE HAMILTONIAN

The system under study consists of a self-assembled, single level quantum dot under the influence of a super-Ohmic phonon reservoir. The two charge states of the confined exciton considered are $|0\rangle$ when the dot is empty and $|1\rangle$ indicating an occupied QD (with an exciton in its ground state). The decoherence of an excitonic superposition state, interacting with the environment by means of deformation potential coupling[20], takes the form of partial pure dephasing, meaning that the occupation of the dot remains unchanged while the phase information of the QD state leaks into the environment, reducing the amplitude of the off-diagonal elements of the density matrix.

The Hamiltonian of the system is

$$H = \epsilon|1\rangle\langle 1| + H_{\mathrm{ph}} + |1\rangle\langle 1| \sum_{\boldsymbol{k}} (f^*_{\boldsymbol{k}} b_{\boldsymbol{k}} + f_{\boldsymbol{k}} b^\dagger_{\boldsymbol{k}}), \quad (1)$$

where the first term describes the energy of the confined exciton (ϵ is the energy difference between the states without phonon corrections),

$$H_{\mathrm{ph}} = \sum_{\boldsymbol{k}} \hbar\omega_{\boldsymbol{k}} b^\dagger_{\boldsymbol{k}} b_{\boldsymbol{k}}$$

is the Hamiltonian of the phonon subsystem and the third term describes the interaction. Here, $\omega_{\boldsymbol{k}} = ck$ is the frequency of the phonon mode with the wave vector $\boldsymbol{k}$ (c is the speed of longitudinal sound), and $b^\dagger_{\boldsymbol{k}}$, $b_{\boldsymbol{k}}$ are phonon creation and annihilation operators. Carrier-phonon interaction constants in eq. (1) are given by

$$f_{\boldsymbol{k}} = (\sigma_{\mathrm{e}} - \sigma_{\mathrm{h}}) \sqrt{\frac{\hbar k}{2\varrho V_{\mathrm{N}} c}} \int_{-\infty}^{\infty} d^3\boldsymbol{r} \psi^*(\boldsymbol{r}) e^{-i\boldsymbol{k}\cdot\mathrm{r}} \psi(\boldsymbol{r}), \quad (2)$$

where ϱ is the crystal density, V_{N} is the normalization volume of the phonon system, $\sigma_{e/h}$ are deformation potential constants for electrons and holes, and $\psi(\boldsymbol{r})$ are exciton wave functions.

The carrier-phonon interaction term in eq. (1) is linear in phonon operators and describes a shift of the lattice equilibrium induced by the presence of a charge distribution in the dot. The stationary state of the system corresponds to the exciton being surrounded by a coherent cloud of phonons (representing the lattice distortion to the new equilibrium). The transformation that creates the coherent cloud is the shift $w b_{\boldsymbol{k}} w^\dagger = b_{\boldsymbol{k}} - f_{\boldsymbol{k}}/(\hbar\omega_{\boldsymbol{k}})$, generated by the Weyl operator[21?]

$$w = \exp\left[\sum_{\boldsymbol{k}} \left(\frac{f_{\boldsymbol{k}}}{\hbar\omega_{\boldsymbol{k}}} b^\dagger_{\boldsymbol{k}} - \frac{f^*_{\boldsymbol{k}}}{\hbar\omega_{\boldsymbol{k}}} b_{\boldsymbol{k}} \right)\right]. \quad (3)$$

A straightforward calculation shows that the Hamiltonian (1) is diagonalized by the unitary transformation $\mathbb{W} = |0\rangle\langle 0| \otimes \mathbb{I} + |1\rangle\langle 1| \otimes w$, where $\mathbb{I}$ is the identity operator and the tensor product refers to the carrier subsystem (first component) and its phonon environment (second component).

Following ref. **?** we can find the exact time-evolution of the QD density matrix under the perturbation of a phonon bath. For a pure (fully coherent) initial state $|\psi\rangle = a|0\rangle + b|1\rangle$ this is

$$\rho(t) = \begin{pmatrix} |a|^2 & a^* b e^{iEt/\hbar} \langle W(t) \rangle \\ a b^* e^{-iEt/\hbar} \langle W^\dagger(t) \rangle & |b|^2 \end{pmatrix}, \quad (4)$$

where $E = \epsilon - \sum_{\boldsymbol{k}} |f_{\boldsymbol{k}}|^2/(\hbar\omega_{\boldsymbol{k}})$ is the shifted exciton energy and the average of Weyl operators at thermal equilibrium is equal to

$$\langle W(t) \rangle = \langle w^\dagger(t) w \rangle = \exp\left[-i \sum_{\boldsymbol{k}} \left| \frac{f_{\boldsymbol{k}}}{\hbar\omega_{\boldsymbol{k}}} \right|^2 \sin\omega_{\boldsymbol{k}} t \right] \quad (5)$$
$$\times \exp\left[\sum_{\boldsymbol{k}} \left| \frac{f_{\boldsymbol{k}}}{\hbar\omega_{\boldsymbol{k}}} \right|^2 (\cos\omega_{\boldsymbol{k}} t - 1)(2n_{\boldsymbol{k}} + 1) \right];$$

$n_{\boldsymbol{k}}$ are bosonic equilibrium occupation numbers. For long times (a few picoseconds), the phase shift (first exponent on the right side of eq. (5)) becomes negligible and the dephasing saturates at a finite, temperature dependent, level, hence, the pure dephasing is partial.

III. REPEATED INITIALIZATION

The creation of an exciton in a superposition state in the solid state environment of the QD perturbs the crystal lattice and leads to a modification of the phonon reservoir state. Thus, it is logical to assume that the quantum Zeno effect (applying repeated measurements in the basis corresponding to the initial QD state) will not only freeze the QD system for the duration of the measurements, but will also affect the degree of partial pure dephasing resulting from the carrier-phonon interaction. It is this pure-dephasing asymptotic value (which can be measured by the amplitude of coherent dipole radiation emitted by the dot which is proportional to the amplitude of the off-diagonal element of the QD-density matrix[?]) that is of interest here.

In the following, the measurement on the QD subsystem is taken into account as a projection measurement in the quantum-mechanical sense[22] (as opposed to a realistic optical measurement which is natural in this system). We are hence dealing with projection operators of the form $P_+ = |\psi\rangle\langle\psi| \otimes \mathbb{I}$ and $P_- = |\psi_\perp\rangle\langle\psi_\perp| \otimes \mathbb{I}$, with $|\psi\rangle$ equal to the pure initial state and the perpendicular $|\psi_\perp\rangle = b^*|0\rangle - a^*|1\rangle$ ($\mathbb{I}$ corresponds to the reservoir subsystem). Note, that regardless of the measurement outcome the degree of coherence,

$$D(t) = \left| \frac{\langle 0|\rho(t)|1\rangle}{\langle 0|\rho(0)|1\rangle} \right|, \quad (6)$$

at last measurement time is retained and equal to one, so that an outcome of $|\psi_\perp\rangle$ is not unfavorable in terms of reducing pure dephasing.

The degree of coherence at any given time may be calculated using a recursive scheme given the state of the reservoir at the last measurement time, $D(t) = |\langle W(t-\tilde{\tau})\rangle_n|$. Here $\tilde{\tau} = \sum_{m=1}^{n} \tau_m$ is the sum of all delay times between the n measurements that occurred until time t, and $\langle ... \rangle_n$ denotes the average over the reservoir degrees of freedom, with the reservoir state at the time of the n-th measurement $R(\tilde{\tau})$. The state of the reservoir at the time of the last measurement $\tilde{\tau}$ can be found, if the state of the reservoir after the one-but-last measurement is known. It depends on the measurement outcome and is equal to

$$R_+(\tilde{\tau}) = \frac{|a|^4 R(\tilde{\tau}-\tau_n) + |b|^4 W^\dagger(\tau_n) R(\tilde{\tau}-\tau_n) W(\tau_n) + |a|^2|b|^2 (e^{i\frac{E}{\hbar}\tau_n} W^\dagger(\tau_n) R(\tilde{\tau}-\tau_n) + e^{-i\frac{E}{\hbar}\tau_n} R(\tilde{\tau}-\tau_n) W(\tau_n))}{|a|^4 + |b|^4 + 2|a|^2|b|^2 \,\mathrm{Re}\left(e^{-i\frac{E}{\hbar}\tau_n}\langle W(\tau_n)\rangle_{n-1}\right)},$$

$$R_-(\tilde{\tau}) = \frac{|a|^2|b|^2 (R(\tilde{\tau}-\tau_n) + W^\dagger(\tau_n) R(\tilde{\tau}-\tau_n) W(\tau_n) - e^{i\frac{E}{\hbar}\tau_n} W^\dagger(\tau_n) R(\tilde{\tau}-\tau_n) - e^{-i\frac{E}{\hbar}\tau_n} R(\tilde{\tau}-\tau_n) W(\tau_n))}{|a|^2|b|^2 \left[2 - 2\,\mathrm{Re}\left(e^{-i\frac{E}{\hbar}\tau_n}\langle W(\tau_n)\rangle_{n-1}\right)\right]},$$

where $R_\pm(\tilde{\tau})$ correspond to outcome $|\psi\rangle$ $(+)$ and $|\psi_\perp\rangle$ $(-)$. The probabilities of measuring outcomes $|\psi\rangle$ and $|\psi_\perp\rangle$ at times τ_n are given by the denominators of the above equations, respectively. Their dependence on τ_n exhibits oscillations around the mean values of $|a|^4+|b|^4$ and $2|a|^2|b|^2$ (the sum of which is obviously equal to one) with the frequency $E/\hbar$. The oscillations are damped as the system undergoes partial pure dephasing; this is governed by the function $\langle W(\tau_n)\rangle_{n-1}$.

IV. SINGLE MEASUREMENT

The recursive scheme outlined in the previous section acquires complexity very rapidly with a growing number of measurements. It is therefore convenient to study a limited number, especially that a pronounced decrease of dephasing can be observed already in the single-measurement scenario.

In the following, an equal-superposition initial state will be considered ($a = b = 1/\sqrt{2}$). The degree of polarization is then, depending on the measurement outcome,

$$D_\pm(t-\tau) = \frac{\frac{1}{4}\left|\langle W(t-\tau)\rangle_0 + \langle W(\tau)W(t-\tau)W^\dagger(\tau)\rangle_0 \pm e^{i\frac{E}{\hbar}\tau}\langle W(t-\tau)W^\dagger(\tau)\rangle_0 \pm e^{-i\frac{E}{\hbar}\tau}\langle W(\tau)W(t-\tau)\rangle_0\right|}{\frac{1}{2} \pm \frac{1}{2}\,\mathrm{Re}\left(e^{-i\frac{E}{\hbar}\tau}\langle W(\tau)\rangle_0\right)}, \quad (7)$$

where $\pm$ differentiates between measurement outcomes $P_\pm$, τ is the delay time between the creation of the state and the measurement, and $\langle ...\rangle_0$ denotes the average over the reservoir at thermal equilibrium. The relevant Weyl operator averages are found to be[23?,24]

$$\langle W(t-\tau)W^\dagger(\tau)\rangle_0 = \langle W(t-2\tau)\rangle_0, \quad (8a)$$

$$\langle W(\tau)W(t-\tau)W^\dagger(\tau)\rangle_0 = \exp\left[-i\sum_{\boldsymbol{k}}\left|\frac{f_{\boldsymbol{k}}}{\hbar\omega_{\boldsymbol{k}}}\right|^2 (2\sin\omega_{\boldsymbol{k}}\tau - \sin\omega_{\boldsymbol{k}}(t-\tau) + 2\sin\omega_{\boldsymbol{k}}(t-2\tau))\right] \times \exp\left[\sum_{\boldsymbol{k}}\left|\frac{f_{\boldsymbol{k}}}{\hbar\omega_{\boldsymbol{k}}}\right|^2 (\cos\omega_{\boldsymbol{k}}(t-\tau) - 1)(2n_{\boldsymbol{k}}+1)\right], \quad (8b)$$

$$\langle W(\tau)W(t-\tau)\rangle_0 = \exp\left[-i\sum_{\boldsymbol{k}}\left|\frac{f_{\boldsymbol{k}}}{\hbar\omega_{\boldsymbol{k}}}\right|^2 (2\sin\omega_{\boldsymbol{k}}\tau + \sin\omega_{\boldsymbol{k}}(t-2\tau))\right] \times \exp\left[\sum_{\boldsymbol{k}}\left|\frac{f_{\boldsymbol{k}}}{\hbar\omega_{\boldsymbol{k}}}\right|^2 (2\cos\omega_{\boldsymbol{k}}\tau + 2\cos\omega_{\boldsymbol{k}}(t-\tau) - \cos\omega_{\boldsymbol{k}}(t-2\tau) - 3)(2n_{\boldsymbol{k}}+1)\right]. \quad (8c)$$

As in the case of eq. (5), the phase shifts of the averages of many Weyl operators (eqs (8)) will become negligible when the delay time τ is longer than the time it takes the system state to reach the saturated value of partial pure dephasing, t_s, and the time t is longer than $2\tau + t_s$. The assumption on the delay time is not needed to state that for long times a finite decrease of the averages will be observed, but it allows for more general statements about the asymptotic ($t > 2\tau + t_s$) behavior of the degree of polarization (eq. (7)). Since then the long-time behavior of averages (8a) and (8b) mimics the long-time behavior of the degree of coherence in the case of no measurement $D_0^\infty = |\langle W(t \to \infty)\rangle_0|$ and the average (8c) behaves as $(D_0^\infty)^3$, the asymptotic degree of polarization depends only on its measurement-free counterpart and is equal to

$$D_\pm^\infty = \frac{\frac{1}{4} D_0^\infty \left| 2 \pm e^{i\frac{E}{\hbar}\tau} \pm e^{-i\frac{E}{\hbar}\tau} (D_0^\infty)^2 \right|}{\frac{1}{2} \pm \frac{1}{2}\cos(\frac{E}{\hbar}\tau) D_0^\infty}. \tag{9}$$

Obviously, the value will oscillate with the delay time, and the frequency of these oscillations depends on the shifted exciton energy E.

In the following calculations we use typical parameters for a self-assembled InAs/GaAs structure: single particle wave functions $\psi(\boldsymbol{r})$ are modeled by Gaussians with 5 nm width in the xy plane and 1 nm along z. The material parameters are $\sigma_\mathrm{e} - \sigma_\mathrm{h} = 9$ eV, $\varrho = 5360$ kg/m^3, and $c = 5100$ m/s. The shifted exciton energy is taken equal to $E = 1$ eV.

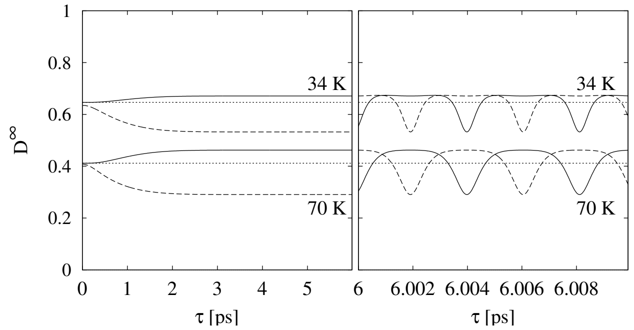

FIG. 1: Asymptotic degree of coherence as a function of the delay time for two temperatures. The maximal (solid line) and minimal (dashed line) values are shown in the left panel. The right panel shows the detail for the measurement outcome $|\psi\rangle$ (solid line) and $|\psi_\perp\rangle$ (dashed line). The dotted lines denote the degree of coherence in the case of no extra measurement in both panels.

The left panel of Fig. 1 shows the maximal and minimal values of the asymptotic degree of coherence as a function of the delay time. As can be seen the gain (or loss) stabilizes at a given level, if the delay time is longer than a few-picosecond threshold value that corresponds to the time after initialization when the maximal partial pure dephasing is reached (t_s). In the right panel in the same figure the full dynamics are shown. The oscillations arise from the interplay of the coherent-QD-evolution-dependent terms in eq. (7). The minima (maxima) for the measurement outcome $|\psi\rangle$ ($|\psi_\perp\rangle$) correspond to the situation when $E\tau/\hbar = (2j+1)\pi$ (point of minimal gain) and the maxima (minima) to $E\tau/\hbar = 2\pi j$ (point of maximal gain), where j is a natural number. A highly relevant point is $E\tau/\hbar = (j + 1/2)\pi$ when the gain in coherence is equal for both measurement outcomes (point of equal gain); interestingly this gain is not much different than that at the point of maximal gain and at some temperatures may even be slightly larger (see the 34 K curves in Fig. 1, right panel).

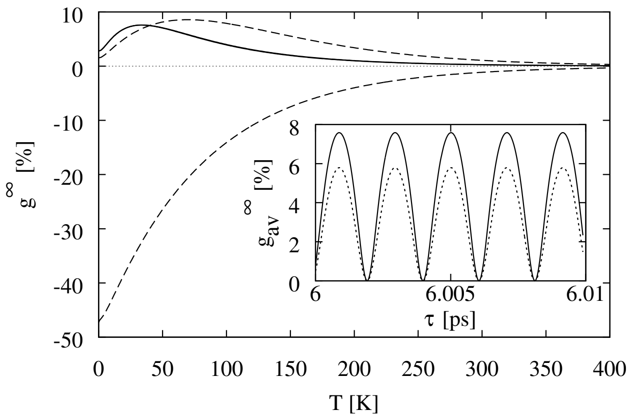

FIG. 2: Temperature dependence of the relative gain in the asymptotic degree of coherence after single measurement. Dashed lines correspond to the point of maximal gain ($E\tau/\hbar = 2\pi j$) for the measurement outcomes $|\psi\rangle$ (gain) and $|\psi_\perp\rangle$ (loss). The solid line corresponds to the point of equal gain ($E\tau/\hbar = (j + 1/2)\pi$). Inset: The average relative gain as a function of the delay time for 34 K (solid line) and 70 K (dotted line).

The temperature dependence of the relative gain in the asymptotic degree of coherence, $g^\infty = (D^\infty - D_0^\infty)/(1 - D_0^\infty)$, at the point of maximal gain for measurement outcome $|\psi\rangle$ (gain, g_+^∞) and $|\psi_\perp\rangle$ (loss, g_-^∞), and point of equal gain (g_e^∞) are shown in Fig. 2. The three curves are related to each other, as can be seen in eq. (9). The relation is particularly simple for the two maximal point curves, where $e^{i\frac{E}{\hbar}\tau} = e^{-i\frac{E}{\hbar}\tau} = 1$, since then $g_-^\infty = -D_0^\infty/2$ and $g_+^\infty = -g_-^\infty(1+2g_-^\infty)/(1-2g_-^\infty)$. This explains the surprising non-monotonous temperature-dependence of g_+^∞; the similar behavior of g_e^∞ is observed for analogous reasons. The maxima of g_+^∞ and g_e^∞ are different and are, respectively, $T_+ \sim 70$ K and $T_e \sim 34$ K for the material parameters used. Note, that for low temperatures the gain at the maximal point is smaller than at the equal point.

Although the fast τ-dependent oscillations of the asymptotic degree of coherence may suggest potential problems in the experimental realization of the decoherence-reducing scheme, this is not, in fact, the case. The reason is that the probability of measuring outcome $|\psi\rangle$ (denominator of eq. 7 for D_+) at delay time τ oscillates synchronously with the degree of coherence around the value of $|a|^4 + |b|^4 = 1/2$. This means that the probability of measuring state $|\psi\rangle$ is maximal when the reduction of dephasing due to the measurement of this state is greatest and likewise for state $|\psi_\perp\rangle$. These maximal probability values are relatively large for the temperatures discussed here and are equal to 0.82 for 34 K and 0.71 for 70 K. In the case of the equal point, the same (positive) gain of coherence is achieved regardless of the measurement outcome. Hence, there is a big chance of increasing coherence by the measurement at any delay time.

To quantify the potential for the reduction of pure dephasing of this Zeno-like effect, we introduce the average relative gain in the asymptotic degree of coherence $g_{av}^{\infty} = p_+ g_+^{\infty} + p_- g_-^{\infty}$, where $p_\pm$ are the probabilities of measurement outcomes $|\psi\rangle$ and $|\psi_\perp\rangle$, corresponding to $g_\pm^{\infty}$. This is plotted in the inset of Fig. 2 as a function of the delay time for 34 K (solid line) and 70 K (dotted line). The foremost quality of the function is its non-negativity; it underlines the usefulness of the anti-decoherence scheme regardless of the experimental capability of targeting a specific delay time. Furthermore, the maxima coincide with points of equal gain and are given by the equal-gain curve in the temperature-dependence plot of Fig. 2. At the minima, which are located at both maximal and minimal points, there is no average gain ($g_{av}^{\infty} = 0$). This is because, although the probabilities of a favorable measurement are much bigger (for moderately small temperatures) than of the unfavorable one, the achieved gain of coherence is appropriately smaller than the loss (see extremal-gain curves in Fig. 2).

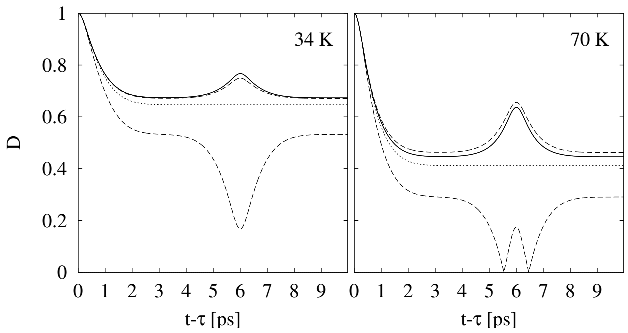

FIG. 3: Degree of coherence after single measurement as a function of the time that elapsed from the measurement. The dotted lines denote the value in case of no extra measurement. Dashed lines correspond to the point of maximal gain ($E\tau/\hbar = 2\pi j$) for the measurement outcomes $|\psi\rangle$ (gain) and $|\psi_\perp\rangle$ (loss). The solid line corresponds to the point of equal gain ($E\tau/\hbar = (j + 1/2)\pi$).

For completeness, the time evolution of the degree of coherence is shown in Fig. 3 at two different temperatures. The measurement times have, in both cases, been chosen as close as possible to 6 ps (which is well beyond the phonon relaxation times) and adjusted in such a way that they correspond to the point of maximal gain (dashed lines) and the point of equal gain (solid line). At 34 K the slight advantage of the equal-point gain over maximal-point gain is noticeable. The revival of coherence in the evolution-curves around $t - \tau = 6$ ps is a robust feature and is related to the character of eqs. (8), where the time $t = 2\tau$ is distinguished. Its appearance is the reason for the long-time behavior of the degree of coherence being observed at times longer than $2\tau + t_s$ (the time scale of the initial phonon-induced dephasing is the same as of the post-revival dephasing).

V. CONCLUSION

We have studied the effect of a series of measurements on an exciton confined in a QD in the basis of its initial superposition state and its orthogonal counterpart. In terms of phase coherence, the two states are equivalent, so the QD state at the time of the last measurement is always fully coherent. The subsequent pure dephasing is, however, affected by the measurement, since the state of the phonon reservoir at last measurement time is not the same as its initial thermal-equilibrium state and acquires information about the phase coherence of the pre-measurement state.

The detailed study of the simplest, single measurement scenario reveals that the quantum-Zeno-like effect leads to abnormalities in the time evolution (such as a temporary peak or dip in the degree of coherence), but also affects the asymptotic value of the partial pure dephasing. This asymptotic value can be both higher or lower than the degree of coherence in the no-measurement case, depending on the measurement outcome and on the delay time between the creation of the state and the measurement. The dependence on the delay time is periodic with a very large frequency, due to the large exciton energy ($E \sim 1$ eV), yet the probabilities of both measurement outcomes oscillate synchronously with the asymptotic degree of coherence in such a way that it is always most likely to measure the state which leads to less decoherence. Additionally, at delay times when both probabilities are similar, a measurement leads to an increase of coherence regardless of its outcome.

Introducing the average gain of coherence which is always non-negative for the studied effect, we have shown that a measurement following the creation of an exciton superposition state is always favorable, regardless of the practical difficulties in targeting a specific delay time. Contrarily to the usual quantum Zeno effect, the scheme works best at long delay times when the phonon-related dynamics steadied. For small self-assembled InAs/GaAs QDs, whose parameters were used in this study, a maximal increase of coherence nearing 10 % and an average increase nearing 8 % can be observed (depending on the temperature).

[1] P. Zanardi and F. Rossi, Phys. Rev. Lett. **81**, 4752 (1998).
[2] P. Borri *et al.*, Phys. Rev. Lett. **87**, 157401 (2001).
[3] A. Vagov, V. M. Axt, and T. Kuhn, Phys. Rev. B **67**, 115338 (2003).
[4] A. Vagov *et al.*, Phys. Rev. B **70**, 201305(R) (2004).
[5] G. Burkard, D. Loss, and D. P. DiVincenzo, Phys. Rev. B **59**, 2070 (1999).
[6] A. Imamoğlu *et al.*, Phys. Rev. Lett. **83**, 4204 (1999).
[7] F. Troiani, E. Molinari, and U. Hohenester, Phys. Rev. Lett. **90**, 206802 (2003).
[8] U. Hohenester and G. Stadler, Phys. Rev. Lett. **92**, 196801 (2004).
[9] V. M. Axt, P. Machnikowski, and T. Kuhn, Phys. Rev. B **71**, 155305 (2005).
[10] M. Cazayous *et al.*, Phys. Rev. B **69**, 125323 (2004).
[11] B. Krummheuer, V. M. Axt, and T. Kuhn, Phys. Rev. B **72**, 245336 (2005).
[12] P. Zanardi and F. Rossi, Phys. Rev. B **59**, 8170 (1999).
[13] A. Grodecka and P. Machnikowski, Phys. Rev. B **73**, 125306 (2006).
[14] B. Misra and E. C. G. Sudarshan, J. Math. Phys. **18**, 756 (1977).
[15] S. Gurvitz, Quantum Information Processing **2**, 15 (2003).
[16] S. A. Gurvitz, Phys. Rev. B **56**, 15215 (1997).
[17] G. S. Agarwal and S. P. Tewari, Physics Letters A **185**, 139 (1994).
[18] G. S. Agarwal, M. O. Scully, and H. Walther, Phys. Rev. Lett. **86**, 4271 (2001).
[19] A. G. Kofman and G. Kurizki, Phys. Rev. A **54**, R3750 (1996).
[20] A. Grodecka, L. Jacak, P. Machnikowski, and K. Roszak, in *Quantum Dots: Research Developments*, edited by P. A. Ling (Nova Science, NY, 2005), p. 47.
[21] K. Roszak, P. Horodecki, and R. Horodecki, Phys. Rev. A **81**, 042308 (2010).
[22] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, 2000).
[23] G. D. Mahan, *Many-Particle Physics* (Kluwer, New York, 2000).
[24] T. Novotný, A. Rossini, and K. Flensberg, Phys. Rev. B **72**, 224502 (2005).