Comparison of decoherence and Zeno dynamics from the context of weak measurement for a two level atom tunneling through squeezed vacuum

Samyadeb Bhattacharya

\textsuperscript{1} Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata 700 108, India

Decay parameter of coherence and population inversion are calculated from the master equation of a two level atom tunneling through a squeezed vacuum. Using those parameters, the timescales for decoherence and zeno effect are calculated in the weak measurement scheme. By comparing those timescales, a certain condition has been found for sustainable coherent dynamics.

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\section{I. INTRODUCTION}

The ability to preserve coherence in a quantum mechanical system is of fundamental importance from the point of view of quantum computation and various other aspects. In practical scenario, quantum systems are sensitive to environmental interactions, which leads to the destruction of coherence. According to the standard theory of quantum measurement, each measurement attempt results in a projection of the state vector to a particular eigenstate corresponding to the eigenvalue of the observable which has been measured. In this very process, the phase relations between different states are destroyed. In other words, the non-diagonal elements of the density matrix, which represents the quantum mechanical coherence, are destroyed. This process is known as the process of “Decoherence” \cite{1}. From the point of view of both theoretical and experimental research, the methods of developing decoherence free subspaces to minimize the destruction of coherent dynamics is extremely important. For example, the spin echo, multiple pulse techniques in NMR \cite{2} and the method of dynamical decoupling for open quantum systems \cite{4,5} are some of the examples of tools for controlling decoherence. Zeno dynamics \cite{6,7} can play a very important role in controlling decoherence. Quantum Zeno effect is the inhibition of transition for decaying states due to the process of frequent observations. The short-time behavior of non-decay probability of unstable particle is shown to be quadratic, not exponential. Wilkinson et al. \cite{8} observed this deviation from the usual quantum mechanical process for decay of unstable states. Misra and Sudarshan \cite{6} showed that this behavior, if combined with the quantum theory of measurement, will lead us to the surprising conclusion of freezing of decay dynamics due to frequent non-selective measurements. Here we intend to discuss the process of coherence control by repetitive measurement and infer the possibility of Zeno dynamics playing an important role in sustaining the quantum coherence of the system. We will consider a two level atom tunneling through a squeezed vacuum of electromagnetic field. External electromagnetic fields play the role of reservoir in open quantum systems. It is possible for squeezed vacuums to assume the role of the reservoir \cite{10,12}. Though the properties of such kind of reservoirs are very much different. It is quite well known that, squeezed vacuum can have considerable effects on quantum dissipative processes \cite{13}. Particularly, when a two-state atomic system interacts with a broadband squeezed vacuum, the transverse polarization quadratures exhibit decay processes, though different from the usual quantum decays \cite{10}. Our aim is to investigate the decay dynamics of the system based on the framework of weak measurement \cite{14,16}. The weak value of a certain observable is the statistical average of a standard measurement procedure performed on a pre selected and post selected (PPS) ensemble of quantum
systems, given that the interaction between the measurement apparatus (or the interacting field) and each system is sufficiently weak. In our case, we interpret measurement as the interaction between the two level atomic system and the squeezed electromagnetic field. Unlike standard measurement of an observable, which sufficiently disturbs the measurement system, a weak measurement of a quantum mechanical observable done on a FPS system does not appreciably disturb the system and yields the weak value as the measured value of the observable. Since each interaction of the field or apparatus with the system is weak, any single measurement does not contain sufficient information about the system. Only an ensemble average number over such interactions can give us some meaningful results. So in our case, we consider numerous interactions of the squeezed field and the two level atom to infer the decay dynamics. By decay dynamics we mean both the decay of pre-selected state and the coherence destruction. In order to do that, we will consider the time dependent weak value of of certain operator as described by Davies [17]. Based on [17], where a generalized decay law for metastable states has been derived, we will calculate the timescales for both Zeno dynamics and coherence destruction. By comparing those timescales, we will derive certain condition for sustainable quantum coherence. In section II we will discuss the master equation for the two level atom tunneling through a squeezed vacuum and find the decay parameters related to state decay and decoherence. In Section III we will derive the weak values of the mentioned timescales and compare them to find the condition for sustainable coherence. After that we will conclude in section IV with some possible implications.

II. MASTER EQUATION FOR TWO LEVEL ATOM TUNNELING THROUGH A SQUEEZED VACUUM

Let us now consider the master equation for the two level atom tunneling through a squeezed vacuum and calculate the decay constants in terms of system and bath parameters. A very important fundamental property of squeezed states is that they reduce quantum fluctuations. The squeezing effect of electromagnetic fields has been studied by many researchers in the field of quantum optics [18–21] over the past years. Here we will follow the work of Tanasić [22], where the problem of two state system tunneling through a squeezed vacuum is dealt in the master equation approach. The total Hamiltonian of the system and reservoir can be defined as

\[ H_T = H_s + H_{em} + H_{int} \]  

(2.1)

where \( H_s, H_{em} \) and \( H_{int} \) are respectively the Hamiltonian for the system, reservoir and the interaction between them. They can be described as

\[
\begin{align*}
H_s &= \frac{1}{2} \hbar \Omega \sigma_z \\
H_{em} &= \hbar \int_0^\infty d\omega \omega b^\dagger(\omega) b(\omega) \\
H_{int} &= \hbar \int_0^\infty K(\omega)[b^\dagger(\omega)\sigma^- - b(\omega)\sigma^+]d\omega
\end{align*}
\]  

(2.2)

where \( b^\dagger(\omega) \) and \( b(\omega) \) are the creation and annihilation operators for the field, which is assumed as a collection of harmonic oscillators. Their correlation functions can be given by

\[
\begin{align*}
\langle b(t) \rangle &= \langle b^\dagger(t) \rangle = 0, \langle b^\dagger(t)b(t') \rangle = N\delta(t-t') \\
\langle b(t)b^\dagger(t') \rangle &= (N+1)\delta(t-t') \\
\langle b^\dagger(t)b(t') \rangle &= M e^{-\Delta t(t+t')}\delta(t-t') \\
\langle b^\dagger(t)b^\dagger(t') \rangle &= M^* e^{\Delta t(t+t')}\delta(t-t')
\end{align*}
\]  

(2.3)

The functions \( N(\omega) \) and \( |M(\omega)| \) are given by

\[
\begin{align*}
N(\omega) &= \frac{\lambda^2 - \mu^2}{4} \left[ \frac{1}{\sigma + \lambda^2} - \frac{1}{\sigma + \mu^2} \right] \\
|M(\omega)| &= \frac{1}{2} \left[ \frac{1}{\sigma + \mu^2} + \frac{1}{\sigma + \lambda^2} \right]
\end{align*}
\]  

(2.4)

\( x = \omega - \omega_L \) is the shift from the original laser frequency \( \omega_L \). \( \lambda \) and \( \mu \) are functions in relation to the cavity damping rate \( \gamma \) and amplification coefficient \( \epsilon \).

\[
\lambda = \gamma + \epsilon, \quad \mu = \gamma - \epsilon
\]  

(2.5)

and \( M = |M| e^{i\phi} \). \( \phi \) is considered as the phase of squeezing. The cavity dissipation constant \( \gamma \) is related to the coupling constant \( (K(\omega)) \) by \( \gamma = 2\pi K(\Omega)^2 \) [21]. The resulting master equation is formulated as

\[
\dot{\rho} = \frac{i}{\hbar}[\rho, H] + \frac{1}{2} \left[ \frac{1}{\hbar^2} \left( \Delta^2 - 1 \right) Re \Upsilon - \Delta^2 \delta \right]
\]  

(2.6)

where

\[
\begin{align*}
\tilde{N} &= N(\omega_L + \Omega') - \frac{1}{2} \left( 1 - \Delta^2 \right) Re \Upsilon_- \\
\tilde{M} &= M(\omega_L + \Omega') - \frac{1}{2} \left( 1 - \Delta^2 \right) Re \Upsilon_- + i \Delta \delta M e^{i\phi}
\end{align*}
\]  

(2.7)

(2.8)

\[
\Upsilon = N(\omega_L) - N(\omega_L + \Omega') - |M(\omega_L)| - |M(\omega_L + \Omega')| e^{i\phi}
\]  

(2.9)

\[
\delta = \frac{\Delta}{\gamma} - \frac{1}{2} \left( 1 - \Delta^2 \right) Im \Upsilon_- + 2 \Delta \delta N
\]  

(2.10)

\[
\beta = \gamma \bar{M} \left[ \delta_N + \Delta \delta M e^{i\phi} - i \Delta \Upsilon_- \right]
\]  

(2.11)
\[ \Omega' = \sqrt{\Omega^2 + \Delta^2}, \quad \tilde{\Omega} = \frac{\Omega}{\Omega'}, \quad \tilde{\Delta} = \frac{\Delta}{\Omega'} \]  

(2.12)

\( \Omega \) is the Rabi frequency. The detuning of the laser field is given by \( \Delta = \omega_L - \omega_A \). \( \omega_L \) and \( \omega_A \) are respectively the laser and atomic frequency. \( \delta_N \) and \( \delta_M \) are the shifts induced due to squeezing. \( M = |M|e^{i\phi} \), where \( \phi \) is the squeezing angle. From the master equation [22] we can get

\[ \langle \dot{\sigma}_- \rangle = -\gamma \left( \frac{1}{2} + \tilde{N} - i\delta \right) \langle \sigma_- \rangle - \gamma \tilde{M} \langle \sigma_+ \rangle + \frac{i}{2} \Omega \langle \sigma_z \rangle \\
\langle \dot{\sigma}_z \rangle = i(\Omega + \beta^*) \langle \sigma_- \rangle - i(\Omega + \beta) \langle \sigma_+ \rangle - \gamma \langle 1 + 2\tilde{N} \rangle \langle \sigma_\gamma \rangle - \gamma 
\]

(2.13)

Equation for \( \langle \dot{\sigma}_+ \rangle \) is the hermitian conjugate of the equation for \( \langle \dot{\sigma}_- \rangle \). So from [2.13] we get

\[ \frac{d}{dt} \langle \sigma_+ + \sigma_- \rangle = -\gamma \left( \frac{1}{2} + \tilde{N} + \tilde{M}^* - i\delta \right) \langle \sigma_- \rangle \\
- \gamma \langle \frac{1}{2} + \tilde{N} + \tilde{M} + i\delta \rangle \langle \sigma_+ \rangle 
\]

(2.14)

From [2.14] we can get the decay rate of \( \langle \sigma_+ + \sigma_- \rangle \) as

\[ \Gamma_{\text{dec}} = \gamma \left( \frac{1}{2} + \tilde{N} + Re \tilde{M} \right) \]  

(2.15)

We interpret this decay parameter as the decay constant associated to the destruction of coherence. \( \sigma_\pm \) operators represent the switching of both the states from one to another. This is only possible if the system is in superposition of both the available states. Decay of the ensemble average of \( \sigma_z \) means the decay of quantum superposition; i.e. the destruction of coherence. Similarly from [2.13] we can get the decay constant for pre-selected \( \sigma_z \) state as

\[ \Gamma_{\text{pop}} = \gamma \left( 1 + 2\tilde{N} \right) \]  

(2.16)

This parameter represents the population inversion from the initial pre-selected state to the other. We will use these parameters to get the weak value of decoherence and zeno timescales in the next section.

**III. WEAK VALUE OF DECOHERENCE TIME AND ZENO TIME**

Now we are going to calculate the timescales associated to the processes of coherence destruction (decoherence) and freezing of state decay by frequent non-selective measurements (zeno effect) in the weak measurement framework. The reason behind using this particular framework is that in our consideration the interaction between the squeezed electromagnetic field and the system is sufficiently weak. So one single measurement or interaction on the system does not give any significant result; or in other words does not disturb the system in a considerable way. So numerous such interactions are taken into account to get an ensemble average for some quantum observable. We will use the framework originally developed by Davies [17] to find the weak value for the decay law of metastable states.

Let us now consider the time evolution for the state of the system

\[ |\psi(t)\rangle = U(t - t_0)|\psi(t_0)\rangle \]  

(3.1)

where the time evolution operator is given by

\[ U(t - t_0) = e^{-iH(t-t_0)} \]  

(3.2)

The time dependent weak value of some operator \( A \) pre-selected at time \( t_i \) and post selected at \( t_f \) can be expressed as

\[ A_w = \frac{\langle \psi_f |U^\dagger(t - t_f)AU(t - t_i)|\psi_i\rangle}{\langle \psi_f |U^\dagger(t - t_f)U(t - t_i)|\psi_i\rangle} \]  

(3.3)

Considering a two level atom in an external magnetic field \( B \), we get the Hamiltonian of the system as

\[ H_s = -\mu \cdot B \]  

(3.4)

where

\[ \mu = \frac{e\hbar S}{2m} \]  

(3.5)

and

\[ S = (\sigma_x, \sigma_y, \sigma_z) \]  

(3.6)

\( \sigma_{i=x,y,z} \) are the usual Pauli spin matrices. If we consider that the magnetic field is in the z-direction, the system Hamiltonian reduces to

\[ H_s = \frac{1}{2}\hbar \Omega \sigma_z \]  

(3.7)

The time evolution operator for the system

\[ U(t) = \begin{pmatrix} e^{i\Omega t/2} & 0 \\ 0 & e^{-i\Omega t/2} \end{pmatrix} \]  

(3.8)

Let us now consider that at initial time \( t_i \) the particle is x-polarized. Then we get

\[ |\psi_i\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \]  

(3.9)

The associated projection operator

\[ P_+ = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \]  

(3.10)

In case of the decay of metastable states, let us consider the system is coupled to a bath of \( 2N \) number of environmental modes initially in their ground states. In presence of the interaction with the environmental bath modes, the system is viable to lose energy to the bath modes. Let us consider for simplicity that the ground states of
all the modes coincides to be zero and the excited state $E_n$ satisfies the relation

$$E_n - E_0 = n\Delta E, \quad -N \leq n \leq N \quad (3.11)$$

It is assumed that the reference atom is equally coupled to all the bath modes. The coupled differential equations describing the decay dynamics are given by

$$a_0 = -\frac{i}{\hbar} \sum_n H a_n e^{-in\Delta Et/\hbar} \quad (3.12)$$

$$\dot{a}_n = -\frac{i}{\hbar} H a_0 e^{in\Delta Et/\hbar} \quad (3.13)$$

$a_0$ and $a_n$ are the amplitudes of the initial pre-selected state and other excited states respectively. Following [17], we find

$$a_0(t) = e^{-\Gamma(t-t_i)} \quad (3.14)$$

where $\Gamma$ is the decay parameter. The time evolution operator $U(t)$ is a $(2N+1) \times (2N+1)$ dimensional matrix, whose components can be calculated from 3.12 and 3.13 as

$$U_{00} = e^{-\Gamma t} \quad (3.15)$$

$$U_{n0} = iH \left[ e^{-\Gamma t + in\Delta Et/\hbar} - 1 \right] / (\Gamma - in\Delta E) \quad (3.16)$$

within the limit $\Delta E \to 0$. Under the relation $U^\dagger(t) = U(-t)$ the time dependent weak value of some operator $A$

$$A_w = \frac{\langle \psi_f | U(t_f-t)AU(t-t_i) | \psi_i \rangle}{\langle \psi_f | U(t_f-t_i) | \psi_i \rangle} \quad (3.17)$$

Now for our purpose of getting the weak value of survival probability, we take the operator $A$ as the projection operator $P_+$. Let us assume that the post selected final state at $t_f$ be

$$|\psi_f\rangle = |\psi_k\rangle \quad (3.18)$$

So the weak value of the projection operator gives

$$P_w = \frac{U_{k0}(t_f-t)U_{00}(t-t_i)}{U_{k0}(t_f-t_i)} \quad (3.19)$$

By using the matrix elements of the time evolution operator given by 3.15 and 3.16 we get that

$$P_w = e^{-\Gamma(t-t_i)} \left[ 1 - e^{-\Gamma(t_f-t_i) + ik\Delta E(t_f-t)} / [1 - e^{-\Gamma(t_f-t_i) + ik\Delta E(t_f-t_i)}] \right] \quad (3.20)$$

We want to get expression for the weak value of the survival probability for the pre-selected state. So choosing $E_k = E_0$ we get the simple expression

$$P_w = e^{-\Gamma(t-t_i)} \left[ 1 - e^{-\Gamma(t_f-t)} / [1 - e^{-\Gamma(t_f-t_i)}] \right] \quad (3.21)$$

$\tau_M = t_f - t_i$ is taken as the the measurement time. This time interval is nothing but the interval between two successive interaction with the field. Now we get the decay time by integrating over the weak survival probability

$$\tau_{decay} = \int_{t_i}^{t_f} e^{-\Gamma(t-t_i)} \left[ 1 - e^{-\Gamma(t_f-t)} / [1 - e^{-\Gamma(t_f-t_i)}] \right] dt \quad (3.22)$$

The amplitude of the squeezed field varies with its frequency $\omega_L$. The amplitude of the field becomes maximum after this interval. So this time period equaling to the inverse of $\omega_L$ can also be interpreted as the time period of maximum interaction. Therefore we infer that the measurement time is equal to the inverse of $\omega_L$. Again here we are considering the Zeno dynamics; i.e. frequent observation. So the measurement time is considered to be quite small. So under the assumption $\tau_M \ll 1/\Gamma$, from 3.22 we get the decay time

$$\tau_{decay} = \frac{1}{\Gamma + 2\omega_L} \quad (3.23)$$

Here we have taken $\tau_M = 1/\omega_L$. Now putting the coherence decay parameter $\Gamma_{dec}$ from 2.15 of the previous section in 3.23 we get the weak value of decoherence time as

$$\tau_{dec} = \frac{1}{\gamma \left( \frac{1}{2} + \tilde{\cal N} + Re \tilde{\cal M} \right) + 2\omega_L} \quad (3.24)$$

This is the timescale within which the system loses it’s coherence; i.e. the non-diagonal components of the reduced density matrix of the system vanishes. Now we turn our attention to calculate the Zeno time for the concerning system. As we have mentioned earlier, the quantum zeno effect is the inhibition of transition of metastable states under frequent observation. So the timescale for Zeno effect is the timescale within which the system stays in it’s initial state. We can get the weak value of this particular timescale by putting the expression of state decay parameter from 2.16 in 3.23 as

$$\tau_{zeno} = \frac{1}{\gamma \left( \frac{1}{2} + 2\tilde{\cal N} \right) + 2\omega_L} \quad (3.25)$$

In our understanding, the dynamics of decoherence and Zeno effect has got an intrinsic reciprocal relation. Let us elaborate the reason behind this statement. Whenever any kind of disturbance in the form of interaction dominates the time evolution of the state, the concerning system evolves in a reduced subspace of the total Hilbert space [23]. This reduced subspace is known as “Zeno subspace”. The appearance of these kind of subspaces is caused by frequent non-selective measurement. Frequent measurements splits the total Hilbert space into these subspaces, within which leakage of probability is not possible. So it can be argued that each of these reduced subspaces acts like an isolated space, within which environmental interaction is absent, or at least minimum.
Under very strong environmental interaction, these subspaces cannot be sustained due to extreme decoherence. So it is our inference that the timescale characterizing Zeno effect must give a certain lower limit to decoherence, below which the process of decoherence is very fast and uncontrollable. So to control the process of decoherence by means of frequent non-selective measurement, we must state a precondition that the decoherence time must be greater than the zeno time for the system. Comparing (3.24) and (3.25) we get
\[ \frac{\tau_{\text{zeno}}}{\tau_{\text{dec}}} = \frac{1}{2} + \frac{2\gamma \Re \tilde{M} + \omega L}{\gamma (1 + 2N) + 2\omega L} \quad (3.26) \]
As per our argument given above: \( \tau_{\text{dec}} \geq \tau_{\text{zeno}} \). Under this condition sustainable coherent dynamics is possible. Imposing this condition on (3.26) we get
\[ 4\Re \tilde{M} \leq (1 + 2N) \quad (3.27) \]
From (3.27) we can calculate further to get
\[ \sqrt{\frac{\Delta^2 \delta_M^2 + |M(\omega_L + \Omega')|^2 \sin(\theta - \phi)}{1 + 2N(\omega_L + \Omega') + 3(1 - \tilde{\delta}^2)\Re \tilde{M}}} \leq \frac{1}{4} \quad (3.28) \]
where
\[ \tan \theta = \frac{|M(\omega_L + \Omega')|}{\Delta \delta_M} \quad (3.29) \]
A special case of squeezing phase (24) can be set as
\[ \phi(\Delta) = \frac{\pi \Delta}{\Omega} \quad (3.30) \]
So the condition (3.28) will surely hold if \( \theta \to \phi \). In our consideration, the cavity damping constant (\( \gamma \)) and the real amplification constant (\( \epsilon \)) are small compared to the Rabi frequency (\( \Omega \)). So \( \Omega \gg \mu, \lambda \). Under this condition, using the expressions of \( \delta_M \) from [22], we find that
\[ \tan \theta = \frac{1 - \mu \lambda}{\Omega \Delta (\mu + \lambda)} = \frac{\gamma^2 - \epsilon^2}{2\Delta \gamma} \quad (3.31) \]
So the sufficient condition for Zeno effect to dominate over decoherence can be stated as
\[ \frac{\gamma^2 - \epsilon^2}{2\gamma} \to \Delta \tan \left( \frac{\pi \Delta}{\Omega} \right) \quad (3.32) \]
For a special case, if \( \Delta \ll \Omega \), we find that the condition will hold if \( \gamma \sim \epsilon \), i.e. for the case where the shift of laser and atomic frequency is very small compared to the Rabi frequency and for small dissipation, the Zeno dynamics will dominate over the decoherence dynamics, if the real amplification constant is comparable in magnitude to the cavity dissipation parameter. Under this condition, sustainable coherent dynamics can be achieved.

**IV. CONCLUSION**

In this work, we have done a comparison between decoherence and Zeno dynamics in the framework of weak measurement. The weak value of decoherence time and Zeno time has been calculated and compared. Based on the assertion that decoherence time must be longer than Zeno time for the Zeno effect to dominate over decoherence, we found a certain condition under which we can have sustainable coherent dynamics. Here we have considered the system of a two level atom tunneling through a squeezed vacuum. These type of systems are used to develop optical ion traps, which are important components for developing quantum memory devices. But the challenge for building quantum memory devices is that of controlling decoherence effect to sustain the “quanthmness” of the system. In this work, we have shown that Zeno dynamics can be an effective process to control such environmental effects. The reason behind using the weak measurement framework is also necessary to mention here. In this type of measurement scheme, the interaction between the system and the measuring device (in our case the squeezed field) is made very small. This is a good way to minimize the environmental interaction, which is in turn helpful for reducing the effect of decoherence. Another important feature of weak measurement process is that, here we take an ensemble average of numerous observations over the pre-selected and post-selected states, because one single measurement interaction cannot bring out enough information about the system. Since the Zeno dynamics is initiated by frequent observations, an ensemble average over many such observations is necessary to observe the dynamics over a finite period of time. So weak measurement scheme is also very much compatible with the Zeno type measurement procedure. Now we have mentioned earlier that controlling decoherence dynamics is essential to build quantum memory devices. As we have shown in this work that this type of effect can be minimized using certain procedures like frequent non-selective measurement and weak measurement scheme, but effectively it cannot be eradicated completely. So it is important to construct the quantum computational schemes in the backdrop of open quantum systems. Considering these facts, we intend to extend our formalism to the area of adiabatic quantum computation in forthcoming publications.

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