## Entanglement dynamics of non-inertial observers in a correlated environment

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Effect of decoherence and correlated noise on the entanglement of X-type state of the Dirac fields in the non-inertial frame is investigated. A two qubit X-state is considered to be shared between the partners where Alice is in inertial frame and Rob in an accelerated frame. The concurrence is used to quantify the entanglement of the X-state system influenced by time correlated amplitude damping, depolarizing and bit flip channels. It is seen that amplitude damping and bit flip channels heavily influence the entanglement of the system as compared to the depolarizing channel. It is found possible to avoid entanglement sudden death (ESD) for all the channels under consideration for  $\mu > 0.75$  for any type of initial state. No ESD behaviour is seen for depolarizing channel in the presence of correlated noise for entire range of decoherence parameter p and Rob's acceleration r. It is also seen that the effect of environment is much stronger than that of acceleration of the accelerated partner. Furthermore, it is investigated that correlated noise compensates the loss of entanglement caused by the Unruh effect.

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### I. INTRODUCTION

Quantum entanglement is the major resource in quantum information science and can be used as a potential source for quantum teleportation of unknown states [1], quantum key distribution [2], quantum cryptography [3] and quantum computation [4, 5]. Entanglement sudden death for bipartite and multipartite systems has been the main focus of researchers during recent years [6-11]. Another important feature, entanglement sudden birth (ESB) has also been investigated where the initially unentangled qubits can be entangled after a finite evolution of time [12-13]. Recently, entanglement behavior in non-inertial frames was investigated by Alsing et al. [14]. They studied the fidelity of teleportation between relative accelerated partners. Quantum information in a relativistic setup has become an interesting topic of research during recent years [15-27].

Since, quantum systems are influenced by their environment that may results in the non-unitary dynamics of the system. Therefore, the environmental effect on a quantum system gives rise to the

phenomenon of decoherence that causes an irreversible transfer of information from the system to the environment [28-29]. Study of decoherence in non-inertial frames have been investigated for bipartite and multipartite systems by number of authors [30-33], where it is shown that entanglement is degraded by the acceleration of the inertial observers. Recently, a qubit-qutrit system in non-inertial frames has been analyzed under decoherence [34], where it is shown that ESB does occur in case of depolarizing channel. On the other hand, quantum channels with memory [35-39] provide a natural theoretical framework for the study of any noisy quantum communication. The main focus of this work is to study the entanglement dynamics in the presence of correlated noise as it has not been studied yet in non-inertial frames.

In this paper, decoherence and correlated noise effects are investigated for X-type states in non-inertial frames by considering using amplitude damping, depolarizing and bit flip channels. The two observers Alice and Rob share an X-type state in non-inertial frames. Alice is considered to be stationary whereas Rob moves with a uniform acceleration. Two important features of entanglement, ESD and ESB are investigated. No ESD occurs in case of depolarizing channel in the presence of correlated noise.

# II. OPEN SYSTEM DYNAMICS OF NON-INERTIAL OBSERVERS UNDER CORRELATED NOISE

The evolution of a system and its environment can be described by

$$U_{SE}(\rho_S \otimes |0\rangle_E \langle 0|) U_{SE}^{\dagger} \tag{1}$$

where  $U_{SE}$  represents the evolution operator for the combined system and  $|0\rangle_E$  corresponds to the initial state of the environment. By taking trace over the environmental degrees of freedom, the evolution of the system can be obtained as

$$L(\rho_S) = \operatorname{Tr}_E \{ U_{SE}(\rho_S \otimes |0\rangle_E \langle 0|) U_{SE}^{\dagger} \}$$
  
=  $\sum_{\mu} E \langle \mu | U_{SE} |0\rangle_E \rho_{SE} \langle 0| U_{SE}^{\dagger} | \mu \rangle_E$  (2)

where  $|\mu\rangle_E$  represents the orthogonal basis of the environment and L is the operator describing the evolution of the system. The above equation can also be written as

$$L(\rho_S) = \sum_{\mu} M_{\mu} \rho_S M_{\mu}^{\dagger} \tag{3}$$

where  $M_{\mu} = E \langle \mu | U_{SE} | 0 \rangle_E$  are the Kraus operators as given in Ref. [40]. The Kraus operators satisfy the completeness relation

$$\sum_{\mu} M_{\mu}^{\dagger} M_{\mu} = 1 \tag{4}$$

The decoherence process can also be represented by a map in terms of the complete systemenvironment state. The dynamics of a d-dimensional quantum system can be represented by the following map [41]

$$U_{SE}|\xi_l\rangle_S \otimes |0\rangle_E = \sum_k M_k |\xi_l\rangle_S \otimes |k\rangle_E \tag{5}$$

where  $\{|\xi_l\rangle_S\}~(l=1,....,d)$  is the complete basis for the system and

$$\begin{aligned} |\xi_1\rangle_S \otimes |0\rangle_E &\to M_0 |\xi_1\rangle_S \otimes |0\rangle_E + \dots + M_{d^2 - 1} |\xi_1\rangle_S \otimes |d^2 - 1\rangle_E \\ |\xi_2\rangle_S \otimes |0\rangle_E &\to M_0 |\xi_2\rangle_S \otimes |0\rangle_E + \dots + M_{d^2 - 1} |\xi_2\rangle_S \otimes |d^2 - 1\rangle_E \end{aligned}$$

$$|\xi_d\rangle_S \otimes |0\rangle_E \to M_0 |\xi_d\rangle_S \otimes |0\rangle_E + \dots + M_{d^2 - 1} |\xi_d\rangle_S \otimes |d^2 - 1\rangle_E \tag{6}$$

Let Alice and Rob (the accelerated observer) share the following X-type initial state

$$\rho_{AR} = \frac{1}{4} \left( I_{AR} + \sum_{i=0}^{3} c_i \sigma_i^{(A)} \otimes \sigma_i^{(R)} \right) \tag{7}$$

where  $I_{AR}$  is the identity operator in a two-qubit Hilbert space,  $\sigma_i^{(A)}$  and  $\sigma_i^{(R)}$  are the Pauli operators of the Alice's and Rob's qubit and  $c_i$   $(0 \le |c_i| \le 1)$  are real numbers satisfying the unit trace and positivity conditions of the density operator  $\rho_{AR}$ . In order to study the entanglement dynamics, different cases for initial state are considered, for example, the general initial state  $(|c_1| = 0.7, |c_2| = 0.9, |c_3| = 0.4)$ , the Werner initial state  $(|c_1| = |c_2| = |c_3| = 0.8)$ , and Bell basis state  $(|c_1| = |c_2| = |c_3| = 1)$ .

Let the Dirac fields, as shown in Refs. [42, 43], from an inertial perspective, can be described by a superposition of Unruh monochromatic modes  $|0_U\rangle = \bigotimes_{\omega} |0_{\omega}\rangle_U$  and  $|1_U\rangle = \bigotimes_{\omega} |1_{\omega}\rangle_U$  with

$$|0_{\omega}\rangle_{U} = \cos r |0_{\omega}\rangle_{I} |0_{\omega}\rangle_{II} + \sin r |1_{\omega}\rangle_{I} |1_{\omega}\rangle_{II}$$
(8)

and

$$|1_{\omega}\rangle_M = |1_{\omega}\rangle_I |0_{\omega}\rangle_{II} \tag{9}$$

where  $\cos r = (e^{-2\pi\omega c/a} + 1)^{-1/2}$ , *a* is the acceleration of the observer,  $\omega$  is frequency of the Dirac particle and *c* is the speed of light in vacuum. The subscripts *I* and *II* of the kets represent the Rindler modes in region *I* and *II*, respectively, as shown in the Rindler spacetime diagram (see Ref. [31], Fig. (1)). By using equations (8) and (9), equation (7) can be re-written in terms of Minkowski modes for Alice (*A*) and Rindler modes for Rob ( $\tilde{R}$ ). The single-mode approximation is used in this study, i.e. a plane wave Minkowski mode is assumed to be the same as a plane wave Unruh mode (superposition of Minkowski plane waves with single-mode transformation to Rindler modes). Therefore, Alice being an inertial observer while her partner Rob who is in uniform acceleration, are considered to carry their detectors sensitive to the  $\omega$  mode. To study the entanglement in the state from their perspective one must transform the Unruh modes to Rindler modes. Hence, Unruh states must be transformed into the Rindler basis. Let Rob detects a single Unruh mode and Alice detects a monochromatic Minkowski mode of the Dirac field. Considering that an accelerated observer in Rindler region *I* has no access to the field modes in the causally disconnected region *II* and by taking the trace over the inaccessible modes, one obtains the following density matrix

$$\rho_{A\tilde{R}} = \frac{1}{4} \begin{pmatrix} (1+c_3)\cos^2 r & 0 \\ 0 & (1+c_3)\sin^2 r + (1-c_3) \\ 0 & c^+ \cos r \\ c^- \cos r & 0 \\ 0 & c^- \cos r \\ c^+ \cos r & 0 \\ (1-c_3)\cos^2 r & 0 \\ 0 & (1-c_3) + (1+c_3)\sin^2 r \end{pmatrix}$$
(10)

where  $c^+ = c_1 + c_2$  and  $c^- = c_1 - c_2$ .

Since noise is a major hurdle while transmitting quantum information from one party to other through classical and quantum channels. This noise causes a distortion of the information sent through the channel. It is considered that the system is strongly correlated quantum system, the correlation of which results from the memory of the channel itself. The action of a Pauli channel with partial memory on a two qubit state can be written in Kraus operator formalism as [35]

$$A_{ij} = \sqrt{p_i[(1-\mu)p_j + \mu\delta_{ij}]}\sigma_i \otimes \sigma_j \tag{11}$$

where  $\sigma_i$  ( $\sigma_j$ ) are usual Pauli matrices,  $p_i$  ( $p_j$ ) represent the decoherence parameter and indices *i* and *j* runs from 0 to 3. The above expression means that with probability  $\mu$  the channel acts on the

second qubit with the same error operator as on the first qubit, and with probability  $(1 - \mu)$  it acts on the second qubit independently. Physically the parameter  $\mu$  is determined by the relaxation time of the channel when a qubit passes through it. The action of a two qubit Pauli channel when both the qubits of Alice and Rob are streamed through it, can be described in operator sum representation as [46]

$$\rho_f = \sum_{k_1, \ k_2 = 0}^{1} (A_{k_2} \otimes A_{k_1}) \rho_{in} (A_{k_1}^{\dagger} \otimes A_{k_2}^{\dagger})$$
(12)

where  $\rho_{in}$  represents the initial density matrix for quantum state and  $A_{k_i}$  are the Kraus operators as expressed in equation (11). A detailed list of single qubit Kraus operators for different quantum channels with uncorrelated noise is given in table 1. Whereas, the Kraus operators for amplitude damping channel with correlated noise are given by Yeo and Skeen [36]

where,  $0 \leq \chi \leq \pi/2$  and is related to the quantum noise parameter as

$$\sin\chi = \sqrt{p} \tag{14}$$

The action of such a channel with memory can be written as

$$\pi \to \rho = \Phi(\pi) = (1 - \mu) \sum_{i,j=0}^{1} A^{u}_{ij} \pi A^{u\dagger}_{ij} + \mu \sum_{k=0}^{1} A^{c}_{kk} \pi A^{c\dagger}_{kk}$$
(15)

where the superscripts u and c represent the uncorrelated and correlated parts respectively. The Kraus operators are of dimension  $2^2$  and are constructed from single qubit Kraus operators by taking their tensor product over all  $n^2$  combinations

$$A_k = \underset{k_i}{\otimes} A_{k_i} \tag{16}$$

where i is the number of Kraus operator for a single qubit channel. The final state of the system after the action of the channel can be obtained as

$$\rho_f = \Phi_{p,\mu}(\rho_{A,I}) \tag{17}$$

where  $\Phi_{p,\mu}$  is the super-operator realizing the quantum channel parametrized by real numbers p and  $\mu$ . Since, the entanglement dynamics of the bipartite subsystems (especially the systemenvironment dynamics) is of interest here, therefore, only bipartite reduced matrices are considered. It is assumed that both Alice and Rob's qubits are influenced by the time correlated environment. The entanglement of a two-qubit mixed state  $\rho$  in a noisy environment can be quantified by the concurrence as defined by [45]

$$C(\rho) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\}, \quad \lambda_i \ge \lambda_{i+1} \ge 0$$
(18)

where  $\lambda_i$  are the square roots of the eigenvalues of the matrix  $\rho_f \tilde{\rho}_f$ , with  $\tilde{\rho}_f$  being the spin flip matrix of  $\rho_f$  and is given by

$$\tilde{\rho}_f = (\sigma_y \otimes \sigma_y) \rho_f(\sigma_y \otimes \sigma_y) \tag{19}$$

where  $\sigma_y$  is the usual Pauli matrix. Since the density matrix under consideration has X-type structure, therefore a simpler expression for the concurrence [46] can be used

$$C(\rho) = 2\max\{0, \tilde{C}_1(\rho), \tilde{C}_2(\rho)\}$$
(20)

where  $\tilde{C}_1(\rho) = \sqrt{\rho_{14}\rho_{41}} - \sqrt{\rho_{22}\rho_{33}}$  and  $\tilde{C}_2(\rho) = \sqrt{\rho_{23}\rho_{32}} - \sqrt{\rho_{11}\rho_{44}}$ . The reduced-density matrix of the inertial subsystem A and the non-inertial subsystem  $\tilde{R}$ , can be obtained by taking the partial trace of  $\rho_{A\tilde{R}E_AE_{\tilde{R}}} = \rho_{A\tilde{R}} \otimes \rho_{A\tilde{R}E_AE_{\tilde{R}}}$  over the degrees of freedom of the environment i.e.

$$\rho_{A\tilde{R}} = \text{Tr}_{E_A E_{\tilde{R}}} \{ \rho_{A\tilde{R}E_A E_{\tilde{R}}} \}$$
(21)

which yields the concurrence for the X-state structure using equation (20), under amplitude damping channel as

$$C^{\rm AD}(\rho) = \frac{1}{8} \begin{pmatrix} 2\sqrt{c^{+2}(p(\mu-1)+1)^2\cos^2(r)} \\ \left( 2(c_3+1)p\mu\cos^2(r) + ((p-2)p(\mu-1)-1)\times \\ (c_3+(c_3+1)\cos(2r)-3) \end{pmatrix} \times \\ \left( (p+1)(\mu-1)(c_3(p-1) + (c_3+1)\cos(2r)(p-1)) \\ -3p-1) - 2(c_3+1)(p-1)\mu\cos^2(r) \end{pmatrix} \end{pmatrix}$$
(22)

The concurrence of X-state system in case of depolarizing channel becomes

$$C^{\text{Dep}}(\rho) = \frac{1}{16} \begin{pmatrix} -\cos^{2}(r) \begin{pmatrix} (c_{3}+1)p(c^{-}\mu+c^{+}(-4p + (4p-7)\mu+4))\cos^{2}(r) - 2c^{+}(p(\mu-2)+4) \end{pmatrix} \times \\ (c_{3}+1)p(c^{-}\mu+c^{+}(-4p + (4p-7)\mu+4))\cos^{2}(r) \\ -2(c^{+}(4(\mu-1)p^{2}+(6-8\mu)p-4)+c^{-}p\mu) \end{pmatrix} \\ -2\left( \frac{\cos^{2}(r) \begin{pmatrix} (-4(\mu-1)p^{2}+8(\mu-1)p+4)c^{-2}-c^{+}p\mu c^{-} \\ +(c_{3}+1)^{2}(p(\mu-4)+4)\cos^{2}(r)+4(c_{3}+1)p \end{pmatrix} \\ \frac{1}{4}(c_{3}+1)^{2}(p(\mu-4)+4)\cos^{4}(r) \\ -\frac{1}{4} \begin{pmatrix} 4((\mu-1)p^{2}-2(\mu-1)p-1)c^{-2}+c^{+}p\mu c^{-} \\ +4c_{3}(p(\mu-3)+4)+4(p(\mu-3)+4) \end{pmatrix} \times \\ \cos^{2}(r)+p(\mu-2)+4 \end{pmatrix} \end{pmatrix} \end{pmatrix}$$
(23)

and the concurrence of the X-state system under the influence of bit flip channel reads

$$C^{\rm BF}(\rho) = \sqrt{\left( \begin{array}{c} c^+ \left( 2(\mu - 1)p^2 - 2(\mu - 1)p - 1 \right) \\ + 2c^- p(-\mu p + p + \mu - 1) \end{array} \right)^2 \cos^2(r)} \\ - \frac{1}{2} \sqrt{\left( \begin{array}{c} (2p - (c_3 + 1)(2p - 1)\cos^2(r)) \\ ((c_3 + 1)(2p - 1)\cos^2(r) - 2p + 2) \end{array} \right)}$$
(24)

where the super-scripts AD, Dep and BF correspond to amplitude damping, depolarizing and bit flip channels respectively. The results are consistent with Refs. [46, 47] and can be easily verified from the expressions (equations 22-24) by setting  $r = \mu = 0$  and  $\mu = 0$  respectively.

#### **III. DISCUSSIONS**

Analytical expressions for the concurrence are calculated for X-type initial state in non-inertial frames influenced by amplitude damping, depolarizing and bit flip channels. In figures 1 and 2, the concurrence is plotted as a function of memory parameter  $\mu$  for p = 0.3 and p = 0.7 respectively, for amplitude damping, depolarizing and bit flip channels. The first panel (column-wise) corresponds to Bell states, whereas the second and third panels correspond to Werner and general initial states, respectively. It is seen that for Bell basis states, entanglement sudden death can be avoided in case of amplitude damping and depolarizing channels in the presence of correlated noise. However, it is possible to fully avoid ESD for all the channels under consideration for  $\mu > 0.75$  (which can be seen from the figure). On the other hand, ESD can also be avoided for Werner and general initial states as well in case of amplitude damping channel at higher degree of correlations. As the value of acceleration r increases, the entanglement degradation is enhanced which is more prominent for lower range of memory parameter  $\mu$ . It is also seen that bit-flip noise heavily influences the entanglement of the system as compared to the amplitude damping and depolarizing channels for lower level of decoherence. Whereas at higher level of decoherence, damping effect of amplitude damping channel becomes more prominent (see figure 2). Furthermore, it can be seen that initial state plays an important role in the system-environment dynamics of entanglement in non-inertial frames.

In figure 3, the concurrence is plotted as a function of decoherence parameter p for  $\mu = 0.5$ for amplitude damping, depolarizing and bit flip channels. It can be seen that the concurrence is heavily damped by different environments. This effect is much prominent for amplitude damping and bit flip channels. It is seen that maximum entanglement degradation occurs at p = 0.5 in case of bit flip channel and entanglement rebound process take place for p > 0.5. Furthermore, no ESD behaviour is seen for depolarizing channel in the presence of correlated noise. The degree of entanglement degradation enhances as one shifts from Bell type initial state to the case of general initial state. However, it saturates for infinite acceleration limit  $(r = \pi/4)$ .

In figures 4 and 5, the concurrence is plotted as a function of Rob's acceleration r and decoherence parameter p with  $\mu = 0.3$  and 0.7 for amplitude damping, depolarizing and bit flip channels. The upper panel (row-wise) corresponds to Bell states, whereas the middle and lower panels correspond to Werner and general initial states respectively. From figure 5, it can be seen that ESD can be fully avoided for all the three types of initial states under depolarizing and bit flip noises at 50% quantum correlations. On the other hand, ESD behaviour is seen only in case of amplitude damping channel for p > 0.75. Therefore, different environments affect the entanglement of the system differently. In figure 6, the concurrence is plotted as a function of memory parameter  $\mu$  and decoherence parameter p with  $r = \pi/4$  for amplitude damping, depolarizing and bit flip channels. It is shown that maximum ESD occurs in case of amplitude damping channel. However, ESD can be avoided for depolarizing channel for  $\mu > 0$  even for maximum value of decoherence i.e. p = 1.

#### IV. CONCLUSIONS

Environmental effects on the entanglement dynamics of Dirac fields in non-inertial frames is investigated by considering X-type initial state shared between the two partners. It is assumed that the Rob is in accelerated frame moving with uniform acceleration whereas Alice is the stationary observer. The concurrence is used to investigate the decoherence and correlated noise effects on the entanglement of the system. Different initial states are considered such as Bell basis, Werner type and general initial states. It is seen that in case of Bell basis states, entanglement sudden death can be avoided for amplitude damping and depolarizing channels in the presence of correlated noise. Whereas, for Werner like and general initial states, the entanglement sudden death occurs more rapidly as the value of decoherence parameter p and Rob's acceleration r increase. Therefore, the initial state plays an important role in the system-environment dynamics of entanglement in non-inertial frames. It is shown that bit-flip channel and amplitude damping channels heavily influence the entanglement of the system as compared to the depolarizing channel. It is possible to avoid ESD for all the channels under consideration for  $\mu > 0.75$  irrespective of the type of initial state considered. The effect of environment is much stronger than that of Rob's acceleration r. Furthermore, no ESD occurs for depolarizing channel for any value of p and r, in the presence of correlated noise. In conclusion, correlated noise compensates the loss of entanglement caused by the Unruh effect.

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# Figures captions

Figure 1. (Color online). The concurrence is plotted as a function of memory parameter  $\mu$  for p = 0.3 for amplitude damping, depolarizing and bit flip channels, where the abbreviations AD, Dep and BF correspond to amplitude damping, depolarizing and bit flip channels respectively.

Figure 2. (Color online). The concurrence is plotted as a function of memory parameter  $\mu$  for p = 0.7 for amplitude damping, depolarizing and bit flip channels.

Figure 3. (Color online). The concurrence is plotted as a function of decoherence parameter p for  $\mu = 0.5$  for amplitude damping, depolarizing and bit flip channels.

Figure 4. (Color online). The concurrence is plotted as a function of Rob's acceleration, r and decoherence parameter, p with  $\mu = 0.3$  for amplitude damping, depolarizing and bit flip channels. Figure 5. (Color online). The concurrence is plotted as a function of Rob's acceleration, r and decoherence parameter, p with  $\mu = 0.7$  for amplitude damping, depolarizing and bit flip channels. Figure 6. (Color online). The concurrence is plotted as a function of memory parameter,  $\mu$  and decoherence parameter, p with  $r = \pi/4$  for amplitude damping, depolarizing and bit flip channels. Table Caption

Table 1. Single qubit Kraus operators for amplitude damping, depolarizing and bit flip channels where p represents the decoherence parameter.

TABLE I: Single qubit Kraus operators for amplitude damping, depolarizing and bit flip channels where p represents the decoherence parameter.

Amplitude damping channel	$A_0 = \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-p} \end{bmatrix}, A_1 = \begin{bmatrix} 0 & \sqrt{p} \\ 0 & 0 \end{bmatrix}$
Depolarizing channel	$A_0 = \sqrt{1 - \frac{3p}{4}I},  A_1 = \sqrt{\frac{p}{4}}\sigma_x$ $A_2 = \sqrt{\frac{p}{4}}\sigma_y, \qquad A_3 = \sqrt{\frac{p}{4}}\sigma_z$
Bit flip channel	$A_0 = \sqrt{1-p}I, A_1 = \sqrt{p}\sigma_x$



FIG. 1: (Color online). The concurrence is plotted as a function of memory parameter  $\mu$  for p = 0.3 for amplitude damping, depolarizing and bit flip channels.



FIG. 2: (Color online). The concurrence is plotted as a function of memory parameter  $\mu$  for p = 0.7 for amplitude damping, depolarizing and bit flip channels.



FIG. 3: (Color online). The concurrence is plotted as a function of decoherence parameter p for  $\mu = 0.5$  for amplitude damping, depolarizing and bit flip channels.



FIG. 4: (Color online). The concurrence is plotted as a function of Rob's acceleration, r and decoherence parameter, p with  $\mu = 0.3$  for amplitude damping, depolarizing and bit flip channels.



FIG. 5: (Color online). The concurrence is plotted as a function of Rob's acceleration, r and decoherence parameter, p with  $\mu = 0.7$  for amplitude damping, depolarizing and bit flip channels.



FIG. 6: (Color online). The concurrence is plotted as a function of memory parameter,  $\mu$  and decoherence parameter, p with  $r = \pi/4$  for amplitude damping, depolarizing and bit flip channels.