Teleportation of three-dimensional single particle state in noninertial frames*

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Considering the spin degree of freedom of the Dirac field, we study the entanglement behavior of a different class of communication channel and teleportation of three-dimensional single particle state in noninertial frames. Numerical analysis shows that the communication channel in our scheme can offer enough distillable entanglement for the teleportation protocol. Moreover, the teleportation protocol could work well if Rob's acceleration is not very big, but the fidelity of the teleportation is still reduced due to the Unruh effect.

Keywords: three-dimensional entangled states, noninertial frames, teleportation, Unruh effect

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1. Introduction

As a remarkable feature of quantum theory, quantum entanglement is considered as an essential resource for quantum information processing (QIP); such as, quantum teleportation,[1–3] quantum cryptography,[4,5] quantum dense coding,[6–8] quantum secrete sharing,[9–11] and so on. However, a quantum system used in QIP inevitably interacts with the surrounding environment, which remains a major obstacle to experimental realizations of the QIP. Much attention has been paid to the investigation of the evolution of entanglement when the quantum systems suffer decoherence.[12–16] Nevertheless, most of these investigations are based squarely on the physical properties of non-relativistic quantum systems. Fortunately, Alsing and Milburn described a process of teleportation between relative accelerated partners and analyzed the fidelity of teleportation in 2003,[17] which is considered as the pioneer work with respect to entanglement behavior in noninertial frames. It has since been a popular trend to extend QIP to noninertial frames.[18–24] Alsing *et al.* showed that the entanglement was degraded by the Unruh effect and asymptotically reached a nonvanishing minimum value in the infinite acceleration limit taking into account the occupation number of Dirac field.[18] Subsequently, León *et al.* studied the Dirac entanglement in both the spin and occupation number cases and showed that the acceleration produced a qubit×four-level quantum system state for spin Bell states.[19] Furthermore, Bruschi *et al.* analyzed the Unruh effect on entanglement beyond the single mode in the bosonic and fermionic cases.[20] All these studies provide us with a deeper understanding on entanglement and promote the development of quantum information science in noninertial frames.

Recent studies show that d-dimensional systems (for instance, qudits $d \geq 3$) are better suited for certain purposes.[25,26] Therefore, from a practical point of view it is interesting to study d-dimensional entangled states. For instance, quantum teleportation with d-dimensional entangled states in noninertial frames. Unfortunately, to the best of our knowledge, there are no analyses of teleportation with three-dimensional entangled states in noninertial frames. Enlightened by the idea of León *et al.*,[19] in this article we will study the entanglement behavior of a different class of communication channel and complete a teleportation of three-dimensional single particle state in noninertial frames.

The organization of this article is as follows. In Section 2, using the approach suggested by León *et al.* we investigate the entanglement behavior of a different class of communication channel in noninertial frames. In Section 3, we provides a brief introduction about the teleportation of three-dimensional single particle state in inertial frames. In Section 4, the teleportation of three-dimensional single particle state in noninertial frames is analyzed. The conclusion appears in Section 5.

2. Entanglement behavior of our communication channel

Suppose that two parties, Alice and Rob, initially share a quantum channel including occupation number entanglement along with spin, which is quite different from traditional quantum channel, in the Minkowski spacetime[19]

$$|\phi\rangle_{AR} = a|0\rangle_A|0\rangle_R + b|\uparrow\rangle_A|\uparrow\rangle_R + c|\downarrow\rangle_A|\downarrow\rangle_R, \qquad (1)$$

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where $|a|^2+|b|^2+|c|^2=1$, and the states $|\uparrow\rangle$, $|\downarrow\rangle$, $|0\rangle$ correspond to particle spin up, spin down, and Minkowski vacuum states, respectively. The subscript A (R) indicates the mode associated with Alice (Rob). By choosing specific coefficients in Eq. (1), we can obtain the maximally three-dimensional entangled state

$$|\phi\rangle^1_{AR} \Rightarrow a=b=c=\frac{1}{\sqrt{3}}. \tag{2}$$

Now, we start to study the entanglement behavior of the communication channel when Rob moves with uniform acceleration while Alice is considered to be inertial. According to Ref. [19], the Minkowski vacuum state and one particle (of spin) state in Rindler coordinates can be written as follows:

$$\begin{aligned}
|0\rangle &= \cos^2 r|0\rangle_{\rm I}|0\rangle_{\rm IV}+{\rm e}^{{\rm i}\phi}\sin r\cos r(|\uparrow\rangle_{\rm I}|\downarrow\rangle_{\rm IV}+|\downarrow\rangle_{\rm I}|\uparrow\rangle_{\rm IV})\\
&\quad+{\rm e}^{2{\rm i}\phi}\sin^2 r|\uparrow\downarrow\rangle_{\rm I}|\uparrow\downarrow\rangle_{\rm IV},\\
|\uparrow\rangle &= \cos r|\uparrow\rangle_{\rm I}|0\rangle_{\rm IV}+{\rm e}^{{\rm i}\phi}\sin r|\uparrow\downarrow\rangle_{\rm I}|\uparrow\rangle_{\rm IV},\\
|\downarrow\rangle &= \cos r|\downarrow\rangle_{\rm I}|0\rangle_{\rm IV}-{\rm e}^{{\rm i}\phi}\sin r|\uparrow\downarrow\rangle_{\rm I}|\downarrow\rangle_{\rm IV},
\end{aligned} \tag{3}$$

where ϕ is an unimportant phase that will turn out to be irrelevant for our calculation, and the subscript I (IV) indicates the region I (IV) of the Rindler space time. The accelerating parameter r is defined as $r=\arctan{\rm e}^{-\pi\omega/a}$, where ω is the Minkowski frequency and a denotes Rob's acceleration. For the sake of convenience, the state's particle spin-up $|\uparrow\rangle$, spin-down $|\downarrow\rangle$, and particle pair $|\uparrow\downarrow\rangle$ will be rewritten as $|1\rangle$, $|2\rangle$, and $|3\rangle$, respectively (we will use the representations here, and throughout the rest of paper). Since Rob is causally disconnected from region IV,[19,22,23] for an intuitive grasp of Unruh effect on the communication channel, we will study the behavior of entanglement of the Alice–Rob and Alice–antiRob. Then, the quantum channel that Alice and Rob (in Rob's region I) shared can be written as

$$\begin{aligned}
\rho_{\phi_{AR_{\rm I}}} &= |a|^2(\cos^4 r|00\rangle\langle 00|+\sin^4 r|03\rangle\langle 03|)\\
&\quad+|a|^2\cos^2 r\sin^2 r(|01\rangle\langle 01|+|02\rangle\langle 02|)\\
&\quad+|b|^2(\sin^2 r|13\rangle\langle 13|+\cos^2 r|11\rangle\langle 11|)\\
&\quad+|c|^2(\sin^2|23\rangle\langle 23|+\cos^2 r|22\rangle\langle 22|)\\
&\quad+(ab^*\cos^3 r|00\rangle\langle 11|+ac^*\cos^3 r|00\rangle\langle 22|\\
&\quad-ac^*\cos r\sin^2 r|01\rangle\langle 23|+ab^*\cos r\sin^2 r|02\rangle\langle 13|\\
&\quad+bc^*\cos^2 r|11\rangle\langle 22|+{\rm H.c.}).
\end{aligned} \tag{4}$$

The quantum channel shared by Alice and anti-Rob (in Rob's region IV) can be written as

$$\begin{aligned}
\rho_{\phi_{AR_{\rm IV}}} &= |a|^2(\cos^4 r|00\rangle\langle 00|+\sin^4 r|03\rangle\langle 03|)\\
&\quad+|a|^2\cos^2 r\sin^2 r(|01\rangle\langle 01|+|02\rangle\langle 02|)\\
&\quad+|b|^2(\cos^2 r|10\rangle\langle 10|+\sin^2 r|11\rangle\langle 11|)\\
&\quad+|c|^2(\cos^2 r|20\rangle\langle 20|+\sin^2 r|22\rangle\langle 22|)\\
&\quad+({\rm e}^{{\rm i}\phi}ac^*\cos^2 r\sin r|01\rangle\langle 20|\\
&\quad+{\rm e}^{{\rm i}\phi}ab^*\cos^2 r\sin r|02\rangle\langle 10|-bc^*\sin^2 r|11\rangle\ \langle 22|\\
&\quad+{\rm e}^{{\rm i}\phi}ab^*\sin^3 r|03\rangle\langle 11|\\
&\quad-{\rm e}^{{\rm i}\phi}ac^*\sin^3 r|03\rangle\langle 22|+{\rm H.c.}).
\end{aligned} \tag{5}$$

Substituting $a=b=c=1/\sqrt{3}$ into Eq. (4) and Eq. (5), we can obtain the maximally three-dimensional entangled quantum channel $\rho_{\phi^1_{AR_{\rm I}}}$ and $\rho_{\phi^1_{AR_{\rm IV}}}$.

In our analysis, we will use the negativity[18,27] $\mathcal{N}$ to evaluate the communication channel capacities for the maximally three-dimensional entangled state. The negativity is defined as the sum of the negative eigenvalues of the partial-transpose density matrix. If $\lambda_{\rm i}$ are the eigenvalues of any partially transposed bipartite density matrix ρ_{AB}, its negativity is $\mathcal{N}_{AB}=\sum_i(|\lambda_{\rm i}|-\lambda_{\rm i})=-2\sum_{\lambda_{\rm i}<0}\lambda_{\rm i}$. It should be noted that the maximum value of the negativity (reached for maximally entangled states) depends on the dimension of the maximally entangled state. It is also worth mentioning that negativity acts only as a measure of distillable entanglement and does not account for the possible bound entanglement the communication channel would have.[28] Therefore, it is worthwhile to study the mutual information[18,29] for our communication channel. For a bipartite density matrix ρ_{AB}, its mutual information is $I_{AB}=S(\rho_A)+S(\rho_B)-S(\rho_{AB})$, where $\rho_{A(B)}$ is the partial density matrix of $A(B)$, and $S(\rho)=-{\rm Tr}(\rho\log_2\rho)$ is the von Neumann entropy.

The negativities and mutual information of $\rho_{\phi^1_{AR_{\rm I}}}$ and $\rho_{\phi^1_{AR_{\rm IV}}}$ as a function of r for the maximally three-dimensional entangled state are given in Fig. 1. As shown in Fig. 1(a), the negativity of $\rho_{\phi^1_{AR_{\rm I}}}$ will decrease while the negativity of $\rho_{\phi^1_{AR_{\rm IV}}}$ will increase as the acceleration increases, and both of them can still keep a high value even in the limit of infinite acceleration. However, $\rho_{\phi^1_{AR_{\rm I}}}$ can always offer enough distillable entanglement in noninertial frames; so, it is the better bipartition to which one can perform informational work. In addition, as we see from Fig. 1(b), the mutual information of $\rho_{\phi^1_{AR_{\rm I}}}$ and $\rho_{\phi^1_{AR_{\rm IV}}}$ as a function of r is not proportional to the negativity. In fact, after calculation, we can find that the ratio of $\mathcal{N}_{AR_{\rm I}}$ to $I_{AR_{\rm I}}$ for the maximally three-dimensional entangled state is always bigger than that of Bell states.[19] In other words, compared with the spin Bell state systems,[19] the three-dimensional entangled system not only has a higher distillable entanglement but also has a higher utilization ratio of information. So, in a sense, the maximally three-dimensional entangled system is better suited for performing informational work in noninertial frames.

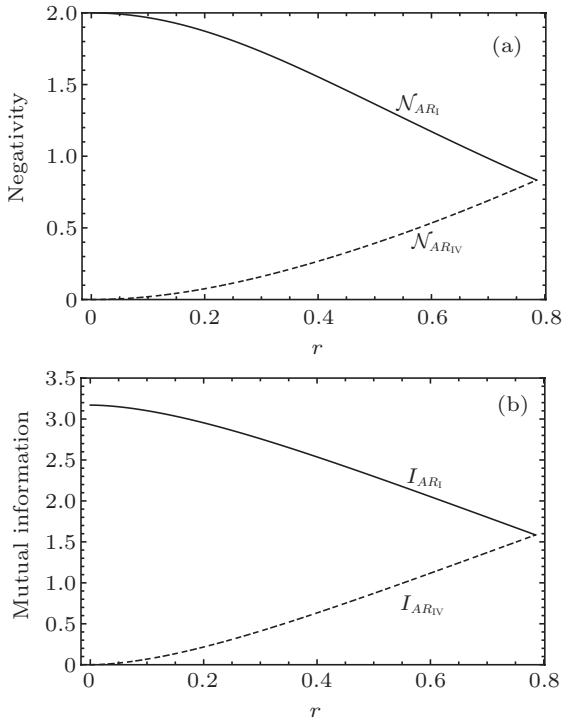


Fig. 1. (a) The negativities and (b) mutual information of $\rho_{\phi^1_{AR_{\rm I}}}$ (black line) and $\rho_{\phi^1_{AR_{\rm IV}}}$ (dash black line) as a function of r for the maximally three-dimensional entangled state.

3. A brief introduction of teleporting three-dimensional single particle state in inertial frames

Before elaborating on our scheme in noninertial frames, we first give a brief introduction about teleporting three-dimensional single particle state in inertial frames.[1] Suppose that Alice wants to teleport the state $|\psi\rangle_{A_0} = \alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle$ (it should be noted that $|\psi\rangle_{A_0}$ is different from traditional three-dimensional input state in which only the occupation number states of fields are considered) to Rob, by using a shared maximally three-dimensional entangled state $(|\phi\rangle^1_{AR})$. The total initial state is given by $|\Psi\rangle = |\psi\rangle_{A_0}|\phi\rangle^1_{AR}$ where the first two qubits of $|\Psi\rangle$ are Alice's and the third is Rob's qubit. Alice starts the teleportation procedure by measuring the self-belonging state in mutual orthogonal basis $\{|\phi\rangle^{A_0A}_{nm}\}$. The mutual orthogonal bases are given by

$$|\phi\rangle^{A_0A}_{nm} = \sum_{j=0}^{2} \mathrm{e}^{2\pi \mathrm{i} jn/3}|j\rangle \otimes |(j+m) \bmod 3\rangle/\sqrt{3}, \qquad (6)$$

where $(n,m,j = 0,1,2)$. Then, the total state will collapse to $|\phi\rangle^{A_0A}_{nm} \otimes |\psi\rangle^{nm}_R$, with probability of 1/9. Where $|\psi\rangle^{nm}_R$ are given by

$$\begin{aligned} |\psi\rangle^{0m}_R &= \alpha|m\rangle + \beta|(m+1) \bmod 3\rangle \\ &\quad + \gamma|(m+2) \bmod 3\rangle, \\ |\psi\rangle^{1m}_R &= \alpha|m\rangle + \beta\,\mathrm{e}^{-2\pi \mathrm{i}/3}|(m+1) \bmod 3\rangle \\ &\quad + \gamma\mathrm{e}^{-4\pi \mathrm{i}/3}|(m+2) \bmod 3\rangle, \\ |\psi\rangle^{2m}_R &= \alpha|m\rangle + \beta\,\mathrm{e}^{-4\pi \mathrm{i}/3}|(m+1) \bmod 3\rangle \\ &\quad + \gamma\mathrm{e}^{-2\pi \mathrm{i}/3}|(m+2) \bmod 3\rangle. \end{aligned} \qquad (7)$$

Subsequently, Alice sends the result of the measurement (n,m) to Rob by using a classical information channel. Consequently, Rob extracts information by performing the unitary operation U_{nm} on the state in his hand, where the unitary operation U_{nm} can be expressed as

$$U_{nm} = \sum_{j=0}^{2} \mathrm{e}^{2\pi \mathrm{i} jn/3}|j\rangle\langle(j+m) \bmod 3|. \qquad (8)$$

The result is given by $|\widetilde{\psi}\rangle = U_{nm}|\psi\rangle^{nm}_R = |\psi\rangle_{A_0}$, and the corresponding teleportation fidelity is $F = |\langle\widetilde{\psi}|\psi\rangle_{A_0}|^2 = 1$.

4. Teleportation of three-dimensional single particle state in noninertial frames

For the teleportation protocol in noninertial frames, we suppose that Alice and Rob initially share the maximally three-dimensional entangled state $(|\phi\rangle^1_{AR})$, and at rest in their local frame. Then, Rob moves with uniform acceleration while Alice is considered to be inertial. Alice now wishes to perform the same teleportation protocol with the uniformly accelerated Rob. The calculation proceeds straightforwardly once we remember three things. First, Rob is uniformly accelerating, so the states associated with Rob must be expanded in terms of the Rindler states according to Eq. (3). Second, Rob is causally disconnected from region IV, the physically accessible information will be encoded in the mode A described by Alice and mode I described by Rob. We should trace over the mode in region IV (anti-Rob). Third, Rob has a four-level quantum system $(|0\rangle,|1\rangle,|2\rangle,|3\rangle)$, so the operations associated with Rob should be changed slightly, and the best state we can expect Rob to recover at the end of the protocol is $|\psi'\rangle_R = \alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle + 0|3\rangle$.

Alice still starts the teleportation procedure by measuring the self-belonging state in mutual orthogonal basis $\{|\phi\rangle^{A_0A}_{nm}\}$. The total state will collapse to $|\phi\rangle^{A_0A}_{nm} \otimes |\psi'\rangle^{nm}_R$, with probability of 1/9. Then, Alice sends the result of the measurement (n,m) to Rob by using a classical information channel. Consequently, Rob extracts information by performing the unitary operation U'_{nm} on the state in his hand. In contrast from U_{nm}, the unitary operation U'_{nm} takes the form as

$$U'_{nm} = \sum_{j=0}^{2} \mathrm{e}^{2\pi \mathrm{i} jn/3}|j\rangle\langle(j+m) \bmod 3| + |3\rangle\langle 3|. \qquad (9)$$

So the information that Rob could extract is

$$\rho'_{n0}=\begin{pmatrix} |\alpha|^2\cos^4 r & \alpha\beta^*\cos^3 r & \alpha\gamma^*\cos^3 r & 0 \\ \beta\alpha^*\cos^3 r & (|\beta|^2+|\alpha|^2\sin^2 r)\cos^2 r & \beta\gamma^*\cos^2 r & -\alpha\gamma^*\cos r\sin^2 r \\ \gamma\alpha^*\cos^3 r & \gamma\beta^*\cos^2 r & (|\gamma|^2+|\alpha|^2\sin^2 r)\cos^2 r & \alpha\beta^*\cos r\sin^2 r \\ 0 & -\gamma\alpha^*\cos r\sin^2 r & \beta\alpha^*\cos r\sin^2 r & \sin^2 r(|\beta|^2+|\gamma|^2+|\alpha|^2\sin^2 r) \end{pmatrix}, \tag{10}$$

$$\rho'_{n1}=\begin{pmatrix} (|\alpha|^2+|\gamma|^2\sin^2 r)\cos^2 r & \alpha\beta^*\cos^2 r & \alpha\gamma^*\cos^3 r & -\exp\left(\frac{\mathrm{i}4n\pi}{3}\right)\gamma\beta^*\cos r\sin^2 r \\ \beta\alpha^*\cos^2 r & (|\beta|^2+|\gamma|^2\sin^2 r)\cos^2 r & \beta\gamma^*\cos^3 r & \exp\left(\frac{\mathrm{i}4n\pi}{3}\right)\gamma\alpha^*\cos r\sin^2 r \\ \gamma\alpha^*\cos^3 r & \gamma\beta^*\cos^3 r & |\gamma|^2\cos^3 r & 0 \\ -\exp\left(\frac{\mathrm{i}2n\pi}{3}\right)\beta\gamma^*\cos r\sin^2 r & \exp\left(\frac{\mathrm{i}2n\pi}{3}\right)\alpha\gamma^*\cos r\sin^2 r & 0 & \sin^2 r(|\alpha|^2+|\beta|^2+|\gamma|^2\sin^2 r) \end{pmatrix}, \tag{11}$$

$$\rho'_{n2}=\begin{pmatrix} (|\alpha|^2+|\beta|^2\sin^2 r)\cos^2 r & \alpha\beta^*\cos^3 r & \alpha\gamma^*\cos^2 r & \exp\left(\frac{\mathrm{i}2n\pi}{3}\right)\beta\gamma^*\cos r\sin^2 r \\ \beta\alpha^*\cos^3 r & |\beta|^2\cos^4 r & \beta\gamma^*\cos^3 r & 0 \\ \gamma\alpha^*\cos^2 r & \gamma\beta^*\cos^3 r & (|\gamma|^2+|\beta|^2\sin^2 r)\cos^2 r & -\exp\left(\frac{\mathrm{i}2n\pi}{3}\right)\beta\alpha^*\cos r\sin^2 r \\ \exp\left(\frac{\mathrm{i}4n\pi}{3}\right)\gamma\beta^*\cos r\sin^2 r & 0 & -\exp\left(\frac{\mathrm{i}4n\pi}{3}\right)\alpha\beta^*\cos r\sin^2 r & \sin^2 r(|\alpha|^2+|\gamma|^2+\beta|^2\sin^2 r) \end{pmatrix}. \tag{12}$$

At $r=0$, corresponding to $a=0$, we are back to the usual case of teleportation between Alice and Rob, both Minkowski observers, and the fidelity is unity. Furthermore, we find that some phase will be introduced to the result if $n,m\neq 0$. But we still can extract much useful information from the result. The fidelities $F_{nm}={}_R\langle\psi'|\rho'_{nm}|\psi'\rangle_R$ are evaluated as

$$\begin{aligned} F_{n0} &= (1-|\alpha|^2+|\alpha|^2\cos r)^2\cos^2 r \\ &\quad +(|\beta|^2+|\gamma|^2)|\alpha|^2\cos^2 r\sin^2 r, \\ F_{n1} &= (1-|\gamma|^2+|\gamma|^2\cos r)^2\cos^2 r \\ &\quad +(|\alpha|^2+|\beta|^2)|\gamma|^2\cos^2 r\sin^2 r, \\ F_{n2} &= (1-|\beta|^2+|\beta|^2\cos r)^2\cos^2 r \\ &\quad +(|\gamma|^2+|\alpha|^2)|\beta|^2\cos^2 r\sin^2 r. \end{aligned} \tag{13}$$

Without loss of generality, the fidelity F_{00} as a function of r and $|\alpha|$ is shown in Fig. 2(a). In this case, we find that the fidelity F_{00} will decrease with the increase of the acceleration and $|\alpha|$. In fact, the change of fidelity F_{01} (F_{02}) is similar to the behavior of F_{00}, and F_{01} as a function of r and $|\gamma|$ is shown in Fig. 2(b).

So far, the derivation of fidelity is based on that Alice knows the result of the measurement. However, we think it is more acceptable to define the total fidelity of teleportation as the minimum of the values in Eq. (13). Since it is more meaningful to evaluate the total performance for teleportation protocol even before implementing the protocol. We have assumed $\alpha=\sin\theta\cos\eta$, $\beta=\sin\theta\sin\eta$, and $\gamma=\cos\theta$ ($\theta\subset[0,2\pi]$, $\eta\subset[0,\pi]$) for the sake of convenience. For an intuitive grasp of the change of fidelity of teleportation in noninertial frames, the total fidelity as a function of θ and η is given in Fig. 3. As we see from Fig. 3(a), a high fidelity (above 0.945) still can

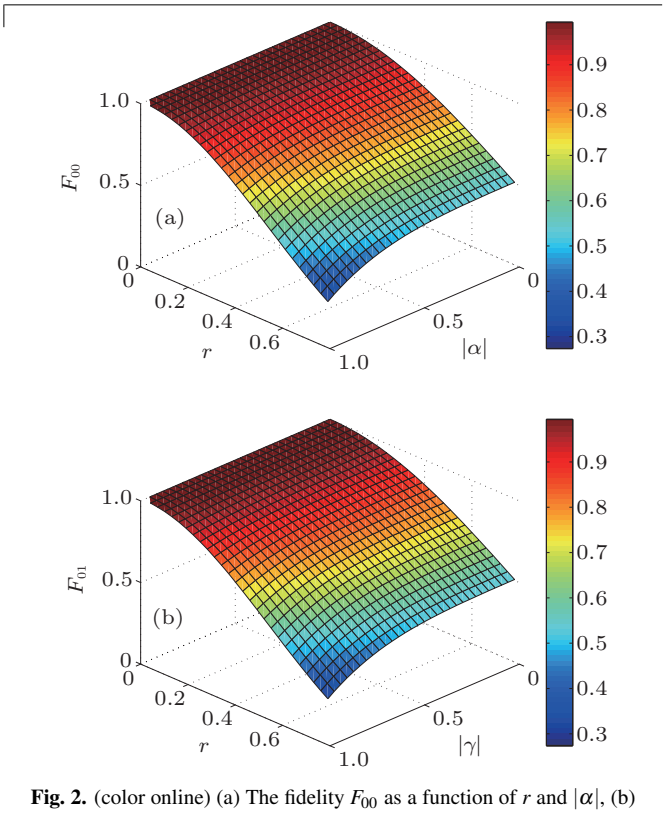


Fig. 2. (color online) (a) The fidelity F_{00} as a function of r and $|\alpha|$, (b) the fidelity F_{01} as a function of r and $|\gamma|$.

be achieved for a wide range of parameters in the red area. Furthermore, the fluctuations in θ and η would not significantly affect the total fidelity with $r=0.2$. However, in Fig. 3(b) (Fig. 3(c)) the fidelity is significantly affected by the fluctuations in θ and η, and the maximal fidelity drops to about 0.83 (0.65). In other words, a relatively high fidelity can always be achieved in the same red area, but the effect of the fluctuations in θ and η on the fidelity will become apparent with the increases of r. Consequently, r is still a detrimental factor for

the teleportation protocol.

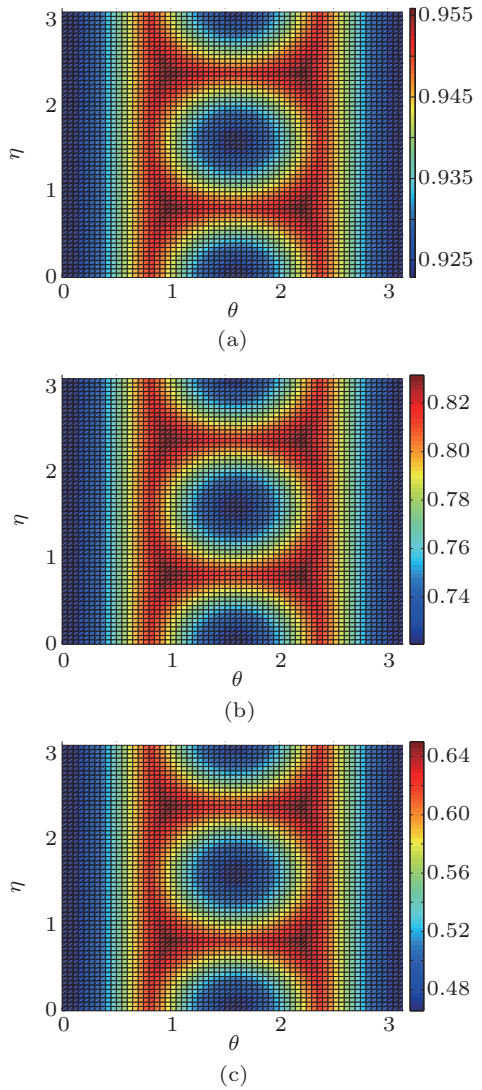


Fig. 3. (color online) Density plot of the total fidelity as a function of θ and η with (a) $r = 0.2$, (b) $r = 0.4$, and (c) $r = 0.6$.

5. Discussion and conclusion

It is well known that Unruh decoherence degrades entanglement of occupation number states of fields. Here, we have shown further study of the Unruh effect on a different class of communication channel when we take into account that each Dirac mode has spin structure. Specifically, we analyzed two possible bipartitions of an entangled system composed of an inertial observer (Alice) and an accelerated observer (Rob), which inhabits a universe with an event horizon.[20] We study the behavior of entanglement of the Alice–Rob and Alice–anti-Rob in the maximally three-dimensional entangled system, which are the two bipartitions to which one could assign physical meaning. We show that the communication channel ($\rho_{\phi^1_{AR_I}}$) in our scheme could offer enough distillable entanglement for the teleportation protocol. In addition, compared with the spin Bell state systems,[19] the three-dimensional entangled system not only has higher distillable entanglement, but also has higher utilization ratio of information. In a sense, the maximally three-dimensional entangled system is better suited for performing informational work in noninertial frames.

In conclusion, we have studied the teleportation of a three-dimensional single particle state by using a shared maximally three-dimensional entangled state in noninertial frames. The effects of Rob's acceleration and different input states have been discussed in detail. Numerical analysis shows that the teleportation protocol could work well if Rob's acceleration is small. Furthermore, a relatively high fidelity always can be achieved for some special input states (which corresponds to the red area in Fig. 3), but the effect of different input states on the fidelity will become apparent with the increases of r. As a matter of fact, the above results can be understood intuitively as follows. In the teleportation protocol, Alice is in the free space and accelerated Rob involves space-time conversion[19] (it is a direct consequence of the existence of Unruh–Hawking radiation[17–20]). Furthermore, because Rob is causally disconnected from region IV, the physically accessible information is obtained from the mode A (Alice) and mode I (Rob), so we have traced over the mode in region IV (anti-Rob); that is, we have removed the information contained in the mode of anti-Rob, therefore, the information that Rob finally could extract in the teleportation protocol only contains the mode I (Rob). Furthermore, it should be emphasized that the information contained in the modes of Alice–antiRob increases with the acceleration increases as shown in Fig. 1(a), which implies that the loss of information in the modes of Alice–Rob will increase with the increasing acceleration. Correspondingly, the effective information contained in the mode of Rob will naturally decrease in some degree with the increasing acceleration. Consequently, the fidelity of the teleportation will decrease with the increasing acceleration. We hope that our work may be useful for the QIP in the near future.

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