

Continuous-variable Gaussian analog of cluster states

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We present a continuous-variable (CV) Gaussian analog of cluster states, a new class of CV multipartite entangled states that can be generated from squeezing and quantum nondemolition coupling $H_I = \hbar \chi X_A X_B$. The entanglement properties of these states are studied in terms of classical communication and local operations. The graph states as general forms of the cluster states are presented. A chain for a one-dimensional example of cluster states can be readily experimentally produced only with squeezed light and beam splitters.

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I. INTRODUCTION

Entanglement is one of the most fascinating features of quantum mechanics and plays a central role in quantum-information processing. In recent years, there has been an ongoing effort to characterize qualitatively and quantitatively the entanglement properties of multiparticle systems and apply them in quantum communication and information. The study of multipartite entangled states in the discrete-variable regime has shown that there exist different types of entanglement, inequivalent up to local operations and classical communication [1] (LOCC). For example, it is now well known that the Greenberger-Horne-Zeilinger (GHZ) and W states are not equivalent up to LOCC. Recently, Briegel and Rausendorf introduced a special kind of multipartite entangled states, the so-called cluster states, which can be created via an Ising Hamiltonian [2]. It has been shown that via cluster states, one can implement a quantum computer on a lattice of qubits. In this proposal, which is known as a “one-way quantum computer,” information is written onto the cluster and then is processed and read out from the cluster by one-qubit measurements [3].

In recent years, quantum communication, or more generally quantum information with continuous variables (CVs), has attracted a lot of interest and appears to yield very promising perspectives concerning both experimental realizations and general theoretical insights [4], due to its relative simplicity and high efficiency in the generation, manipulation, and detection of the CV state. The investigation of CV multipartite entangled states has made significant progress in theory and experiment. The quantification and scaling of multipartite entanglement has been developed by different methods, for example, by determining the necessary and sufficient criteria for their separability [5–7], and by the entanglement of formation [8]. Multipartite quantum protocols were proposed and performed experimentally, such as quantum teleportation networks [9], controlled dense coding [10], and quantum secret sharing [11] based on tripartite entangle-

ment. The study of entanglement properties of the harmonic chain has aroused great interest [12], which is in direct analogy to a spin chain with an Ising interaction. To date, the study and application of CV multipartite entangled states has mainly focused on CV GHZ-type states. However, a richer understanding and more definite classification of CV multipartite entangled states are needed for developing a CV quantum-information network. In this paper, we introduce a class of CV Gaussian multipartite entangled states, CV clusterlike states, which are different from CV GHZ-like states. We propose an interaction model to realize CV clusterlike states and compare these states to GHZ-like states in terms of LOCC. It is worth noting that a CV Gaussian cluster state in our protocol cannot be used in universal quantum computers over continuous variables [13]; however, it may be applied in quantum network communication as a different type of multipartite entanglement.

II. CV GAUSSIAN CLUSTER STATE

We consider an N -mode N -party system described by a set of quadrature operators $R = (X_1, P_1; X_2, P_2, \dots; X_N, P_N)$ obeying the canonical commutation relation $[X_l, P_k] = i\delta_{lk}$. The quantum nondemolition (QND) coupling Hamiltonian is employed in the form $H_I = \hbar \chi X_l X_k$, so in this process quadrature-amplitude (“position”) and quadrature-phase (“momentum”) operators are transformed in the Heisenberg picture according to the following expressions:

$$\begin{aligned} X_l' &= X_l, & P_l' &= P_l + gX_k, \\ X_k' &= X_k, & P_k' &= P_k + gX_l, \end{aligned} \quad (1)$$

where $g = -\chi t$ is the gain of the interaction, and χ and t are the coupling coefficient and the interaction time, respectively. The important feature of this Hamiltonian is that the momentum P_l and P_k pick up the information of the position X_k and X_l , respectively, while the position remains unchanged. The QND coupling of light was widely investigated in many previous experiments [14] and recently has been experimentally observed between light and the collective spin of atomic samples [15].

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Considering first a one-dimensional example of a chain of N modes which are numbered from 1 to N with next-neighbor interaction. Initially, all modes are prepared in the quadrature-phase squeezed state $X_j = e^{+r}X_j^{(0)}$, $P_j = e^{-r}P_j^{(0)}$, where r is the squeezing parameter and the superscript (0) denotes initial vacuum modes. Applying QND coupling to next-neighbor modes of a chain at different or the same time yields a CV clusterlike state in the form

$$\begin{aligned} X_1^C &= e^{+r}X_1^{(0)}, & P_1^C &= e^{-r}P_1^{(0)} + e^{+r}X_2^{(0)}, \\ &\vdots & &\vdots \\ X_i^C &= e^{+r}X_i^{(0)}, & P_i^C &= e^{-r}P_i^{(0)} + e^{+r}X_{i-1}^{(0)} + e^{+r}X_{i+1}^{(0)}, \\ &\vdots & &\vdots \\ X_N^C &= e^{+r}X_N^{(0)}, & P_N^C &= e^{-r}P_N^{(0)} + e^{+r}X_{N-1}^{(0)}. \end{aligned} \quad (2)$$

Here, without loss of generality, we put the gain of the interaction $g=1$. For simplicity we discuss the properties of CV clusterlike states in the ideal case $r \rightarrow \infty$ corresponding to infinite squeezing. When $N=2$, one obtains a state with total position $X_1^C + X_2^C \rightarrow 0$ and relative momentum $P_1^C - P_2^C \rightarrow 0$ by applying a local -90° rotation transformation $X^C \rightarrow P^C$, $P^C \rightarrow -X^C$ on mode 2, which corresponds to Einstein-Podolsky-Rosen or two-mode squeezed states. The entanglement of a state is not affected by local unitary transformation. It obviously exhibits maximum bipartite entanglement. Similarly, one obtains the state for $N=3$ with total position $X_1^C + X_2^C + X_3^C \rightarrow 0$ and relative momentum $P_i^C - P_j^C \rightarrow 0$ ($i, j=1, 2, 3$), which corresponds to a CV three-mode GHZ-like state [9]. However, quantum correlation of position and momentum of the state for the $N=4$ case become $X_1^C + X_2^C + X_3^C \rightarrow 0$, $X_3^C + X_4^C \rightarrow 0$ and $P_1^C - P_2^C \rightarrow 0$, $P_2^C - P_3^C + P_4^C \rightarrow 0$ by applying a local -90° rotation transformation on modes 2 and 4. Clearly, a CV four-partite clusterlike state is not equivalent to a GHZ-like state with total position $X_1 + X_2 + X_3 + X_4 \rightarrow 0$ and relative momentum $P_i - P_j \rightarrow 0$ ($i, j=1, 2, 3, 4$). Note that when the CV clusterlike state is generated by finite squeezing, quantum correlation is expressed by the variance, such as $\langle \delta^2(X_1^C + X_2^C + X_3^C) \rangle$. More generally, CV N -partite clusterlike states and GHZ-like states are not equivalent for $N > 3$, as we shall see below.

We now compare the entanglement properties of CV cluster and GHZ-like states by LOCC in the limit of infinite squeezing. First, we discuss the persistence of entanglement of an entangled N -partite state, which means the minimum number of local measurements such that, for all measurement outcomes, the state is completely disentangled [2]. An explicit strategy to disentangle the CV cluster-type state (2) is to measure the positions of all even-number parties, $j=2, 4, 6, \dots$, and then displace momentum of the remaining (unmeasured) parties with the measured results; such as the momentum of party 1 displaced as $P_1'^C = P_1^C - X_2^C = e^{-r}P_1^{(0)}$ by the measured result X_2^C of party 2; and party 3 as $P_3'^C = P_3^C - X_2^C - X_4^C$ by parties 2 and 4. It is obvious that the remaining parties become the originally prepared quadrature-phase squeezed states that are product states and completely unentangled. Thus the minimum number of measurements to disentangle the cluster state is $\text{int}(N/2)$. For the GHZ state, in contrast, a single local measurement suffices to bring it into a

product state. From this point of view, it is impossible to destroy all the entanglement of the cluster if fewer than $\text{int}(N/2)$ parties are traced out (discarded). But only if one party for the GHZ state is traced, will the remaining state be completely unentangled. Note that this is not true in the case of finite squeezing. For example, if three weakly squeezed vacuum states are used to generate a tripartite GHZ state, the state is a fully inseparable tripartite entangled state, but the remaining bipartite state after tracing out one of the three subsystems is still entangled [9,10].

Next, we investigate the entanglement properties of the quantum teleportation network. In other words, we will answer the question of how many parties need to be measured from an N -partite entangled state to make bipartite entanglement between any two of the N parties ‘‘distilled,’’ which enables quantum teleportation. We first show that the parties at the ends of the chain, i.e., parties 1 and N , can be brought into bipartite entanglement by measuring the parties $2, \dots, N-1$. After measurement of the momentum of party 2, the remaining parties are identical to an entangled chain of length $N-1$ when one displaces the position of party 1 as $X_1'^C = X_1^C - P_2^C$ and measuring the result P_2^C on party 2, then applies a local rotation transformation $X^C \rightarrow -P^C$, $P^C \rightarrow X^C$ on parties 1. We can repeat this procedure and measure party 3, and so on. At the end, party 1 and N are brought into a bipartite entanglement. To bring any two parties j, k ($j < k$) from the chain $\{1, 2, \dots, N\}$ into bipartite entanglement, we first measure the position of the ‘‘outer’’ parties $j-1$ and $k+1$, then displace the momentum of parties j and k as $P_j'^C = P_j^C - X_{j-1}^C$ and $P_k'^C = P_k^C - X_{k+1}^C$, which projects the parties $j, j+1, \dots, k$ into an entangled chain of length $k-j+1$. This process that breaks chain into parts is called ‘‘disconnection’’; for example, one breaks a chain into two independent chains when measuring the position of party j and displacing the momentum of parties $j-1$ and $j+1$ as $P_{j-1}'^C = P_{j-1}^C - X_j^C$ and $P_{j+1}'^C = P_{j+1}^C - X_j^C$. A subsequent measurement of the ‘‘inner’’ parties $j+1, \dots, k-1$ will then project parties j, k into a bipartite entanglement, as shown previously. Note that the assistance of all the ‘‘inner’’ parties is necessary to bring any two parties from the chain into a bipartite entanglement; however, for the ‘‘outer’’ parties it depends on which strategy is chosen. The optimum strategy as shown previously is to measure next-neighbor parties $j-1$ and $k+1$. The other strategies may be with the help of parties $j-2, j-3$ and $k+2, k+3$, or $j-2, j-4, j-5$ and $k+2, k+4, k+5$, and so on. For the N -partite GHZ state, in contrast, bipartite entanglement between any two of the N parties is generated with the help of a local position measurement of $N-2$ modes [9].

In the following we will generalize the one-dimensional CV cluster to graph states that correspond to mathematical graphs, where the vertices of the graph play the role of quantum physical systems, i.e., the individual modes and the edges represent interactions. A graph $G=(V, E)$ is a pair of a finite set of n vertices V and a set of edges E , the elements of which are subsets of V with two elements each [16]. We will consider only simple graphs, which are graphs that contain neither loops (edges connecting a vertex with itself) nor multiple edges. When the vertices $a, b \in V$ are the end points of

an edge, they are referred to as being adjacent. An $\{a, c\}$ path is an ordered list of vertices $a=a_1, a_2, \dots, a_{n-1}, a_n=c$, such that for all i , a_i and a_{i+1} are adjacent. A connected graph is a graph that has an $\{a, c\}$ path for any two $a, c \in V$. Otherwise it is referred to as disconnected. The neighborhood $N_a \subset V$ is defined as the set of vertices b for which $\{a, b\} \in E$. In other words, the neighborhood is the set of vertices adjacent to a given vertex. The CV graph states with a given graph G are conveniently defined as

$$X_a^G = e^{+r} X_a^{(0)},$$

$$P_a^G = e^{-r} P_a^{(0)} + e^{+r} \sum_{b \in N_a} X_b^{(0)} \quad \text{for } a \in V. \quad (3)$$

Equation (3) can be used to generalize some of the entanglement properties from the one-dimensional case to graph states. To bring any two parties on sites $a, d \in V$ into bipartite entanglement, we first select a one-dimensional path $P \subset V$ that connects sites a and d . Then we measure all neighboring modes surrounding this path in the position component. By this procedure, we project the parties on the path P into a state that up to local displacement on the momentum with measured results is identical to the linear chain Eq. (2). We have thereby reduced the graph states to the one-dimensional problem.

III. PHYSICALLY REALIZABLE MODELS

We briefly mention that, to embody Eqs. (2) and (3), we can use the off-resonant interaction of linearly polarized optical buses with N ensembles of atoms (confined in a vapor cell), providing the Hamiltonian $H_{OA} = \hbar \chi X_O X_A$. Here, X_O (X_A) is the position operator of the bus (atomic ensemble). First, we prepare the spin-squeezed atomic ensembles by means of QND coupling H_{OA} and projection measurements on light [15,17]. In the second step, the QND coupling $H_{A_{lk}} = \hbar \chi' X_{A_l} X_{A_k}$ between ensembles can be implemented by first letting an optical bus interact with ensemble l , then applying a 90° rotation transformation on the optical bus, then letting the optical bus interact with ensemble k , then applying -90° rotation transformation on the optical bus, and finally letting the optical bus interact with ensemble l .

Stimulating opportunities also come from the experimental demonstration of CV entanglement swapping [18], in which a four-partite entangled state may be generated. Here we show that a chain for a one-dimensional example of cluster states can be experimentally produced with only squeezed light and beam splitters as shown in Fig. 1 and give an explicit example where the quantum teleportation network is implemented with four-partite clusterlike states compared with GHZ-like states. To make this example simple and easy to compare quadripartite clusterlike states with GHZ-like states, we employ the scheme in Ref. [9] to generate the cluster and GHZ-like states and implement the quantum teleportation network. Applying the beam splitter operations (beam splitters 1, 2, and 3 give 1:3, 1:2, and 1:1, respectively) to momentum squeezing in modes 1,4 and position squeezing in modes 2,3 yields a clusterlike state (momentum

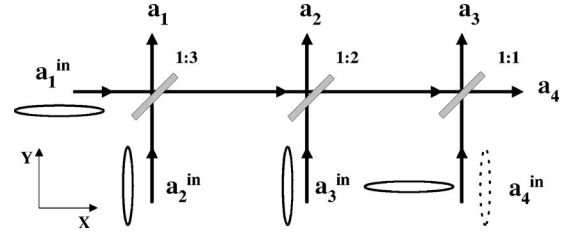


FIG. 1. A schematic diagram for generating a CV four-partite cluster and GHZ-like state by means of squeezed light and beam splitters.

squeezing in mode 1 and position squeezing in modes 2,3,4 yields a GHZ-like state). The four-partite clusterlike (GHZ-like) states are expressed by the Heisenberg operators

$$X_1^{C(Z)} = \frac{1}{2} e^{+r} X_1^{(0)} + \frac{\sqrt{3}}{2} e^{-r} X_2^{(0)},$$

$$P_1^{C(Z)} = \frac{1}{2} e^{-r} P_1^{(0)} + \frac{\sqrt{3}}{2} e^{+r} P_2^{(0)},$$

$$X_2^{C(Z)} = \frac{1}{2} e^{+r} X_1^{(0)} - \frac{1}{\sqrt{12}} e^{-r} X_2^{(0)} + \sqrt{\frac{2}{3}} e^{-r} X_3^{(0)},$$

$$P_2^{C(Z)} = \frac{1}{2} e^{-r} P_1^{(0)} - \frac{1}{\sqrt{12}} e^{+r} P_2^{(0)} + \sqrt{\frac{2}{3}} e^{+r} P_3^{(0)},$$

$$X_3^{C(Z)} = \frac{1}{2} e^{+r} X_1^{(0)} - \frac{1}{\sqrt{12}} e^{-r} X_2^{(0)} - \sqrt{\frac{1}{6}} e^{-r} X_3^{(0)} + \frac{1}{\sqrt{2}} e^{+(-)r} X_4^{(0)},$$

$$P_3^{C(Z)} = \frac{1}{2} e^{-r} P_1^{(0)} - \frac{1}{\sqrt{12}} e^{+r} P_2^{(0)} - \sqrt{\frac{1}{6}} e^{+r} P_3^{(0)} + \frac{1}{\sqrt{2}} e^{-(+r)} P_4^{(0)},$$

$$X_4^{C(Z)} = \frac{1}{2} e^{+r} X_1^{(0)} - \frac{1}{\sqrt{12}} e^{-r} X_2^{(0)} - \sqrt{\frac{1}{6}} e^{-r} X_3^{(0)} - \frac{1}{\sqrt{2}} e^{+(-)r} X_4^{(0)},$$

$$P_4^{C(Z)} = \frac{1}{2} e^{-r} P_1^{(0)} - \frac{1}{\sqrt{12}} e^{+r} P_2^{(0)} - \sqrt{\frac{1}{6}} e^{+r} P_3^{(0)} - \frac{1}{\sqrt{2}} e^{-(+r)} P_4^{(0)}. \quad (4)$$

In the ideal case $r \rightarrow \infty$ corresponding to infinite squeezing, the four-partite clusterlike state is a simultaneous eigenstate of position $X_1^C - X_2^C \rightarrow 0$, $2X_2^C - X_3^C - X_4^C \rightarrow 0$ and momentum $P_1^C + P_2^C + 2P_3^C \rightarrow 0$, $P_3^C - P_4^C \rightarrow 0$; however, a GHZ-like state is a simultaneous eigenstate of total momentum $P_1^Z + P_2^Z + P_3^Z + P_4^Z \rightarrow 0$ and relative position $X_i^Z - X_j^Z \rightarrow 0$ ($i, j = 1, 2, 3, 4$).

IV. APPLICATION TO THE TELEPORTATION NETWORK

The teleportation network protocol involving four participants Alice, Bob, Claire, and Doris is shown as follows. Let us send the four modes of Eq. (4) to Alice, Bob, Claire, and

Doris, respectively. Alice wants to teleport an unknown quantum state and couples her mode 1 with the unknown input mode $X_u=(X_{in}-X_1)/\sqrt{2}$, $P_v=(P_{in}+P_1)/\sqrt{2}$. Alice measures classical values x_u and p_v for X_u and P_v . Alice sends her classical results x_u and p_v to Bob or Claire or Doris via classical channels. For clusterlike states, Bob, Claire, or Doris want to reconstitute the input state provided that additional classical information is received: Bob needs the result of a momentum detection by Claire reducing P_3^C to p_3^C ; Claire needs the results of a momentum detection by Bob reducing P_2^C to p_2^C and a position detection by Doris reducing X_4^C to x_4^C ; Doris needs the results of a momentum detection by Bob reducing P_2^C to p_2^C and a position detection by Claire reducing X_3^C to x_3^C . Assuming that Claire detects her mode 3 and sends the result to Bob, a displacement of Bob's mode 2, $X_2^C \rightarrow X_{tel}=X_2^C+g\sqrt{2}X_u$, $P_2^C \rightarrow P_{tel}=P_2^C+g\sqrt{2}P_v+g_3P_3^C$, accomplishes the teleportation. Here, the parameters g and g_3 describe the normalized gain. For $g=1$, the teleported mode becomes

$$\begin{aligned} X_{tel}^{Bob} &= X_{in} - \frac{2}{\sqrt{3}}e^{-r}X_2^{(0)} + \sqrt{\frac{2}{3}}e^{-r}X_3^{(0)}, \\ P_{tel}^{Bob} &= P_{in} + \left(1 + \frac{g_3}{2}\right)e^{-r}P_1^{(0)} + \frac{1}{\sqrt{3}}\left(1 - \frac{g_3}{2}\right)e^{+r}P_2^{(0)} \\ &\quad + \sqrt{\frac{2}{3}}\left(1 - \frac{g_3}{2}\right)e^{+r}P_3^{(0)} + \frac{g_3}{\sqrt{2}}e^{-r}P_4^{(0)}. \end{aligned} \quad (5)$$

Now we assume arbitrary coherent-state input $a_{in}=X_{in}+iP_{in}$ and calculate teleportation fidelity, in this case defined by $\mathcal{F}=\langle a_{in} | \rho_{tel} | a_{in} \rangle$. It describes the overlap between the input and the teleported states. In the case of unity gain $g=1$, the fidelity for the Gaussian states is simply given by $\mathcal{F}=2/\sqrt{(1+\langle \delta^2 \hat{X}_{tel} \rangle)(1+\langle \delta^2 \hat{P}_{tel} \rangle)}$. The optimum teleportation fidelity for Bob is achieved with $g_3=2(e^{+4r}-1)/(e^{+4r}+3)$ and becomes

$$\mathcal{F}_{opt} = \left[(1+e^{-2r}) \left(1 + \frac{3e^{+6r} + 10e^{+4r} + 3e^{-2r}}{(e^{+4r} + 3)^2} \right) \right]^{-1/2}. \quad (6)$$

For $r=0$, we obtain $\mathcal{F}_{class}=1/2$, which corresponds to the classical limit. When $r>0$, the fidelity of Bob's output is larger than $1/2$; thus the quantum teleportation is successful. Assuming that Alice teleports the unknown state to Claire, Claire needs Alice's classical values x_u and p_v and the additional classical information of the momentum detection by Bob and the position detection by Doris. Claire performs a local unitary squeezed transform $a_3'=\frac{1}{2}X_3^C+2P_3^C$ and displaces her mode 3, $X_3^C \rightarrow X_{tel}=\frac{1}{2}X_3^C+g\sqrt{2}X_u+g_4X_4^C$, $P_3^C \rightarrow P_{tel}=2P_3^C+g\sqrt{2}P_v+g_2P_2^C$, to accomplish the teleportation. For $g=1$, the teleported mode becomes

$$\begin{aligned} X_{tel}^{Claire} &= X_{in} - \frac{1}{4}(1-2g_4)e^{+r}X_1^{(0)} - \frac{1}{4\sqrt{3}}(7+2g_4)e^{-r}X_2^{(0)} \\ &\quad - \left(\frac{1}{2\sqrt{6}} + \frac{g_4}{\sqrt{6}} \right) e^{-r}X_3^{(0)} + \frac{1}{2\sqrt{2}}(1-2g_4)e^{+r}X_4^{(0)}, \end{aligned}$$

$$\begin{aligned} P_{tel}^{Claire} &= P_{in} + \left(\frac{3}{2} + \frac{g_2}{2} \right) e^{-r}P_1^{(0)} + \frac{1}{2\sqrt{3}}(1-g_2)e^{+r}P_2^{(0)} \\ &\quad - \sqrt{\frac{2}{3}}(1-g_2)e^{+r}P_3^{(0)} + \sqrt{2}g_2e^{-r}P_4^{(0)}. \end{aligned} \quad (7)$$

We may achieve the optimum teleportation by the optimum g_2 and g_4 . Similarly, if Alice teleports the unknown state to Doris, Doris needs Alice's classical values x_u and p_v and the additional classical information of the momentum detection by Bob and the position detection by Claire. Thus we see that the quantum teleportation network using a CV clusterlike state is quite asymmetric among the parties, and the required additional classical information and fidelity for the finite squeezing depend on the partners. In contrast, the quantum teleportation network using a CV GHZ-like state is symmetric among the parties, and the required additional classical information and fidelity for the finite squeezing are independent of the partners [9].

V. CONCLUSION

We have introduced a continuous-variable Gaussian analog of cluster states. We have proposed an interaction model to realize CV clusterlike states and compared these states to GHZ-like states in terms of LOCC. Those states are different from GHZ states and the entanglement of the states is harder to destroy than for GHZ states. We have generalized the one-dimensional CV cluster to graph states. To embody CV cluster states, we have described experimental setups of atomic ensembles and squeezed light that offer nice perspectives in the study of CV multipartite entangled states. Cluster states for CV multipartite entanglement may be applied to multipartite quantum protocols and are of practical importance in realizing more complicated quantum communication among many parties.

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