Hyperentanglement witness

Giuseppe Vallone,1,2∗ Raino Ceccarelli,1 Francesco De Martini,1,2,3 and Paolo Mataloni1,2

1 Dipartimento di Fisica della Sapienza Università di Roma, Roma, 00185 Italy
2 Consorzio Nazionale Interuniversitario per le Scienze Fisiche della Materia, Roma, 00185 Italy
3Accademia Nazionale dei Lincei, via della Lungara 10, Roma 00165, Italy

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A new criterium to detect the entanglement present in a hyperentangled state, based on the evaluation of an entanglement witness, is presented. We show how some witnesses recently introduced for graph states, measured by only two local settings, can be used in this case. We also define a new witness $W_3$ that improves the resistance to noise by increasing the number of local measurements.

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I. INTRODUCTION

Quantum entanglement represents the basic property underlying many quantum computation processes and quantum cryptographic schemes. It guarantees in principle secure cryptographic communications and a huge speedup of some important computation tasks. In this respect entanglement represents the basis of the exponential parallelism of the future quantum computers.

By using optical techniques the entanglement was realized in many experiments, either with quantum states based on two [1], four [2, 3, 4], or even six photons [5], or, more recently, with multiphoton states, containing more than 10000 entangled particles [6].

By hyperentanglement more degrees of freedom (DOF’s) of the photons are involved and entangled states spanning a high-dimension Hilbert space can be created [7, 8, 9, 10]. A hyperentangled (HE) state encoded in $n$ DOF’s is expressed by the product of $n$ Bell states, one for each DOF. Double Bell HE states of two photons (i.e. with $n = 2$) are currently realized in the laboratories and enable to perform tasks that are usually not achievable with normally entangled states. Among many applications, the realization of a complete Bell state analysis [11, 12, 13], and the recently realized enhanced dense coding [14], are particularly worth of noting. By operating with HE states of two photons and $n$ independent DOF’s we are able to encode the information in $2n$ qubits. This significatively reduces the typical decoherence problems of multiphoton states based on the same number of qubits and dramatically increases the detection efficiency. HE states of increasing size are also important for the realization of advanced quantum nonlocality tests and represent a viable resource to increase the power of computation of a scalable quantum computer operating in the one-way model [14, 16]. Indeed it has been recently demonstrated that efficient 4-qubit 2-photon cluster states are easily created starting from 2-photon HE

states [17, 18, 19, 20].

The analysis of multiqubit entangled states performed by quantum state tomography is particularly demanding since the number of required measurements scales exponentially with the number of qubits. Furthermore, in practical realizations entanglement is degraded by decoherence and by any dissipation processes deriving from the unavoidable coupling with the environment. Being entanglement an expensive resource, its efficient detection with the minimum number of measurements is a crucial issue and new efficient analysis tools are necessary to characterize the entanglement of a particular multiparticle state. The method of “entanglement witness” [21, 22] (see Fig. 1 for a geometrical representation of an entanglement witness), first demonstrated for entangled states of two photons [23] allows us to assess the presence

*URL: http://quantumoptics.phys.uniroma1.it/
of entanglement by using only a few local measurements. After its introduction the use of entanglement witness was extended to the detection of entanglement of various kinds of four qubit entangled states \([3][1][7][24]\) and \(N\)-qubit cluster states. At the same time a big effort was spent in the study of the entanglement witness operator properties \([25][26][27][28][29]\) and their non-linear generalization \([30][31]\).

By the present paper we address the timely question of finding a criterium to determine the presence of entanglement in HE states and introduce an entanglement witness which enables to detect entanglement in these states. This criterium is different from those used in case of multiparticle entangled states, where each qubits is encoded in a different particle. The difference resides in the different partitions that can be made in the two cases as it will be shown in the following section.

II. WITNESS FOR HYPERENTANGLED STATE

Let’s consider the generic DOF \(A_j (B_j)\), with \(j = 1, \ldots, n\), of particle \(A (B)\). Each DOF spans a 2-dimensional Hilbert space (i.e. it is equivalent to a qubit) whose basis is \([\{0\}_A, \{1\}_A]\) \((\{0\}_B, \{1\}_B)\) for particle \(A (B)\). In this way each particle encodes exactly \(n\) qubits. Let’s define

\[U ≡ \{A_1, B_1, \ldots, A_n, B_n\}\] (1)

the set containing the entire number of DOF’s. The (pure) HE state is written as

\[|\Xi⟩ = |φ^+⟩_{A_1B_1}|φ^+⟩_{A_2B_2} \cdots |φ^+⟩_{A_nB_n}, (2)\]

where

\[|φ^+⟩_{A_jB_j} ≡ \frac{1}{\sqrt{2}} (|0⟩_A |0⟩_B + |1⟩_A |1⟩_B)\] (3)

represents a maximally entangled Bell state. In general \(|φ^+⟩\) can be replaced with any maximally entangled state (this corresponds to apply single qubit unitaries on the HE state). In the language of graph states, a HE state can be interpreted as a graph state up to a Hadamard gate applied to each qubit \(A_j\) (see Fig. 2). Let’s define now the following \(N = 2n\) operators

\[
\begin{cases}
S_{2j} = Z_j^A Z_j^B \\
S_{2j-1} = X_j^A X_j^B
\end{cases}
\]

\(j = 1, \ldots, n\) (4)

where \(Z_j^A : X_j^A (Z_j^B : X_j^B)\) are respectively the Pauli matrices \(σ_z\) and \(σ_x\) acting on the \(j\)th DOF of particle \(A (B)\). By using the stabilizer formalism \([32]\) the HE state can be also defined as the state satisfying

\[S_k|\Xi⟩ = |\Xi⟩, \quad \forall k = 1, \ldots, N\] (5)

In general we can define the stabilizer basis as

\[S_k|s⟩ = (-1)^{s_k}|s⟩ \quad \forall k = 1, \ldots, N\]

\[|s⟩ = \{|s_1, s_2, \ldots, s_N⟩\}\] \(s_k = 0, 1\) (6)

and \(|Ξ⟩ ≡ \{|0, 0, \ldots, 0⟩\}\).

How can we detect entanglement in this case? And also: which kind of entanglement we would like to detect? The entanglement witness method is based on the introduction of a witness \(W\), i.e. a hermitian operator whose expectation value is non negative for a generic separable state, while it is negative for the entangled state we want to detect. Since the witness is defined up to a multiplicative positive constant, here and in the following we fix the normalization of a generic witness \(W\) for the HE state by requiring that

\[⟨Ξ|W|Ξ⟩ = -1\] (7)

The advantages of this choice will become evident when the resistance to noise of the entanglement witness will be evaluated (see Section III).

Let’s define the entanglement we want to discriminate. A state \(|ϕ⟩\) is separable (in the hyperentangled sense) if it satisfies the following condition:

\[\exists j\, \text{such that } |ϕ⟩ = |ϕ_1⟩_{A_I}|ϕ_2⟩_{B_J}\] (8)

In this equation \(\{I, J\}\) represents a generic bi-partition of the set \(T_j ≡ \{A_1, B_1, \ldots, A_n, B_n\}\) \(\{A_j, B_j\}\), so that \(I \cup J = T_j\) and \(I \cap J = \emptyset\).

Definition: A (mixed) state is defined to be hyper-entangled in \(n\) degrees of freedom if it is separately entangled in each of them and cannot be written as a mixture of states that satisfy (8).

In this way the possibility that a classical mixture of two or more states that are not entangled in each DOF, such as those satisfying eq. (8), can be interpreted as hyperentangled, is avoided. This definition of separability is different from the usual definition used in the multiparticle entanglement, where separability is referred to every possible partition of the qubits. In the hyperentangled case a state is separable if it can be expressed by a partition that separates the same DOF, as written in equation (8). This condition is weaker then the usual multiparticle entanglement as it can be immediately seen.

\[\begin{array}{c}
\begin{array}{c}
A_1 \quad B_1 \\
A_2 \quad B_2 \\
A_3 \quad B_3 \\
\vdots \\
A_n \quad B_n
\end{array}
\end{array}\]

\[\text{FIG. 2: (Color online) A Hyperentangled state represented as a graph state where a dots corresponds to a qubit and the links represent the entanglement existing between the corresponding qubits. Dark (green) and bright (yellow) dots represent the degrees of freedom of particles }A\text{ and }B\text{ respectively.}\]
by looking at the state $|\Xi\rangle$ in equation (2); this is a hyperentangled state if $A_1, \cdots, A_n$ ($B_1, \cdots, B_n$) refer to the different DOF's of particle $A$ ($B$). However if any $A_j$ (or $B_j$) represents a different particle, the state $|\Xi\rangle$ is no more completely entangled (or “genuine multipartite entangled”).

The first condition is the entanglement in every DOF. We can then measure $n$ entanglement witnesses. For each DOF $j$ we can introduce a witness given by:

$$W^{(j)} = \mathbb{I}_2 - S_{2j} - S_{2j-1}. \quad (9)$$

If all of them are negative,

$$\text{Tr}[W^{(j)} \rho] < 0 \quad \forall j = 1, \cdots, n \quad (10)$$

we know that there is entanglement in each DOF. Hence all the reduced matrices

$$\rho_j = \text{Tr}_{t \setminus A_j B_j}|\Xi\rangle\langle\Xi|,$$  

obtained by tracing all the DOF’s but $A_j$ and $B_j$, are entangled.

In case of pure states the previous condition assures that each DOF of $A$ is entangled with the corresponding one of $B$. However this condition, although necessary, is not sufficient to demonstrate that the state cannot be created by a classical (i.e. mixed) superposition of states that are not entangled in all the DOF’s. This is clearly explained by a simple example. Let’s consider the case with $n = 2$ and two states

$$\begin{align*}
|\psi_1\rangle &= |0\rangle_{A_1}|0\rangle_{B_1}|\phi^+\rangle_{A_2B_2} \\
|\psi_2\rangle &= |\phi^+\rangle_{A_1B_1}|0\rangle_{A_2}|0\rangle_{B_2}
\end{align*} \quad (12)$$

They are not entangled in every DOF since $|\psi_1\rangle$ ($|\psi_2\rangle$) is separable in the first (second) DOF. Then the two states are not hyperentangled:

$$\begin{align*}
\langle \psi_1 | W^{(2)} | \psi_1 \rangle &= \langle \psi_2 | W^{(1)} | \psi_2 \rangle = -1, \\
\langle \psi_1 | W^{(1)} | \psi_1 \rangle &= \langle \psi_2 | W^{(2)} | \psi_2 \rangle = 0.
\end{align*} \quad (13)$$

However by taking the mixture of these two states with equal weights, $\rho' = \frac{1}{2} |\psi_1\rangle\langle\psi_1| + \frac{1}{2} |\psi_2\rangle\langle\psi_2|$, we obtain

$$\text{Tr}[W^{(1)} \rho'] = \text{Tr}[W^{(2)} \rho'] = -\frac{1}{2}. \quad (14)$$

In this case the mixture of two non HE states is entangled in every DOF. Note that this feature doesn’t depend on the particular choice of the witness $W^{(j)}$ in eq. (10).

The correct identification of a hyperentangled state can be obtained by introducing a hyperentanglement witness for the HE state $|\Xi\rangle$:

$$\tilde{W} = \mathbb{I} - 2|\Xi\rangle\langle\Xi| = \mathbb{I} - \frac{2}{2^N} \sum_{s_1} S_1^{s_1} S_2^{s_2} \cdots S_N^{s_N} \quad (15)$$

In the Appendix we will show that

$$||\langle\varphi|\Xi\rangle|^2 \leq \frac{1}{2} \quad (16)$$

for all the states $|\varphi\rangle$ that satisfy eq. 8. The expectation value of $\tilde{W}$ is thus negative for $|\Xi\rangle$ but is positive for all the states expressed in the form (2), and then it is positive for all their mixtures. For example, it can be easily verified that for the state $\rho'$ in (14) it holds $\text{Tr}[\tilde{W} \rho'] = 0$ and hence $\rho'$ is (correctly) not hyperentangled.

Given a witness $W$, other witnesses $W'$ can be derived on the basis of the following argument [33, 34]: if we can find a constant $\alpha > 0$ such that the operator $O \equiv W' - \alpha W$ is positive definite (i.e. $\text{Tr}[O \rho] \geq 0, \forall \rho$), then $W'$ is a witness. In fact if $\text{Tr}[W' \rho] < 0$ on a generic state $\rho$ it comes out that $\text{Tr}[\tilde{W} \rho] \leq \frac{1}{\alpha} \text{Tr}[W' \rho] < 0$ and thus $\rho$ is entangled.

Following this observation, it is shown in [33, 34] that the following operators

$$\begin{align*}
W_1 &= (N - 1) - \sum_{k=1}^N S_k, \\
W_2 &= 3 - 2 \left( \prod_{\text{odd } k} \frac{S_k + 1}{2} + \prod_{\text{even } k} \frac{S_k + 1}{2} \right) \quad (18)
\end{align*}$$

are witnesses for a generic connected graph state. The same argument can be repeated here, since it uses only the stabilizer equation. In fact, even in the case of a HE state (or whatever state defined in terms of the stabilized equation) the operators $W_1 - \tilde{W}$ and $W_2 - \tilde{W}$ are positive definite. This is simply checked in the stabilizer basis $|s\rangle$ where they are diagonal and thier eigenvalues are non-negative.

We can also introduce here another witness by using the same argument:

$$W_3 = 2 - 3 \prod_{j=1}^n \left( \frac{1 + S_{2j-1} + S_{2j}}{3} \right) \quad (19)$$

In order to demonstrate that $W_3$ is a witness, let’s consider $W_3' = c_0 - 3 \prod_{j=1}^n \left( \frac{1 + S_{2j-1} + S_{2j}}{3} \right)$ and calculate the lowest eigenvalues of $O_3 \equiv W_3' - \alpha \tilde{W}$. If they are positive then $O_3$ is positive definite. The lowest eigenvalues are $\lambda_1 = c_0 - \alpha - 3 + 2\alpha$ for $|\Xi\rangle$ and $\lambda_2 = c_0 - \alpha - 1$ for a state with only one $s_k$ equal to 1. They are equal when $\alpha = 1$ and are both positive when $c_0 \geq 2$. 

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1 The choice of this witness at this stage is arbitrary. Other witnesses, such as $W^{(j)} = \mathbb{I}_2 - 2|\phi^+\rangle_{A_jB_j} \langle \phi^+| = \frac{1}{2} (\mathbb{I}_2 - S_{2j} - S_{2j-1} - S_{2j-2})$ can be chosen. The witness chosen in equation 9 is useful in terms of the measurement settings, as shown in the following.
III. RESISTANCE TO NOISE

The strength of a witness if often measured by its resistance to noise, i.e. the amount of noise that can be added to the entangled state in such a way that the witness still measures it as entangled. Consider the following states

$$\rho = (1 - p_{\text{noise}})\langle \Xi \rangle \langle \Xi \rangle + p_{\text{noise}} \frac{1}{D} \mathbb{I}$$

where we have defined $D = 2^N$ and $p_{\text{noise}}$ measures the amount of (white) noise present in the state. The expectation value of a generic witness (normalized such that $\langle \Xi | W | \Xi \rangle = -1$) is given by

$$\text{Tr}[W \rho] = -1 + p_{\text{noise}} + p_{\text{noise}} \frac{1}{D} \text{Tr}[W]$$

so the state is entangled if

$$p_{\text{noise}} < \frac{D}{\text{Tr}[W] + D} \equiv p_M$$

where $p_M$ is the maximum allowed amount of noise. The trace of $W$ is thus a good measurement of the weakness of the witness: the lower the trace the stronger the resistance to noise. In Table I we show the traces of the above defined witnesses in order of the increasing resistance to noise. While $\widetilde{W}$ is highly resistant to white noise ($p_M$ is always greater than 50%) but requires many measurement settings, $W_1$ and $W_2$ requires only two measurement settings but they are less resistant to noise. For any value of $N$ the resistance to noise of our defined witness $\Psi$ is larger than the witness $W_2$ and $W_1$, and $W_3$ can be seen as a compromise between the need of lowering the number of settings and that of increasing the noise resistance. In general (for any $N$) the noise tolerance of $W_3$ is at least 33%. In conclusion, the resistance to noise of the witness grows with the number of settings needed to evaluate it.

IV. NEW ENTANGLEMENT WITNESS FOR GENERIC GRAPH STATES

The same witness defined in (19) can be used for a generic graph state $|G_N\rangle$ associated to a connected graph of $N$ vertices. The graph state is defined by the stabilizer equation as

$$S_k|G_N\rangle = |G_N\rangle, \quad \forall k = 1, \ldots, N$$

where

$$S_k = X_k \prod_{j \in N_k} Z_j \quad k = 1, \ldots, N$$

Here $X_k (Z_k)$ are the Pauli matrix $\sigma_x (\sigma_z)$ acting on qubit $k$ and $N_k$ is the set of qubits to which it is linked. As shown in (3), for a given connected graph, the following witness detects the genuine N-qubit entanglement of the corresponding graph state $|G_N\rangle^2$:

$$\tilde{W} = 1 - 2|C_N\rangle\langle C_N|$$

Each state of the form $|\phi_1\rangle_A |\phi_2\rangle_B$ (where $A, B$ is a generic partition of the $N$ qubits) has a positive expectation value of this witness.

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2 This witness is slightly different from that defined in [8], due to the normalization constant needed to satisfy [9].
Following the same arguments of the previous section it is possible to show that the followign operator is a witness

\[ W_3 = \begin{cases} 
2 - 3 \prod_{j=1}^{n} \left( \frac{1+S_{j-1}+S_j}{3} \right) & N = 2n \\
2 - 3 \prod_{j=1}^{n} \left( \frac{1+S_{j-1}+S_j}{3} \right) \frac{1+S_N}{2} & N = 2n + 1 
\end{cases} \]

The number of settings needed for \( \tilde{W} \) scales exponentially with the number of qubits \([33]\), while we need more than two measurement settings to determine \( W_3 \). The maximum amount of noise \( p_M \) allowed for \( W_3 \) is shown in table [1].

\[ \text{V. CONCLUSIONS} \]

In this paper we have introduced a method to detect if a 2-particle state is hyperentangled. The method is based on the initial detection of entanglement for each separate degree of freedom. Once this condition is satisfied the negative value of a hyperentanglement witness operator detects the hyperentanglement. We introduced four different hyperentanglement witnesses, namely \( \tilde{W}, W_1, W_2 \) and \( W_3 \). They are characterized by different values of the resistance to noise which grows with the number of measurement settings needed for their evaluation. Precisely, only two local settings are required in the case of \( W_1 \) and \( W_2 \), while for \( W_3 \) and \( W \) their number scales exponentially with the number of DOFs. It is worth noting that the local setting used to measure \( \tilde{W}, W_1, W_2 \) and \( W_3 \) can be also used to measure the witnesses \( W^{(j)} \) (see equation [3]) and then reveal the entanglement corresponding to each DOF separately. For example with the local setting \( Z_1Z_2Z_3Z_4Z_5Z_6 \ldots \) it is possible to measure the observables \( S_2, S_1, S_5, \ldots \) and all their products.

A low number of measurements corresponds to a reduced resistance to noise. Indeed, it is shown that the amount of white noise tolerated by \( W_3 \) and \( \tilde{W} \) exceeds those tolerated by \( W_1 \) and \( W_2 \) (see table [1]).

In general, a hyperentangled state \([2]\) can also be expressed as a maximally entangled state of two qudit, where \( d = 2^n \), since each particle encodes \( n \) qubits. However our approach is different from the usual bipartite qudit entanglement since the witness detecting the bipartite entanglement between the two particles is (up to normalization) \( W = \frac{I}{2^n} - \langle \Xi \rangle \langle \Xi \rangle \) since the maximum overlap between a maximally entangled state of two qudit and a separable state is exactly \( \frac{1}{2^n} \). The witness \([13]\) is far more stringent since many entangled states in the bipartite sense are not hyperentangled. For example the state \( |\psi_1\rangle \) in \([12]\) can be written as \( |00\rangle_A|00\rangle_B + |01\rangle_A|01\rangle_B \). This state clearly shows entanglement between \( A \) and \( B \) but it is not hyperentangled.

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\[ \text{APPENDIX A: DEMONSTRATION} \]

Let the state \( |\varphi\rangle \) satisfy eq. \( [8] \). This means that \( j \) must exist such that \( |\varphi\rangle \) can be written as

\[ |\varphi\rangle = |\varphi_1\rangle_{A,j} |\varphi_2\rangle_{B,j} \]

\[ = (a|0\rangle_{A,j} |\gamma_1\rangle_{j} + b|1\rangle_{A,j} |\gamma_2\rangle_{j}) \]

\[ \otimes (c|0\rangle_{B,j} |\chi_3\rangle_{j} + d|1\rangle_{B,j} |\chi_4\rangle_{j}) \]

with \( |\gamma_i\rangle \) normalized and \( |a|^2 + |b|^2 = |c|^2 + |d|^2 = 1 \). Let’s define \( \gamma_{\mu\nu} \) the overlap between \( |\gamma_\mu\rangle_{j} |\gamma_\nu\rangle_{j} \) and \( \langle \phi^+ |_{A_{j-1}B_{j-1}} \cdots \langle \phi^+ |_{A_{j}B_{j-1}} \langle \phi^+ |_{A_{j+1}B_{j+1}} \cdots \langle \phi^+ |_{A_nB_n} | \phi^+ \rangle_{A_{j}B_{j}} \cdots | \phi^+ \rangle_{A_{j+1}B_{j}} \cdots | \phi^+ \rangle_{A_nB_n} \).

Since the states \( |\gamma_i\rangle \) are normalized we have \( |\gamma_{\mu\nu}|^2 \leq 1 \). By calculating the overlap we obtain

\[ |\langle \Xi | \varphi \rangle |^2 = \langle \phi^+ | (ac\gamma_{13}|00\rangle + ad\gamma_{14}|01\rangle + bc\gamma_{23}|10\rangle + bd\gamma_{24}|11\rangle) | \phi^+ \rangle_{A_{j}B_{j}} = \frac{1}{2} |(ac\gamma_{13} + bd\gamma_{24})|^2 \]

\[ \leq \frac{1}{2} \left( |ac\gamma_{13}|^2 + |bd\gamma_{24}|^2 \right) \leq \frac{1}{2} \left( |ac|^2 + |bd|^2 \right) \leq \frac{1}{2} \left( |a|^2 + |b|^2 \right) = \frac{1}{2} \]

where we used \( |\gamma_{\mu\nu}|^2, |c|^2, |d|^2 \leq 1 \) and the property \( |r + s|^2 \leq |r|^2 + |s|^2 \). The bound is easily saturated, for example by the states of the form

\[ |\phi^+\rangle_{A_1B_1} \cdots |\phi^+\rangle_{A_{j-1}B_{j-1}}|0\rangle_{A_j}|0\rangle_{B_j} |\phi^+\rangle_{A_{j+1}B_{j+1}} \cdots |\phi^+\rangle_{A_nB_n} \]

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