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Entanglement of linear cluster states in terms of averaged entropies

CAO Ye[1], LI Hui[1] & LONG GuiLu[1,2*]

[1] *State Key Laboratory of Low-Dimensional Quantum Physics and Department of Physics, Tsinghua University, Beijing 100084, China;*
[2] *Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing 100084, China*

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An entanglement measure, multiple entropy measures (MEMS) was proposed recently by using the geometric mean of partial entropies over all possible i-body combinations of the quantum system. In this work, we study the average subsystem von Neumann entropies of the linear cluster state and investigated the quantum entanglement of linear cluster states in terms of MEMS. Explicit results with specific particle numbers are calculated, and some analytical results are given for systems with arbitrary particle numbers. Compared with other example quantum states such as the GHZ states and W states, the linear cluster states are "more entangled" in terms of MEMS, namely their averaged entropies are larger than the GHZ states and W states.

average subsystem entropies, cluster states, multiple entropy measures, quantum entanglement

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Entanglement [1, 2] is one of the most salient properties of quantum systems. Quantum entanglement led to the experimental verification for Bell inequality which confirmed quantum mechanics [3]. In recent years, quantum entanglement has been one of the key driving forces that advanced the explosive development of quantum information and quantum computation [4–12]. Entanglement has developed from a philosophical concept into a frontier research paradigm, and much more attention has been paid to the quantification of entanglement. Two measures of entanglement, formation and distillation [15, 16] , were proposed by Bennett et al. Partial von Neumann entropy [15, 16], relative entropy [17, 18], concurrence [19–23] and other contributions [24–48] were also studied and recognized as "good" entanglement measures.

In studying quantum entanglement, the density matrices are often used. It should be mentioned that density matrix can represent different physical quantities. In the case of proper mixture, the density matrix represents the averaged "state" of an ensemble of "molecules", while the improper mixture describes the averaged "state" of a subsystem in a coupled quantum system. Though the mathematical expressions are the same, their physical properties are quite different [49, 50]. In studying quantum entanglement, we are actually using the improper mixture meaning of the density matrix. The reduced density matrix is obtained by tracing out other degrees of freedom of a composite quantum system. Based on separating the correlations encoded by a density matrix into a common set of marginals, Partovi [37] proposed a measurement in which $N!/2$ quantities are used to quantify an N-qubit system. In the case of $N \leqslant 3$, a "good" measurement [38] can be constructed from the arithmetic average entropy of single reduced density matrices. Realizing the lack of one-qubit reduction, Higuchi et al. [51, 52] proposed using the arithmetic mean of two-particle entropies as a measure of entanglement, and reported on a four-qubit entangled state:

$$|M_4\rangle = \sqrt{\frac{1}{6}}[|0011\rangle + |1100\rangle) + \omega(|1010\rangle + |0101\rangle + \omega^2(|1001\rangle + |0110\rangle)], \quad \omega = e^{2i\pi/3}, \tag{1}$$

which is more entangled than the four-qubit GHZ state.

More recently, Liu et al. [53] proposed multiple averaged entropy measures based on a vector with $m = [N/2]$ components: $[S_1, S_2, \cdots, S_m]$, where the S_i is the geometric mean of i-body partial entropy of the system

*Corresponding author (email: gllong@mail.tsinghua.edu.cn)

$$S_n = \left[\prod_{i_1 i_2 \cdots i_n}^{N}, E_{i_1,i_2,\cdots,i_n} \right]^{\frac{1}{C_N^n}}. \quad (2)$$

$E_{i_1,i_2,\cdots,i_n}$ is the i-body von Neumann entropy for the $\{i_1, i_2, \cdots, i_n\}$ particles

$$E_{i_1 i_2 \cdots i_n} = -\mathrm{Tr}[(\rho_\Psi)_{i_1 \cdots i_n} \log_2 (\rho_\Psi)_{i_1 \cdots i_n}], \quad (3)$$

where $\rho_{i_1,i_2,\cdots,i_n}$ is the reduced density matrix with the average of other $N-n$ particles and C_N^n is the combination number

$$C_N^n = \frac{N!}{(N-n)!n!}. \quad (4)$$

The physical picture for S_i can be understood in the following way. First, when i equals 1, it reflects the entanglement feature in terms of single particles. Later on, when $i \geqslant 2$, S_i describes the entanglement of the i-body system as a whole with other $N-n$ particles. The upper bound for $E_{i_1,i_2,\cdots,i_n}$ is n, so if an N-particle state maximizes all the $E_{i_1,i_2,\cdots,i_n}, n = 1,2,\cdots,[N/2]$, it makes S_n equals to n and presents a maximally entangled state. For $N = 2,3$, $[N/2] = 1$, the quantum states that satisfy $S_1 = 1$ are maximum entangled states. For $N = 4$, Higuchi and Sudbery [51] proved that the ideal entangled state which maximizes all the E_{i_1,i_2} does not exist. It should be noted that the MEMS constitutes only part of the entanglement measure. To describe quantum entanglement fully, more quantities are required in addition to the $N/2$ MEMS quantities. While the GHZ states have smaller MEMS than the cluster state, they are bigger in other entanglement measures. For instance, GHZ states have the maximal violation of Bell inequality. This is the reason why a cluster state cannot be reduced to a GHZ state by local operation and classical communication. This is still an interesting and important issue being studied.

Liu et al. [53] studied the W state

$$|W_N\rangle = \sqrt{\frac{1}{N}} \{|0\cdots01\rangle + \cdots + |10\cdots0\rangle\}, \quad (5)$$

and the analytic MEMS were obtained as

$$S_i = \left[-\frac{N-i}{N} \log_2 \frac{N-i}{N} - \frac{i}{N} \log_2 \frac{i}{N} \right]. \quad (6)$$

Obviously, all the S_i are less than 1. Hence, the W state is generally less entangled than the GHZ state in terms of multiple entropy measures (MEMS). The MEMS for the GHZ-states were also obtained and all the GHZ-states S_i are equal to 1. Liu et al. [56] used MEMS and studied the entanglement properties of nine families four-qubit pure states which are classified by SLOCC [47].

In this work, we study the entangled properties of linear cluster state which was proposed by Briegel and Raussendorf for the purpose of persistent entanglement and used to construct a one-way quantum computer [54,55].

The N-qubit linear cluster state [54] is defined as

$$|C_N\rangle = \frac{1}{2^{N/2}} \otimes \left(|0\rangle_a \sigma_z^{a+1} + |1\rangle_a \right). \quad (7)$$

It holds a high persistency of entanglement which means that $\sim N/2$ qubits have to be measured to eliminate the entanglement. Through the Schmidt decomposition, the state can be transformed into another clear form

$$|C_N\rangle = \sum_{i_1,\cdots,i_N} \alpha_{i_1,\cdots,i_N} |i_1\rangle \cdots |i_n\rangle, \quad (8)$$

where i_k is 0 or 1, $k = 1,\cdots,N$. However, the expansion coefficients are not obvious. From the original definition of the linear cluster state, we can find that the expansion contains 2^N items. Under local unitary operation or basis transformation, some items cancel each other. After some tedious calculation, the simplified expressions for $|C_8\rangle, |C_9\rangle, \cdots, |C_{14}\rangle$ are obtained. The simplest expression of $|C_N\rangle$ holds $2^{[N/2]}$ items.

First, we study the S_3 and S_4 of $|C_8\rangle$, whose simplest form is

$$\begin{aligned} |C_8\rangle = & |00101010\rangle + |00100111\rangle + |00010001\rangle \\ & + |00011100\rangle + |11001001\rangle + |11000100\rangle \\ & + |11110010\rangle + |11111111\rangle - |00101001\rangle \\ & - |00100100\rangle - |00010010\rangle - |00011111\rangle \\ & - |11001010\rangle - |11000111\rangle - |11110001\rangle \\ & - |11111100\rangle. \end{aligned} \quad (9)$$

There are $C_8^3 = 56$ combinations of the reduced positions for S_3. We traced all the possible conditions and listed the results in Table 1. It can be found that the entropies are all integers with separate values of 1, 2, and 3. The result of 3 occurs 38 times, 2 occurs 16 times, and 1 occurs only 2 times. S_3 for the eight-qubit linear cluster state is $\sqrt[56]{2^{16}3^{38}} \simeq 2.67$, which is slightly less than 3.

Now it is interesting to check the S_4 of $|C_8\rangle$. After some numerical cyclic reductions, we found that the results of von Neumann entropy are also the same integers as S_3. There are four separate values, 1, 2, 3, and 4. The result of 4 occurs 16 times, 3 occurs 36 times, 2 occurs 16 times, and 1 occurs 2 times. The occurrences of 1 and 2 are the same as S_3. The S_4 for $|C_8\rangle$ is $\sqrt[70]{2^{16}3^{36}4^{16}} = 2^{\frac{\log_2(2^{16}3^{36}4^{16})}{70}} \simeq 2.94$.

Next, we give the results of S_3 and S_4 for the nine-qubit linear cluster state

$$\begin{aligned} |C_9\rangle = & |001010101\rangle - |001010010\rangle - |001001001\rangle \\ & + |001001110\rangle - |000100101\rangle + |000100010\rangle \\ & - |111111001\rangle + |111111110\rangle + |000111001\rangle \\ & - |000111110\rangle - |110010101\rangle + |110010010\rangle \\ & + |110001001\rangle - |110001110\rangle + |111100101\rangle \\ & - |111100010\rangle. \end{aligned} \quad (10)$$

The simplest expression of $|C_9\rangle$ keeps $2^{[9/2]}$ direct product items, which verifies the formula $2^{[N/2]}$ given obove. We list all the resources of S_3 for $|C_9\rangle$ in Table 2. In the case of S_4,

Table 1 Combinations and entropies of $|C_8\rangle$ for S_3. The numbers under the column "reduction" are those qubits that are being traced. The numbers in the column under "remain" are those qubits that are left over after tracing over the "reduction" qubits. The number under column "entropy" is the entropy of the reduced density matrix of the "remain" subsystem

Reduction	Remain	Entropy	Reduction	Remain	Entropy
1 2 3 4 5	6 7 8	1	1 2 3 4 6	5 7 8	2
1 2 3 4 7	5 6 8	2	1 2 3 4 8	5 6 7	2
1 2 3 5 8	4 6 7	3	1 2 3 5 6	4 7 8	2
1 2 3 5 7	4 6 8	3	1 2 3 7 8	4 5 6	2
1 2 3 6 8	4 5 7	3	1 2 3 6 7	4 5 8	3
1 2 4 6 7	3 5 8	3	1 2 4 5 7	3 6 8	3
1 2 4 7 8	3 5 6	3	1 2 4 6 8	3 5 7	3
1 2 4 5 6	3 7 8	2	1 2 4 5 8	3 6 7	3
1 2 5 7 8	3 4 6	3	1 2 6 7 8	3 4 5	2
1 2 5 6 7	3 4 8	3	1 2 5 6 8	3 4 7	3
1 3 5 6 8	2 4 7	3	1 3 4 5 8	2 6 7	3
1 3 5 7 8	2 4 6	3	1 3 6 7 8	2 4 5	3
1 3 4 6 8	2 5 7	3	1 3 4 7 8	2 5 6	3
1 3 4 5 7	2 6 8	3	1 3 5 6 7	2 4 8	3
1 3 4 5 6	2 7 8	2	1 3 4 6 7	2 5 8	3
1 4 6 7 8	2 3 5	3	1 4 5 7 8	2 3 6	3
1 5 6 7 8	2 3 4	2	1 4 5 6 8	2 3 7	3
1 4 5 6 7	2 3 8	3	2 4 5 6 7	1 3 8	3
2 3 4 6 7	1 5 8	3	2 4 6 7 8	1 3 5	3
2 4 5 7 8	1 3 6	3	2 3 4 5 7	1 6 8	3
2 3 4 7 8	1 5 6	3	2 3 6 7 8	1 4 5	3
2 5 6 7 8	1 3 4	2	2 3 5 6 7	1 4 8	3
2 3 5 7 8	1 4 6	3	2 3 4 5 8	1 6 7	3
2 3 4 6 8	1 5 7	3	2 4 5 6 8	1 3 7	3
2 3 4 5 6	1 7 8	2	2 3 5 6 8	1 4 7	3
3 5 6 7 8	1 2 4	2	3 4 5 7 8	1 2 6	2
3 4 6 7 8	1 2 5	2	4 5 6 7 8	1 2 3	1
3 4 5 6 7	1 2 8	2	3 4 5 6 8	1 2 7	2

we just give the total number of each classification for the sake of space.

Using mathematical induction from the complex results obtained for the specific qubit numbers, we found that three types of subsystem von Neumann entropies are the same as in $|C_8\rangle$. The number of $E = 3$ is 63, $E = 2$ is 19, and $E = 1$ is just 2. The S_3 for $|C_9\rangle$ is $\sqrt[84]{2^{19}3^{63}} = 2^{\frac{\log_2(2^{19}3^{63})}{84}} \simeq 2.74$. In the case of S_4, the number of $E = 4$ is 48, $E = 3$ is 57, $E = 2$ is 19 and $E = 1$ is 2. S_4 for $|C_9\rangle$ is $\sqrt[126]{2^{16}3^{36}4^{16}} = 2^{\frac{\log_2(2^{19}3^{57}4^{48})}{126}} \simeq 3.16$.

We studied the S_3 and S_4 for N from 8 to 14, and arranged the results in Tables 3 and 4, respectively. From the classification, we got the rules of S_3 and S_4, which are listed in eqs. (11) and (12), respectively. The number of $E = 1$ is always 2. By means of curve fitting, the numbers of $E = 2$ and $E = 3$ were found to increase linearly and quadratically.

The construction of S_3 component of MEMS for a N-qubit cluster state,

$$\begin{cases} \quad\text{Times} & \text{Entropy} \\ \qquad\quad 2 & E = 1, \\ \quad 3N - 8 & E = 2, \\ C_N^3 - 3N + 6 & E = 3. \end{cases} \tag{11}$$

Table 2 Combinations and entropies of $|C_9\rangle$ for S_3

Reduction	Remain	Entropy	Reduction	Remain	Entropy
1 2 3 4 5 6	7 8 9	1	1 2 3 4 5 7	6 8 9	2
1 2 3 4 5 8	6 7 9	2	1 2 3 4 5 9	6 7 8	2
1 2 3 4 6 9	5 7 8	3	1 2 3 4 6 7	5 8 9	2
1 2 3 4 6 8	5 7 9	3	1 2 3 4 8 9	5 6 7	2
1 2 3 4 7 9	5 6 8	3	1 2 3 4 7 8	5 6 9	3
1 2 3 5 7 8	4 6 9	3	1 2 3 5 6 8	4 7 9	3
1 2 3 5 8 9	4 6 7	3	1 2 3 5 7 9	4 6 8	3
1 2 3 5 6 7	4 8 9	2	1 2 3 5 6 9	4 7 8	3
1 2 3 6 8 9	4 5 7	3	1 2 3 7 8 9	4 5 6	2
1 2 3 6 7 8	4 5 9	3	1 2 3 6 7 9	4 5 8	3
1 2 4 6 7 9	3 5 8	3	1 2 4 5 6 9	3 7 8	3
1 2 4 6 8 9	3 5 7	3	1 2 4 7 8 9	3 5 6	3
1 2 4 5 7 9	3 6 8	3	1 2 4 5 8 9	3 6 7	3
1 2 4 5 6 8	3 7 9	3	1 2 4 6 7 8	3 5 9	3
1 2 4 5 6 7	3 8 9	2	1 2 4 5 7 8	3 6 9	3
1 2 5 7 8 9	3 4 6	3	1 2 5 6 8 9	3 4 7	3
1 2 6 7 8 9	3 4 5	2	1 2 5 6 7 9	3 4 8	3
1 2 5 6 7 8	3 4 9	3	1 3 5 6 7 8	2 4 9	3
1 3 4 5 7 8	2 6 9	3	1 3 5 7 8 9	2 4 6	3
1 3 5 6 8 9	2 4 7	3	1 3 4 5 6 8	2 7 9	3
1 3 4 5 8 9	2 6 7	3	1 3 4 7 8 9	2 5 6	3
1 3 6 7 8 9	2 4 5	3	1 3 4 6 7 8	2 5 9	3
1 3 4 6 8 9	2 5 7	3	1 3 4 5 6 9	2 7 8	3
1 3 4 5 7 9	2 6 8	3	1 3 5 6 7 9	2 4 8	3
1 3 4 5 6 7	2 8 9	2	1 3 4 6 7 9	2 5 8	3
1 4 6 7 8 9	2 3 5	3	1 4 5 6 8 9	2 3 7	3
1 4 5 7 8 9	2 3 6	3	1 5 6 7 8 9	2 3 4	2
1 4 5 6 7 8	2 3 9	3	1 4 5 6 7 9	2 3 8	3
2 4 5 6 7 9	1 3 8	3	2 3 4 6 7 9	1 5 8	3
2 4 6 7 8 9	1 3 5	3	2 4 5 6 8 9	1 3 7	3
2 3 4 5 6 9	1 7 8	3	2 3 4 6 8 9	1 5 7	3
2 3 4 7 8 9	1 5 6	3	2 4 5 7 8 9	1 3 6	3
2 3 4 5 7 9	1 6 8	3	2 3 4 5 8 9	1 6 7	3
2 3 5 6 8 9	1 4 7	3	2 3 6 7 8 9	1 4 5	3
2 5 6 7 8 9	1 3 4	2	2 3 5 6 7 9	1 4 8	3
2 3 5 7 8 9	1 4 6	3	2 3 4 5 7 8	1 6 9	3
2 3 4 5 6 8	1 7 9	3	2 3 4 6 7 8	1 5 9	3
2 4 5 6 7 8	1 3 9	3	2 3 4 5 6 7	1 8 9	2
2 3 5 6 7 8	1 4 9	3	3 5 6 7 8 9	1 2 4	2
3 4 5 7 8 9	1 2 6	2	3 4 5 6 8 9	1 2 7	2
3 4 6 7 8 9	1 2 5	2	4 5 6 7 8 9	1 2 3	1
3 4 5 6 7 9	1 2 8	2	3 4 5 6 7 8	1 2 9	2

Table 3 Results of the three-body von Neumann entropy

N	8	9	10	11	12	13	14
$E = 1$	2	2	2	2	2	2	2
$E = 2$	16	19	22	25	28	31	34
$E = 3$	38	63	96	138	190	253	328

Table 4 Results of the four-body von Neumann entropy

N	8	9	10	11	12	13	14
$E = 1$	2	2	2	2	2	2	2
$E = 2$	16	19	22	25	28	31	34
$E = 3$	36	57	82	111	144	181	222
$E = 4$	16	48	104	192	321	501	743

The construction of S_4 component of MEMS for a N-qubit cluster state,

$$\begin{cases} \text{Times} & \text{Entropy} \\ 2 & E = 1, \\ 3N-8 & E = 2, \\ 2N^2-13N+12 & E = 3, \\ C_N^4 - 2N^2 + 10N - 6 & E = 4. \end{cases} \tag{12}$$

By the definition of MEMS, we obtain the analytic results of S_3 and S_4 for a cluster state with N qubits,

$$S_3 = \left[2^{3N-8}3^{C_N^3-3N+8}\right]^{\frac{1}{C_N^3}}, \tag{13}$$

$$S_4 = \left[2^{3N-8}3^{2N^2-13N+12}4^{C_N^4-2N^2+10N-6}\right]^{\frac{1}{C_N^4}}. \tag{14}$$

We plot the S_3 and S_4 versus N in Figures 1 and 2, respectively. The curves show that as N increases, S_3 and S_4 tend toward the upper bound.

In summary, we used the MEMS entanglement measures to study the linear cluster state with focus on three-body and four-body average von Neumann entropies. All the data were obtained by numerical calculation for N up to 14. The results show that the linear cluster state is more entangled than the GHZ state and the W state in terms of the MEMS quantities. For large N value, the S_3 and S_4 are close to 3 and 4, which are the upper bounds of the three- and four-body von Neumann entropy, respectively. Analytic results of S_3 and S_4 for arbitrary N qubit linear cluster states are obtained, and explicit expressions for them are given. These results are helpful for understanding the entanglement nature of the linear cluster states.

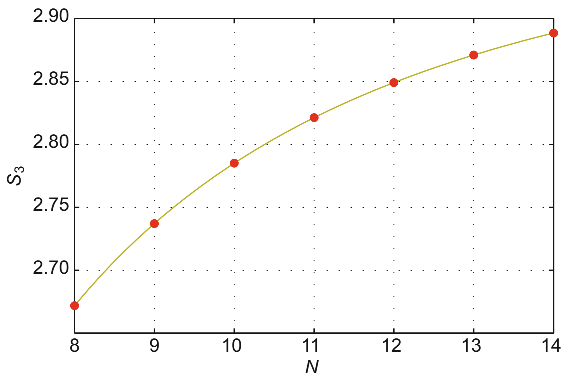

Figure 1 (Color online) S_3 versus N for the linear cluster state.

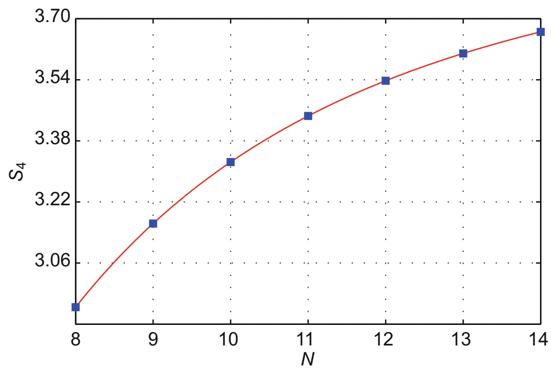

Figure 2 (Color online) S_4 versus N for the linear cluster state.

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