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Controllable quantum correlation of the Heisenberg models with inhomogeneous magnetic field

Q1 Jia-Dong Shi [a], Wen-Chao Ma [a], Xue-Ke Song [b], Dong Wang [a], Liu Ye [a,*]

[a] School of Physics and Material Science, Anhui University, Hefei, 230601, People's Republic of China

[b] Department of Physics, Applied Optics Beijing Area Major Laboratory, Beijing Normal University, Beijing 100875, People's Republic of China

HIGHLIGHTS

- TDD is more robust against temperature than thermal entanglement.
- By increasing coupling coefficients, we create the controllable correlation.
- In ferromagnetic case, TDD always exists while entanglement is destroyed.
- The revival of TDD occurs at critical point, which hinders entanglement.

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ABSTRACT

In this paper, we investigate the quantum correlation witnessed by trace distance discord and thermal entanglement in Heisenberg spin models with an inhomogeneous magnetic field. The results show that quantum correlation can be considerable controlled, and trace distance discord is more robust against temperature than thermal entanglement. Moreover, the quantum correlation at the fixed temperature T can be enhanced with coupling coefficient J increasing or magnetic field thinning. On the other hand, for any T and J both of them always exhibit the strict symmetry with respect to the inversion of magnetic field. Interestingly, we confirm that z-component J_z in XXZ model greatly influences its phase diagram.

1. Introduction

As is well known, one of the most fundamental properties of quantum systems is quantum correlation [1,2], which can distinguish the quantum realm from that of the classical one. These distinctive quantum properties in the past decades have been exploited as the crucial resources in the nontrivial quantum computation and quantum information processing tasks [3–7]. To date, how to precisely quantify and understand quantum correlation remains the subject of active issue in the field of quantum theory [8,9]. Therefore, we will draw our attention to two important quantum correlation witnesses, i.e. trace distance discord and thermal entanglement.

Entanglement [10], as a strong nonclassical correlation among the quantum systems, has been at the forefront of research due to its potential applications in the quantum tasks. However, entanglement cannot account for all aspects of the nonclassical correlations [11,12]. Therefore, quantum discord proposed by Ollivier and Zurek [13] is another well-accepted

* Corresponding author.
E-mail address: yeliu@ahu.edu.cn (L. Ye).

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measure of quantum correlation [14–16]. However, there is an inherent difficult to capture the quantum discord owing to its optimization procedure [17–21]. To avoid this problem, we will use an alternative method to characterize the quantum correlation, i.e. trace distance discord (TDD) [22,23]. Now, TDD has been calculated for the general Bell-diagonal states [24,25] and, more recently, it has been extended for an arbitrary two-qubit X state [26]. On the other hand, in comparison with the other quantum correlation measures, TDD turns out to be more computable and shows some striking properties, such as double sudden change and freezing behaviors [27,28] under the decoherence environment.

In particular, quantum spin system is one of the important physical systems to research the affluent properties of quantum correlation. Motivated by this, we here investigate the trace distance discord and thermal entanglement in Heisenberg models [29–34] with an inhomogeneous magnetic field. Our results show that no matter what kind of spin models, quantum correlation is controllable, and trace distance discord is more robust against temperature than entanglement. Moreover, we can readily obtain the controllable stepwise behaviors of quantum correlation by enhancing coupling coefficients at the fixed temperature. On the other hand, for any T and J both of them show strict symmetry with respect to the inversion of magnetic field all along, which are mainly due to the obvious symmetry properties of the model. At last, we confirm that z-component J_z in XXZ model greatly influences its phase diagram.

The paper is organized as follows. In Section 2 we introduce the physical model of spin-1/2 Heisenberg model with an inhomogeneous magnetic field in detail. In Section 3 we briefly review tow reliable quantum correlation witnesses, i.e. trace distance discord and thermal entanglement. Section 4 is devoted to studying the robustness and controllability of quantum correlation in the Heisenberg spin model. Finally conclusions are given in Section 5.

2. The physical model: Heisenberg model with inhomogeneous magnetic field

In this paper, we consider a two-qubit anisotropic spin-1/2 Heisenberg XYZ-type model in the presence of an inhomogeneous external magnetic field. Then, the Hamiltonian can be expressed as [35,36]

$$H = \frac{1}{2}\left[J_x\sigma_1^x\sigma_2^x + J_y\sigma_1^y\sigma_2^y + J_z\sigma_1^z\sigma_2^z + (B+b)\,\sigma_1^z + (B-b)\,\sigma_2^z\right], \tag{1}$$

where σ_i^k $(k = x, y, z)$ are the Pauli operators acting on qubit i $(i = 1, 2)$, and J_k are the real coupling coefficients for the spin–spin interaction between two nearest neighbor spins in the corresponding spin direction. The chain is antiferromagnetic for $J_k > 0$ and ferromagnetic for $J_k < 0$. For simplicity, we here take the magnetic field along the z-direction into account, and on the two spins B controls the degree of homogeneity while b is the inhomogeneity part.

Without loss of generality, we choose $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$ as the standard base and the Hamiltonian (1) can be expressed as

$$H = \frac{1}{2}\begin{pmatrix} J_z + 2B & 0 & 0 & J_x - J_y \\ 0 & -J_z + 2b & J_x + J_y & 0 \\ 0 & J_x + J_y & -J_z - 2b & 0 \\ J_x - J_y & 0 & 0 & J_z - 2B \end{pmatrix}. \tag{2}$$

By diagonalizing the above Hamiltonian, the eigenvalues $\{E_m\}$ and the corresponding eigenstates $\{|\varphi_m\rangle\}$ are, respectively

$$E_1 = \frac{1}{2}\left(J_z + \sqrt{4B^2 + J_-^2}\right), \qquad |\varphi_1\rangle = \frac{1}{\sqrt{1+\eta^2/J_-^2}}\left(\frac{\eta}{J_-}|00\rangle + |11\rangle\right),$$

$$E_2 = \frac{1}{2}\left(J_z - \sqrt{4B^2 + J_-^2}\right), \qquad |\varphi_2\rangle = \frac{1}{\sqrt{1+\gamma^2/J_-^2}}\left(\frac{\gamma}{J_-}|00\rangle + |11\rangle\right),$$

$$E_3 = \frac{1}{2}\left(-J_z + \sqrt{4b^2 + J_+^2}\right), \qquad |\varphi_3\rangle = \frac{1}{\sqrt{1+\kappa^2/J_+^2}}\left(\frac{\kappa}{J_+}|01\rangle + |10\rangle\right),$$

$$E_4 = \frac{1}{2}\left(-J_z - \sqrt{4b^2 + J_+^2}\right), \qquad |\varphi_4\rangle = \frac{1}{\sqrt{1+\mu^2/J_+^2}}\left(\frac{\gamma}{J_+}|01\rangle + |10\rangle\right),$$

where $J_+ = J_x + J_y, J_- = J_x - J_y$, $\eta = 2B + \sqrt{4B^2 + J_-^2}$, $\gamma = 2B - \sqrt{4B^2 + J_-^2}$, $\kappa = 2b + \sqrt{4b^2 + J_+^2}$ and $\mu = 2b - \sqrt{4b^2 + J_+^2}$.

When the system is in thermal equilibrium temperature T, we can describe the state of the system by following density operator, which based on above eigenvalues and eigenstates as follows

$$\rho(T) = \exp(-\beta H)/Z = \frac{1}{Z}\sum_{i=1}^{4} \mathrm{e}^{-\beta E_m}|\varphi_m\rangle\langle\varphi_m|, \tag{3}$$

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