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Simultaneous observation of quantum contextuality and quantum nonlocality

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Abstract Quantum nonlocality and quantum contextuality are the most curious properties that change our understanding of nature, and were observed independently in recent decades. One important question is whether both properties can be observed simultaneously. In this letter, we show that in a qutrit-qutrit system we can observe quantum nonlocality and quantum contextuality at the same time. From the perspective of quantum information, our experiment proves in principle that the two resources, quantum nonlocality and quantum contextuality, can be utilized simultaneously.

Keywords Quantum contextuality, Quantum nonlocality, Monogamy, qutrit-qutrit system

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1. INTRODUCTION

Quantum mechanics (QM) has radically subverted our intuition of nature. The most striking aspects of it is quantum nonlocality which is revealed by Bell theorem [1] and quantum contextuality which is revealed by Bell-Kochen-Specker theorem [2, 3]. It has been recently recognized that quantum nonlocality is essential for device-independent secure communication [4–6], and quantum contextuality supplies the power for universal quantum computation via magic state distillation [7–11].

The relation between quantum contextuality and quantum nonlocality is a fundamental problem in QM. Stairs [12], Heywood and Readhead [13] found that single-particle contextuality can be transferred to two-particle nonlocality in the presence of Einstein-Podolsky-Rosen (EPR) correlations between two particles of spin 1 or higher. In a recent work, Cabello [14] claimed that contextuality played a fundamental role in quantum nonlocality. This means that contextuality may play a more important role in QM, and this phenomenon has been observed in experiment [15]. It is very surprising that if one restricts oneself to simple forms of nonlocality, such as Clauser-Horne-Shimony-Holt (CHSH) inequality [16], and single-particle contextuality, such as Klyachko-Can-Binicioglu-Shumovsky (KCBS) inequality [17], there are monogamies between them [18–21]. So an important question is arisen, "Can we have single-particle contextuality and two-particle non-locality in the same system?".

In this paper, we show that in our scheme one can observe quantum contextuality and quantum nonlocality simultaneously in a qutrit-qutrit system. Alice and Bob shares two maximally entangled qutrits, and they can observe a violation of a nonlocal Bell inequality [22], and at the same time, Alice can observe a violation of local BKS inequality [22] using the same observables that used to disprove the nonlocal Bell inequality. This sheds new light on the old problem: what is the relation between contextuality and nonlocality, and whether both resources can be observed simultaneously in an experiment.

2. THEORY

Suppose the two qutrits are initially prepared on a maximally entangled state

$$|\Psi\rangle = (|00\rangle + |11\rangle + |22\rangle)/\sqrt{3}. \tag{1}$$

The measurements can be defined as $A_i = B_i = I - 2|a_i\rangle\langle|a_i|$ $(i = 1, 2, ..., 13)$ in which I is a 3×3 identity matrix and $|a_i\rangle$ are the following three-dimensional unit vectors

$$\begin{aligned}
|a_1\rangle &= \frac{1}{\sqrt{3}}\begin{pmatrix}-1\\1\\1\end{pmatrix}, |a_{5,6}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\\pm1\end{pmatrix}, |a_{11}\rangle = \begin{pmatrix}1\\0\\0\end{pmatrix},\\
|a_2\rangle &= \frac{1}{\sqrt{3}}\begin{pmatrix}1\\-1\\1\end{pmatrix}, |a_{7,8}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\0\\\pm1\end{pmatrix}, |a_{12}\rangle = \begin{pmatrix}0\\1\\0\end{pmatrix},\\
|a_3\rangle &= \frac{1}{\sqrt{3}}\begin{pmatrix}1\\1\\-1\end{pmatrix}, |a_{9,10}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\\pm1\\0\end{pmatrix}, |a_{13}\rangle = \begin{pmatrix}0\\0\\1\end{pmatrix},\\
|a_4\rangle &= \frac{1}{\sqrt{3}}\begin{pmatrix}1\\1\\1\end{pmatrix}.
\end{aligned} \tag{2}$$

Any local hidden variable theories (LHVTs) satisfies