Experimental Demonstration of the Einstein-Podolsky-Rosen Steering Game Based on the All-Versus-Nothing Proof

Kai Sun,[1,2] Jin-Shi Xu,[1,2,*] Xiang-Jun Ye,[3] Yu-Chun Wu,[1,2] Jing-Ling Chen,[3,4,†]
Chuan-Feng Li,[1,2,‡] and Guang-Can Guo[1,2]
[1]*Key Laboratory of Quantum Information, University of Science and Technology of China, CAS, Hefei 230026, People's Republic of China*
[2]*Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, People's Republic of China*
[3]*Theoretical Physics Division, Chern Institute of Mathematics, Nankai University, Tianjin 30071, People's Republic of China*
[4]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore*
(Received 1 April 2014; revised manuscript received 27 July 2014; published 30 September 2014)

Einstein-Podolsky-Rosen (EPR) steering, a generalization of the original concept of "steering" proposed by Schrödinger, describes the ability of one system to nonlocally affect another system's states through local measurements. Some experimental efforts to test EPR steering in terms of inequalities have been made, which usually require many measurement settings. Analogy to the "all-versus-nothing" (AVN) proof of Bell's theorem without inequalities, testing steerability without inequalities would be more strong and require less resources. Moreover, the practical meaning of steering implies that it should also be possible to store the state information on the side to be steered, a result that has not yet been experimentally demonstrated. Using a recent AVN criterion for two-qubit entangled states, we experimentally implement a practical steering game using quantum memory. Furthermore, we develop a theoretical method to deal with the noise and finite measurement statistics within the AVN framework and apply it to analyze the experimental data. Our results clearly show the facilitation of the AVN criterion for testing steerability and provide a particularly strong perspective for understanding EPR steering.

DOI: 10.1103/PhysRevLett.113.140402 PACS numbers: 03.65.Ud, 03.67.-a, 42.50.Ex, 42.50.Xa

In 1935, Einstein-Podolsky-Rosen (EPR) published their famous paper proposing a now well-known paradox (the EPR paradox) that cast doubt on the completeness of quantum mechanics [1]. To investigate the EPR paradox, Schrödinger introduced the concept of "steer" [2], now known as the EPR steering [3]. As an asymmetric concept, EPR steering describes the ability of a system to nonlocally affect the states of another system through local measurements. EPR steering exists between the concepts of entanglement and Bell nonlocality [4]; these steerable states are a subset of the entangled states and a superset of Bell nonlocal states [3]. A quantitative criterion for realizing EPR steering based on the uncertainty relation has been proposed [5] and experimentally demonstrated [6,7], and the steerability of quantum states has been further formulated and characterized by general EPR steering inequalities [8]. This method, which usually requires many measurement settings, has been used to demonstrate the steerability of a class of Bell-local states, where states are still steerable even if they do not violate the Bell inequalities [9]. Recently, a new family of EPR steering inequalities based on entropic uncertainty relations have also been proposed and demonstrated experimentally [10,11].

When characterizing Bell nonlocality, the strongest conflict between the predictions of quantum mechanics and the local-hidden-variable theory appears in the so-called all-versus-nothing (AVN) demonstration [12], in which the outcomes predicted by quantum mechanics occur with a probability of 0 and with a probability of 1 for the local-hidden-variable theory and vice versa. In the AVN demonstration, inequalities are not needed [13,14] and so has been used to test nonlocality using a hyperentangled source [15–17]. An AVN proof for EPR steering was recently proposed for two-qubit entangled states [18], in which the different pure normalized conditional states (NCS) in one qubit were used as a criterion along with a given projective measurement on the other. According to quantum mechanics, two different pure NCS should be obtained, while the local hidden state (LHS) model predicts that one cannot obtain two different pure NCS when the other qubit is performed by a projective measurement [18].

There is practical meaning in the concept of steering, which implies that it should be possible to store the state information on the side to be steered. Physically, Bob measures his qubit after receiving the measurement results sent by Alice. However, there has been no related experimental demonstration of this result. Therefore, in this Letter we propose a practical steering game using quantum memory and experimentally demonstrate it by employing the AVN criterion [18]. The particle to be steered is initially stored in quantum memory. After measurement of the other particle, we can then check the states of the particle in the

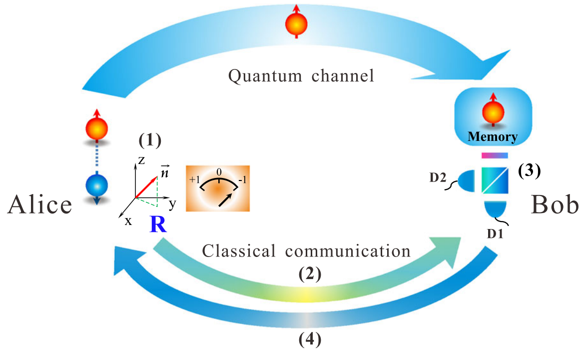

FIG. 1 (color online). Illustration of the EPR steering game. (1) Alice measures her own qubit along the direction $\vec{n}$ and obtains the outcomes of $+1$ and -1. (2) Through a classical channel, Alice tells Bob her measurement outcome and the corresponding output state that Bob should obtain. (3) Bob verifies the normalized conditional states. (4) Alice and Bob implement a joint measurement. They determine the value of $\langle\mathcal{W}\rangle_{\max}$ and compare it with the upper bound predicted by the LHS model (C_{LHS}).

quantum memory and verify the steerability of the states they shared.

The EPR steering game is shown in Fig. 1. Two-qubit entangled states are first prepared by one participant, Alice, who claims that these states are steerable. However, the other participant, Bob, does not trust Alice. Alice then starts the game by sending the steerable qubit to Bob through quantum channels, who stores it in quantum memory. To verify steerability, Alice then chooses a measurement direction $\vec{n}$ to make sure two different pure NCS are collapsed to the particle owned by Bob (denoted as $\rho_B^{\vec{n}}$). According to the measurement outcome, Alice tells Bob though classical communication which pure states ($|\phi\rangle_B$) he should obtain. Bob then reads the qubit from quantum memory, which is an indispensable part because the qubit through the quantum channel comes earlier than the signal from Alice via the classical channel and checks it by projecting the qubit into the corresponding states and replies to Alice. The detector $D1$ is used to detect $|\phi\rangle_B$ with the probabilities denoted by P_+ and P_- according to the outcomes $+1$ and -1 of Alice, respectively. The detector $D2$ is used to detect the states that are orthogonal to $|\phi\rangle_B$, where the corresponding probabilities are denoted by P'_+ and P'_- which correspond to $\mathcal{W}_1$ and $\mathcal{W}_2$ in Ref. [18]. If two different pure NCS are obtained by Bob, i.e., the values of P_+ and P_- are both equal to 1, and P'_+ and P'_- are both equal to 0, the entangled states they shared are steerable. In general, there is no reason for Bob to agree with Alice that the initial state they shared is entangled. For example, Alice may cheat Bob, or there could be some sort of environmental disturbance that changes the state properties. To verify the result and rule out the possibility of cheating, Alice and Bob implement a joint measurement. It has been shown that a value of the equation

$$\Delta = \langle\mathcal{W}\rangle_{\max} - C_{\mathrm{LHS}} \tag{1}$$

should further be checked to verify the steerability of the shared states even if two different pure NCS are obtained by Bob [18]. In the equation, $\langle\mathcal{W}\rangle_{\max}$ represents the maximal mean value of the joint operator $\mathcal{W} = |n^\perp\rangle\langle n^\perp| \otimes |\hat{n}_B\rangle\langle\hat{n}_B|$, with Alice measuring along the $n^\perp$ direction (perpendicular to n) and Bob measuring along $|\hat{n}_B\rangle = \cos(\theta_B/2)|0\rangle + \sin(\theta_B/2)e^{i\phi_B}|1\rangle$. Furthermore, the equation

$$C_{\mathrm{LHS}} = \max_{n_B}\mathrm{Tr}(\rho_{AB} I \otimes |\hat{n}_B\rangle\langle\hat{n}_B|) \tag{2}$$

represents the upper bound predicted by the LHS model, where $I = \frac{1}{2}(|+n\rangle\langle+n| + |-n\rangle\langle-n|)$ is the identity operation of $\vec{n}\vec{\sigma}$ with $|\pm n\rangle$ being the eigenstates of $\vec{n}\vec{\sigma}$ and $\vec{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ representing the vectors of the Pauli matrices. If $\Delta > 0$, the steering game is verified to be successful, while $\Delta \leq 0$ indicates the steering game failed.

However, in practice, the measured states on Bob's side can never be sure to be indeed pure due to the effect of noise and finite measurement statistics. We develop a theoretical method to deal with the experimental errors within the AVN framework [19]. Assuming the values of P'_+ and P'_- whose results should be both 0 in theory are ϵ_1 and ϵ_2, i.e.,

$$\begin{aligned} P'_+ &= \epsilon_1, \qquad P_+ = 1 - \epsilon_1, \\ P'_- &= \epsilon_2, \qquad P_- = 1 - \epsilon_2, \end{aligned} \tag{3}$$

we prove that the shared state is steerable in the case of two settings if the following inequation is violated,

$$\Delta' = (OB - OG)_{\min} \leq 0, \tag{4}$$

where OB is the length of a Bloch vector predicted by the LHS model, and OG is the corresponding length determined by the experimental results of P'_+, P'_-, $\mathcal{W}_{\max}$ with its probability P_D and $\mathcal{W}'$ which represents the other eigenvalue of the $n^\perp$ direction relative to $\mathcal{W}_{\max}$. The inequation (4) is derived and discussed in detail in the Supplemental Material [19]. Here we give a short discussion on the main idea of the criterion. According to the definition of steering, if a state is not steerable, then there is a LHS model to describe the conditional states on Bob's side after Alice's measurement. In the case of two measurement settings, it has been proved that four hidden states are enough to simulate the four conditional states on Bob's side [20]. We show that these states can be mapped to states in the X-Z plane of a Bloch sphere. We further show that if there is not a LHS model on an isosceles trapezoid to represent the symmetrical conditional states, then there is not a LHS model for the four conditional states on Bob's side. As a result, according to the geometry relationship between the states in the X-Z plane (corresponding figures can be found in the Supplemental Material [19]), we can derive the criterion; i.e., if $OB > OG$, then the state we discussed is steerable. There are experimental errors in measuring the corresponding experimental values. We need to find the minimum value of $OB - OG$ by scanning the region given by the measured value with the corresponding errors. The final criterion is then given by the form of inequation (4).

In our experiment, we prepare two kinds of polarization entangled states to demonstrate the EPR steering game

$$\rho_1 = \eta|\Psi(\theta)\rangle\langle\Psi(\theta)| + (1-\eta)|\Phi(\theta)\rangle\langle\Phi(\theta)|,$$
$$\rho_2 = \eta|\Psi(\theta)\rangle\langle\Psi(\theta)| + \frac{1-\eta}{2}(|HH\rangle\langle HH| + |VV\rangle\langle VV|), \tag{5}$$

where $0 \leq \eta \leq 1$. Here, $|\Psi(\theta)\rangle = \cos\theta|HH\rangle + \sin\theta|VV\rangle$ and $|\Phi(\theta)\rangle = \cos\theta|VH\rangle + \sin\theta|HV\rangle$, where $|H\rangle$ denotes the horizontal polarization of the photons and $|V\rangle$ denotes the vertical polarization. Our experimental setup is shown in Fig. 2. The entangled photon pairs are generated via spontaneous parametric down-conversion (SPDC) [21]. The two-photon states ρ_1 and ρ_2 are prepared by Alice using the unbalanced Mach-Zehnder (UMZ) interferometer setup [22] which is explained in detail in the Supplemental Material [19]. The unit consisting of a quarter-wave plate (QWP) and a half-wave plate (HWP), denoted as Mu, is used to set the measurement direction $\vec{n}$. Single-photon detectors (SPD) equipped with 3 nm interference filters (IF) are used to count the photons. The electric signal from the SPD on Alice's side is divided into two parts. One part is used as the trigger signal for the function generator (FG) while the other part is sent to the coincidence unit. The photon sent to Bob is then delayed by a 50 m long single mode fiber (SMF), which works as a quantum memory cell [23]. We use a free-space electro-optic modulator (EOM) (Qioptiq, LM0202 PHAS) on Bob's side to set the measurement basis, which is triggered by the signal from Alice (connected by FG). Phase compensation (PC) crystals compensate for the birefringent effect. The performance quality of the quantum memory cell and EOM in

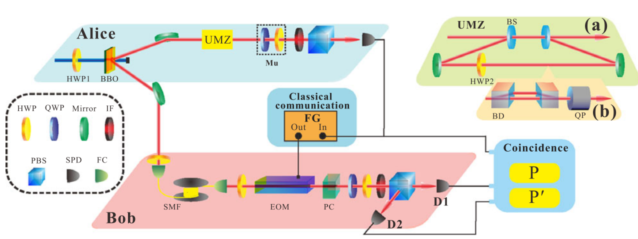

FIG. 2 (color online). Experimental setup. The entangled photon pairs are produced via SPDC. An unbalanced Mach-Zehnder (UMZ) interferometer (a) is employed to prepare the states ρ_1. The state ρ_2 is prepared by inserting UMZ (b) consisting of two beam displacers (BD) and a quartz plate (QP) in the long arm of UMZ (a).

the absence of a signal from Alice is characterized using quantum process tomograph [24–26], with a resulting experimental fidelity of about 0.9802 ± 0.0057 [19]. The state of the photon on Bob's side is analyzed by a QWP, HWP, and a polarization beam splitter (PBS). The results detected by detector $D1$ are denoted as P_+ and P_- (successful probabilities), and the results detected by $D2$ are denoted by P'_+ and P'_- (error probabilities).

For the kind of states ρ_1, Alice measures along the x direction, which leads to two different pure NCS on Bob's side. The eigenvectors of the projector σ_x are $1/\sqrt{2}(|H\rangle + |V\rangle)$ and $1/\sqrt{2}(|H\rangle - |V\rangle)$. The corresponding NCS for Bob will be $\cos\theta|H\rangle + \sin\theta|V\rangle$ and $\cos\theta|H\rangle - \sin\theta|V\rangle$, with the detected probabilities denoted as P_+ and P_-, respectively. When $\theta = 0$ or $\theta = \pi/2$, the steering game fails, as the initial states represent separable states (i.e., Bob's two NCS are now both equal to $|H\rangle$ or $|V\rangle$). We first show the experimental results for four initial situations, with $\eta = 1$ (different θ), and $\theta = \pi/6$, $\theta = \pi/4$, and $\theta = \pi/3$ (different η) shown in Figs. 3(a)–3(d), respectively. For each case, the errors (supported by the LHS model) are low. As a result, the AVN demonstration of the steering game is over if Alice and Bob share an entangled state. To check the result, the measurement direction chosen by Alice is z, which is orthogonal to x. Bob obtains the maximum value of $\langle\mathcal{W}\rangle$ by scanning angle θ_B (i.e., ϕ_B is zero). Figure 3(e) shows some of the experimental results. The angle θ_B required to obtain the maximal value of $\langle\mathcal{W}\rangle$ depends on the initial conditions. According to the LHS model, the upper bound is $C_{\mathrm{LHS}} = (1 + |\cos 2\theta|)/4$, while the quantum prediction for $\langle\mathcal{W}\rangle_{\max}$ is $(1/2 + |1/2 - \eta|)\cos^2\theta$ when $\theta \in [0, \pi/4]$ and θ_B is 0. When $\theta \in [\pi/4, \pi/2]$, $\langle\mathcal{W}\rangle_{\max}$ is obtained as $(1/2 + |1/2 - \eta|)\sin^2\theta$ with θ_B being π. The value of $\Delta = \langle\mathcal{W}\rangle_{\max} - C_{\mathrm{LHS}}$, which should not be larger than 0 according to the LHS model, is shown in the Supplemental Material [19]. According to the AVN criterion, the steering game is successful when $\Delta > 0$ as well as $P_+ = 1, P'_+ = 0$ and $P_- = 1, P'_- = 0$. However, in practice, $P_\pm < 1$ and $P'_\pm > 0$. Then we should check whether the inequation (4) is violated or not. Figure 3(f) shows the value of Δ'. Taking the noise into consideration, we find that for some states, the steering game fails according to the new criterion. To clarify this fact, the not steerable states are marked by the hollow points while the steerable states are marked by the solid points in Figs. 3(a)–3(d). Note, when $\theta = 0$ or $\theta = \pi/2$ in the case of $\eta = 1$, it is obvious that the state could not be steerable, and the Δ' is not shown in the figure as its value is much less than zero.

We further prepared a second kind of states ρ_2 and again implemented the steering game for some states. For these states, Bob's NCS are different pure states if Alice performs the measurement along the z direction. The NCS correspond to $|H\rangle$ and $|V\rangle$ when the eigenvectors of σ_z are $|H\rangle$ and $|V\rangle$, respectively. Figures 4(a)–4(d) show the experimental probability of a successful detection and the errors

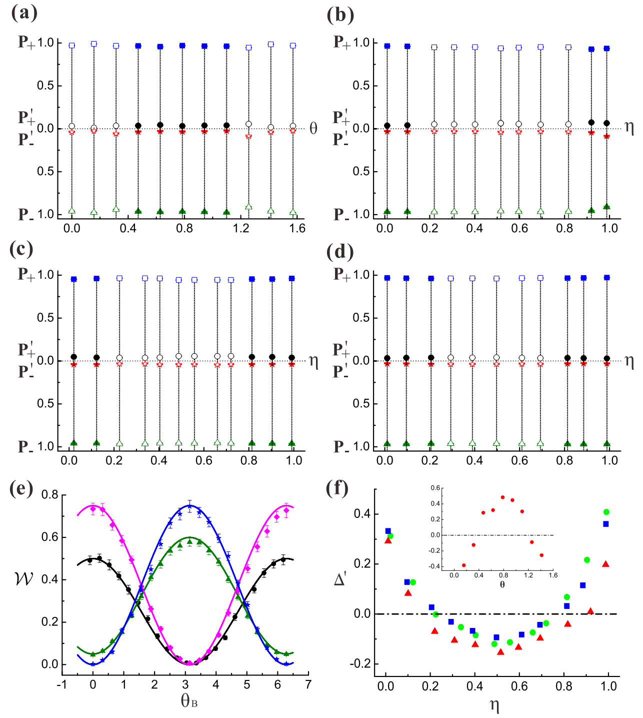

FIG. 3 (color online). Experimental results for ρ_1. (a)–(d) show the detected probabilities of the NCS on Bob's side. The hollow points represent the states are not steerable in the case of two measurement settings based on the values of Δ' which are shown in (f), while the solid ones mean the states are steerable. The blue squares and black circles represent the values of P_+ and P'_+, respectively. The green up triangles and red stars represent the values of P_- and P'_-, respectively. (e) The values of $\langle \mathcal{W} \rangle$ as a function of θ_B. The black circles, green up triangles, magenta diamonds, and blue stars represent cases with input parameters of $\theta = \pi/4$ and $\eta = 1$, $\theta = \pi/3$ and $\eta = 0.2$, $\theta = \pi/6$ and $\eta = 0$, and $\theta = \pi/3$ and $\eta = 1$, respectively. The black, red, green, magenta, and blue lines represent the corresponding theoretical predictions. (f) The results for Δ'. The red triangles, blue squares, and green circles represent the cases with initial parameters of $\theta = \pi/6$, $\theta = \pi/3$, and $\theta = \pi/4$, respectively. The inset in (f) shows the value of Δ' as a function of θ. The red circles represent the cases with initial parameters of $\eta = 1$. The error bars correspond to the counting statistics.

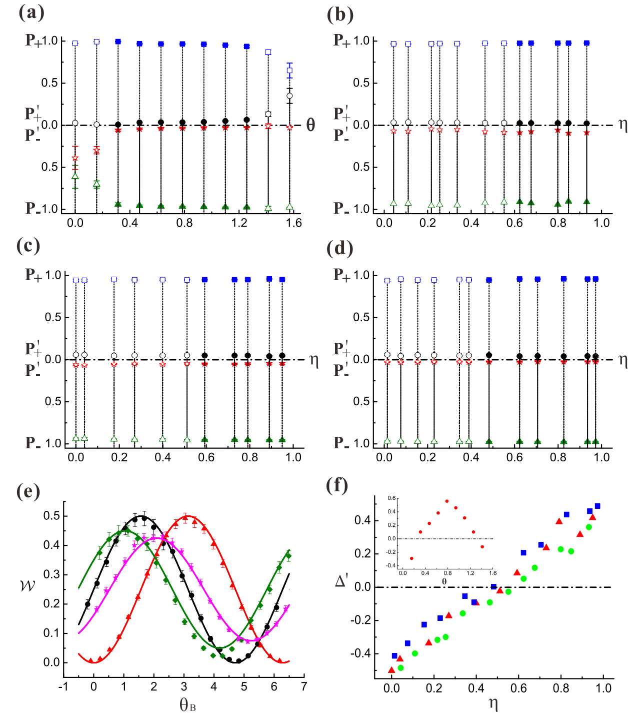

FIG. 4 (color online). Experimental results for ρ_2. (a)–(d) show the detected probabilities of the NCS on Bob's side. The hollow points represent the states are not steerable in the case of two measurement settings based on the values of Δ' which are shown in (f), while the solid ones mean the states are steerable. The blue squares and black circles represent the values of P_+ and P'_+, respectively. The green up triangles and red stars represent the values of P_- and P'_-, respectively. (e) The values of $\langle \mathcal{W} \rangle$ as a function of θ_B. The black circles, red up triangles, green diamonds, and magenta stars represent the cases with input parameters of $\theta = \pi/4$ and $\eta = 1$, $\theta = \pi/2$ and $\eta = 1$, $\theta = \pi/6$ and $\eta = 0.8$, and $\theta = \pi/3$ and $\eta = 0.7$, respectively. The black, red, green, and magenta lines represent the corresponding theoretical predictions. (f) The results for Δ'. The red triangles, blue squares, and green circles represent the cases with initial parameters of $\theta = \pi/6$, $\theta = \pi/3$, and $\theta = \pi/4$, respectively. The inset in (f) shows the value of Δ' as a function of θ. The red circles represent the case with an initial parameter of $\eta = 1$. The error bars correspond to the counting statistics.

for NCS given corresponding initial parameters of 4(a) $\eta = 1$, 4(b) $\theta = \pi/6$, 4(c) $\theta = \pi/4$, and 4(d) $\theta = \pi/3$. When $\eta = 1$ and θ is close to 0, Bob's NCS $|V\rangle$ almost vanishes. In fact, Bob can isolate the NCS $|H\rangle$, especially when $\theta = 0$ (product state). We can see that the error probability approaches the success probability for P_- as θ approaches 0, and this is the same case for P_+ when $\theta = \pi/2$. Therefore, these two states are clearly not steerable. To check the results, Alice and Bob perform a joint measurement, where the measurement direction on Alice's side is x, and Bob scans θ_B to maximize $\langle \mathcal{W} \rangle$. The experimental result of $\langle \mathcal{W} \rangle$ as a function of θ_B is shown in Fig. 4(e). The quantum prediction is $\langle \mathcal{W} \rangle = V/2\cos^2(\theta \pm \theta_B/2) + (1-\eta)/4$, where $\langle \mathcal{W} \rangle_{\max}$ is bounded by $C_{\mathrm{LHS}} = (1 + \eta|\cos 2\theta|)/4$ according to the LHS model. We further show the difference between the results Δ in the Supplemental Material [19]. When $\Delta > 0$, Bob is convinced that Alice can steer his state in the ideal situation where $P_+ = 1, P'_+ = 0$ and $P_- = 1, P'_- = 0$. In the experiment, we further check the inequation (4) to confirm whether the states are steerable or not. The value of Δ' is shown in Fig. 4(f). We can find that some states are verified to be not steerable in the case of two measurement settings. The hollow and solid points represent the not steerable and steerable states, respectively. The states with ρ_1 when $\theta = 0$ or $\theta = \pi/2$ in the case of $\eta = 1$ are product states which are not steerable states and Δ' is much less than zero which is not shown in the figure. In our experiment, error bars are estimated from standard deviations of the values whose statistical variation are considered to satisfy a Poisson distribution.

In conclusion, we experimentally demonstrated, for the first time, an EPR steering game employing an AVN criterion that strictly follows the practical concept of steering. In our experiment, the AVN criterion was dependent on obtaining two different NCS on Bob's side. To check the results, we measured Δ for all cases. However, Δ can be randomly checked if Alice and Bob promise that the initial states are entangled to rule out any cheating from a third party, just like in quantum key distribution [27]. Moreover, considering the noise, we develop a new criterion to check the steering. We can, therefore, verify whether the states are steerable depending on the experimental values obtained from the two-setting measurement. Our experimental results provide a particularly strong perspective for understanding EPR steering and has experimental potential applications in the implementation of long-distance quantum information processing [28–30].

This work is supported by the National Basic Research Program of China (Grant No. 2011CB921200), National Natural Science Foundation of China (Grants No. 11274297, No. 11004185, No. 61322506, No. 60921091, No. 11274289, No. 11325419, No. 61327901, and No. 11275182), the Fundamental Research Funds for the Central Universities (Grants No. WK 2030020019 and No. WK2470000011), Program for New Century Excellent Talents in University (Grant No. NCET-12-0508), Science foundation for excellent Ph.D. thesis (Grant No. 201218), and the CAS. J. L. C. acknowledges the support by National Basic Research Program of China under Grant No. 2012CB921900 and NSF of China (Grants No. 11175089 and No. 11475089). This work is also partly supported by National Research Foundation and Ministry of Education, Singapore.

*jsxu@ustc.edu.cn
†chenjl@nankai.edu.cn
‡cfli@ustc.edu.cn

[1] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 0777 (1935).
[2] E. Schrödinger, Proc. Cambridge Philos. Soc. **31**, 555 (1935).
[3] H. M. Wiseman, S. J. Jones, and A. C. Doherty, Phys. Rev. Lett. **98**, 140402 (2007).
[4] J. S. Bell, J. Appl. Phys. **1**, 195 (1964).
[5] M. D. Reid, Phys. Rev. A **40**, 913 (1989).
[6] Z. Y. Ou, S. F. Pereira, H. J. Kimble, and K. C. Peng, Phys. Rev. Lett. **68**, 3663 (1992).
[7] W. P. Bowen, R. Schnabel, P. K. Lam, and T. C. Ralph, Phys. Rev. Lett. **90**, 043601 (2003).
[8] E. G. Cavalcanti, S. J. Jones, H. M. Wiseman, and M. D. Reid, Phys. Rev. A **80**, 032112 (2009).
[9] D. J. Saunders, S. J. Jones, H. M. Wiseman, and G. J. Pryde, Nat. Phys. **6**, 845 (2010).
[10] J. Schneeloch, C. J. Broadbent, S. P. Walborn, E. G. Cavalcanti, and J. C. Howell, Phys. Rev. A **87**, 062103 (2013).
[11] J. Schneeloch, P. B. Dixon, G. A. Howland, C. J. Broadbent, and J. C. Howell, Phys. Rev. Lett. **110**, 130407 (2013).
[12] N. D. Mermin, Phys. Rev. Lett. **65**, 1838 (1990).
[13] A. Cabello, Phys. Rev. Lett. **86**, 1911 (2001).
[14] A. Cabello, Phys. Rev. Lett. **87**, 010403 (2001).
[15] T. Yang, Q. Zhang, J. Zhang, J. Yin, Z. Zhao, M. Żukowski, Z.-B. Chen, and J.-W. Pan, Phys. Rev. Lett. **95**, 240406 (2005).
[16] C. Cinelli, M. Barbieri, R. Perris, P. Mataloni, and F. De Martini, Phys. Rev. Lett. **95**, 240405 (2005).
[17] G. Vallone, E. Pomarico, P. Mataloni, F. De Martini, and V. Berardi, Phys. Rev. Lett. **98**, 180502 (2007).
[18] J. L. Chen, X.-J. Ye, C. F. Wu, H.-Y. Su, A. Cabello, L. C. Kwek, and C. H. Oh, Sci. Rep. **3**, 02143 (2013).
[19] See Supplemental Material http://link.aps.org/supplemental/10.1103/PhysRevLett.113.140402 for details.
[20] C. F. Wu, J.-L. Chen, X.-J. Ye, H.-Y. Su, D.-L. Deng, Z. H. Wang, and C. H. Oh, Sci. Rep. **4**, 4291 (2014).
[21] P. G. Kwiat, E. Waks, A. G. White, I. Appelbaum, and P. H. Eberhard, Phys. Rev. A **60**, R773 (1999).
[22] J.-S. Xu, K. Sun, C.-F. Li, X.-Y. Xu, G.-C. Guo, E. Andersson, R. Lo Franco, and G. Compagno, Nat. Commun. **4**, 2851 (2013).
[23] R. Prevedel, D. R. Hamel, R. Colbeck, K. Fisher, and K. J. Resch, Nat. Phys. **7**, 757 (2011).
[24] I. L. Chuang and M. A. Nielsen, J. Mod. Opt. **44**, 2455 (1997).
[25] J. F. Poyatos, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **78**, 390 (1997).
[26] J. L. O'Brien, G. Pryde, A. Gilchrist, D. James, N. Langford, T. Ralph, and A. White, Phys. Rev. Lett. **93**, 080502 (2004).
[27] V. Scarani, H. Bechmann-Pasquinucci, N. Cerf, M. Dušek, N. Lütkenhaus, and M. Peev, Rev. Mod. Phys. **81**, 1301 (2009).
[28] I. Marcikic, H. de Riedmatten, W. Tittel, H. Zbinden, and N. Gisin, Nature (London) **421**, 509 (2003).
[29] R. Ursin *et al.*, Nat. Phys. **3**, 481 (2007).
[30] J. T. Barreiro, T.-C. Wei, and P. G. Kwait, Nat. Phys. **4**, 282 (2008).