In 1935, Einstein, Podolsky and Rosen (EPR) described a “spooky” action permissible under the rules of quantum mechanics: “as a consequence of two different measurements performed upon the first system, the second system may be left in states with two different (ensembles of) wave functions” [1]. As a response to EPR’s work, Schrödinger generalized this argument and referred to the ability of Alice to remotely affect Bob’s state by choosing her measurement basis as steering [2, 3]. The rigorous definition and operational framework for understanding steering were recently formulated by Wiseman et al. [4, 5], in which the authors showed the hierarchy of nonlocality: steerable states are a subset of the entangled states and a superset of Bell nonlocal states [6].

Another interesting property of steering according to the definition is its asymmetry: Alice and Bob play different roles in the steering scenario. For a given two-party system, one can ask whether Alice can steer Bob, which shows Alice’s ability to remotely affect Bob’s states and vice versa. This formal asymmetry can never be found in entanglement or Bell nonlocality by their definitions, which may provide potential applications for the one-sided device-independent quantum key distribution [7–9].

It is natural to verify steering by violating steering inequalities. However, to certify a one-way steerable state, one needs to solve two obstacles. The first difficulty is when all those one-way steerable states are Bell-local states [4]; thus, a highly efficient and experimental error-tolerant steering criterion is required to verify Alice’s ability to steer Bob. The second difficulty, which is the most challenging part, is to prove, for any measurement settings, that Bob cannot steer Alice. Great efforts have been made in designing one-way EPR steering tests. The asymmetry of the EPR-steering correlation was first investigated by Wiseman et al. They offered the problem of whether there exists an asymmetric quantum steering state as the foremost open question in their work [4]. Later, it was shown theoretically [10–12] that such a phenomenon could occur in continuous variable systems. However, these results hold only for a restricted class of measurements, i.e., Gaussian measurements, and there was no evidence that this asymmetry would persist for more general measurements. A year later, Bowles et al. theoretically confirmed for the first time that quantum nonlocality can be fundamentally asymmetric [13]. They presented a class of one-way steerable states in a two-qubit system with at least 13 projective measurements. However, the requirement for the state preparation is very high, and it is difficult to experimentally demonstrate the corresponding steerability. Recently, they further investigated the one-way steering problem by presenting a sufficient criterion (a nonlinear criterion) for guaranteeing that a two-qubit state is unsteerable [14], which provides a general method for constructing the one-way steerable states.

A few experiments have also been carried out over the past few years to study the asymmetric steering. The first experimental demonstration was restricted to Gaussian measurements for Gaussian states [15]. Recently, two more experiments were conducted to observe the one-way steering. Based on the analysis of detector efficiency, Wollmann et al. [16] designed an experiment to demonstrate one-way steering in a qubit-qutrit system, which consisted of a Werner state with a lossy channel at one side [17, 18]. However, because the dimensionality of the prepared state is asymmetric, one may doubt where the one-way steering characteristic comes from. The lossy
channel, which introduces an additional vacuum state on one side, is essential to their protocol. Without this increased dimension, the asymmetric steering cannot be demonstrated in principle. The other experiment regarding asymmetric EPR-steering was reported by Sun et al. [19], in which the protocol is restricted to two-measurement settings. The one-way steering characteristic may disappear with more measurement settings. The demonstration of genuine one-way steering with multi-measurement settings in the simplest bipartite system would be of fundamental interest and provide practical applications in one-way quantum information tasks, which are still lacking. This suggests that further experimental efforts are needed.

In this work, we experimentally demonstrate the multi-setting one-way steering in a two-qubit system for the first time. The steerability is quantified by a necessary and sufficient steering criterion, i.e., the steering radius \( R \). These results will provide a deeper understanding of the asymmetric characteristic of steering.

### Multi-setting one-way EPR steering and steering radius

To clarify the steering scenario, we show the process of Alice steering Bob in the case of three-measurement settings in Fig. 1. Bob is not sure whether the received qubit state is from half of a steerable state \((\rho_{AB}, \text{from channel a})\) or from a local hidden state model (LHSM, from channel b). He asks Alice to measure her qubit in one of the directions \( \{\vec{n}_1, \vec{n}_2, \vec{n}_3\} \) through classical communication. Alice then sends Bob the measurement result \( a \in \{0, 1\} \). Correspondingly, Bob obtains a conditional state \( \tilde{\rho}_{a|\vec{n}} = Tr_A((M_{a|\vec{n}} \otimes I_B)\rho_{AB}) \). \( M_{a|\vec{n}} = (I_A + (-1)^a\vec{n} \cdot \vec{\sigma})/2 \) is the measurement operator of Alice’s state. \( I_A \) (\( I_B \)) represents the identity matrix on Alice’s (Bob’s) side, and \( \vec{\sigma} = (\sigma_x, \sigma_y, \sigma_z) \) is the Pauli vector. When Bob’s state can be described by a LHSM, the conditional state can be written as

\[
\tilde{\rho}_{a|\vec{n}} = \sum_i P(a|\vec{n}, i)p_i\rho_i, \tag{1}
\]

where \( P(a|\vec{n}, i) \) is a conditional probability, \( \{p_i\rho_i\} \) is the local hidden state ensemble, with the state \( p_i \) and corresponding probability \( p_i \). Otherwise, Bob is convinced that Alice can steer his state and that the qubit he received is from channel a.

Here, we use a value called steering radius \( R_{A\rightarrow B} \) to quantify the ability of Alice to steer Bob [19]. In the case of three-measurement settings, it has been proven that eight local hidden states are sufficient to reproduce the six conditional states if a LHSM exists [20]. The radius of the Bloch vector of the corresponding local hidden state \( \rho_i \) is represented as \( |\vec{R}_i| \), with \( i \in \{1, 2, \cdots, 8\} \). For a different solution set of \( \{p_i\rho_i\} \) of Eq. 1, the minimum radius is defined as \( r_{\{\vec{n}_1, \vec{n}_2, \vec{n}_3\}} = \min \{\max\{|\vec{R}_i|\}\} \). Obviously, \( r_{\{\vec{n}_1, \vec{n}_2, \vec{n}_3\}} \) is dependent on a given measurement direction assemblage \( \{\vec{n}_1, \vec{n}_2, \vec{n}_3\} \). The steering radius is defined as \( R_{A\rightarrow B} = \max_{\{\vec{n}_1, \vec{n}_2, \vec{n}_3\}} \{r_{\{\vec{n}_1, \vec{n}_2, \vec{n}_3\}}\} \). If \( R_{A\rightarrow B} > 1 \), there is no physical solution of Eq. 1, which indicates that there is no LHSM to describe the conditional states obtained on Bob’s side. The steering task from Alice to Bob is successful. Otherwise, if \( R_{A\rightarrow B} < 1 \), the EPR steering task fails. The analysis can be extended to more measurement settings, and the steering radius for the case in which Bob steers Alice \( R_{B\rightarrow A} \) can be analyzed in a similar way.

In this work, we prepare a family of two-qubit states:

\[
\rho_{AB}(p, \theta) = p|\psi(\theta)\rangle\langle\psi(\theta)| + (1 - p)I_A/2 \otimes \rho_B^0, \tag{2}
\]

where \( |\psi(\theta)\rangle = \cos(\theta)|HH\rangle + \sin(\theta)|VV\rangle \), with \( H \) and \( V \) representing the horizontal and vertical polarizations, respectively. \( \rho_B^0 = Tr_A(|\psi(\theta)\rangle\langle\psi(\theta)|) \). It has been demonstrated [14] that for \( \theta \in [0, \pi/4] \) and \( \cos^2(2\theta) \geq 2p - 1 \), the steering from Bob to Alice is impossible even for an infinite number of projective measurements carried out by Alice. However, Alice can steer Bob for \( p > 1/2 \).

Experimentally, we focus on two- and three-measurement settings. The conditions of states \( \rho_{AB} \) satisfying one-way steering from Alice to Bob are \( R_{A\rightarrow B} > 1 \) and \( R_{B\rightarrow A} < 1 \). In the case of two-measurement settings,
the condition can be rewritten as: $\theta \in (0, \pi/4)$ and
\[
\frac{1}{\sqrt{2}} < p \leq \frac{1}{\sqrt{1 + \sin^2(2\theta)}}.
\]
while the condition for three-measurement settings is $\theta \in (0, \pi/4)$ and
\[
\frac{1}{\sqrt{3}} < p \leq \frac{1}{\sqrt{1 + 2\sin^2(2\theta)}}.
\]

The detailed calculation and proof are shown in the Supplementary Material [21].

Experimental setup and results.—Fig. 2 shows our experimental setup. A 404 nm continuous-wave diode laser (L) with polarization set by a half-wave plate is used to pump a 20 mm-long PPKTP crystal inside a polarization Sagnac interferometer [22] to generate polarization-entangled photons in the state $|\psi(\theta)\rangle$. Two interference filters with a bandwidth of 3 nm are used to filter the photons. One of the two photons is sent to an unbalanced interferometer (UI). The state is one-way steerable by evaluating the steering parameters. For two- and three-measurement settings, the condition can be rewritten as:
\[
\frac{1}{\sqrt{2}} < p \leq \frac{1}{\sqrt{1 + \sin^2(2\theta)}}.
\]
while the condition for three-measurement settings is $\theta \in (0, \pi/4)$ and
\[
\frac{1}{\sqrt{3}} < p \leq \frac{1}{\sqrt{1 + 2\sin^2(2\theta)}}.
\]

The state of path $i_1$ remains unchanged. Half-wave plates (HWP) along paths $i_2$ and $i_3$ are set at 22.5° and two sufficiently long birefringent crystals (PCs) introduce a sufficiently large time delay between $|H\rangle$ and $|V\rangle$ components, which can completely destroy the coherence. The time difference between these three paths is much larger than the coherence time of the photons. By combining these three paths into one, arbitrary two-qubit states $\rho_{AB}(p, \theta)$ can be prepared. The parameter $p$ can be controlled conveniently by employing removable shutters (RSs).

The measurement setup, comprising a quarter-wave plate (QWP), a HWP, and a PBS on both sides allows us to measure along arbitrary axes on the Bloch sphere for each qubit. For two- and three-measurement settings, according to the symmetrical property of the steering ellipsoid of $\rho_{AB}(p, \theta)$ [23, 24], the optimal choice of measurement settings is $\{\bar{x}, \bar{z}\}$ and $\{\bar{x}, \bar{y}, \bar{z}\}$ for both steering directions, respectively. When the measurement is carried out on one side, the other will obtain the corresponding conditional states. Then, we can check whether the state is one-way steerable by evaluating the steering radii $R_{A\rightarrow B}$ and $R_{B\rightarrow A}$.

We prepared 40 entangled states in the form of $\rho_{AB}(p, \theta)$ to perform the EPR steering task. The detailed process for determining the experimental parameters $p$ and $\theta$ is shown in the Supplementary Material [21]. Fig. 3a presents the distribution of the experimental states with different $p$ and $\theta$. In the scenario of three-measurement settings, the light red region described by Ineq. 4 denotes the case of one-way steering in which Alice can steer Bob, but Bob cannot steer Alice. In other cases, states located in the light brown region are steerable, and states located in the light blue region are unsteerable in both directions. It is clear that a tunable $p$ allows the state to be shifted from a region where it is unsteerable in both directions to a region where it is one-way steerable and finally to a region where it is two-way steerable. We further show the one-way steering region in the case of two-measurement settings, which is bounded by the dashed black lines according to Ineq. 3. With more measurement settings, more states are shown to be steerable. One-way steerable states can be turned into two-way steerable states by increasing the measurement settings for some parameters. For the infinite-measurement settings, there is still a parameter region where states are shown to be one-way steerable, which could not be demonstrated in the previous work restricted to two-measurement settings [19]. As shown in Fig. 3a, the states below the solid red curve described by the relation $\cos^2(2\theta) = \frac{2p}{(2-2p)^2}$ are one-way steerable with infinite-measurement settings [14].

We further consider the ability of Bob to steer Alice
using the linear EPR-steering inequality, which is represented as $S_n = \frac{1}{n} \sum_{k=1}^{n} (\sigma_A^k B^k) \leq C_n$. $\sigma_A^k$ is the Pauli operator for Alice’s state, and $B^k \in \{-1,1\}$ is the random variable on Bob’s side. $C_n$ is the bound given by the LHSM with $n$-measurement settings. The difference between $S_n$ and $C_n$ ($S_n - C_n$) for the one-way steerable states in the black box in Fig. 3a is shown in Fig. 3b. If $S_n - C_n > 0$, the steerability is demonstrated. We find that $S_n - C_n$ slowly increases as the number of measurement settings increases. All $S_n$ are shown to be well below $C_n$.

However, $S_n - C_n$ is not a necessary and sufficient criterion to quantify steering for states $\rho_{AB}(p,\theta)$. It only shows, for a specific linear function, whether there exists a LHSM to obtain the value predicted by quantum mechanics. Thus, it just tests partial properties of the conditional states. However, the steering radius, as a simplified variant of steering robustness [26], which is discussed in Ref. [19], directly shows whether there exists a LHSM to simulate the corresponding conditional states and gives a necessary and sufficient criterion for steerability. We measure the steering radii $R_{A\rightarrow B}$ and $R_{B\rightarrow A}$ of the corresponding states in Fig. 3a to clearly demonstrate the one-way EPR steering, as shown in Fig. 4. The blue dots represent states for which the EPR steering task fails in both directions ($A\leftrightarrow B$, $R_{A\rightarrow B} \leq 1$ and $R_{B\rightarrow A} \leq 1$). The states represented by red triangles show the case in which Alice steers Bob ($A\rightarrow B$, $R_{A\rightarrow B} > 1$ and $R_{B\rightarrow A} \leq 1$). The brown squares represent the cases in which Alice and Bob can steer each other ($A\leftrightarrow B$, $R_{A\rightarrow B} > 1$ and $R_{B\rightarrow A} > 1$). The values of $R_{A\rightarrow B}$ and $R_{B\rightarrow A}$ clearly distinguish different steering situations, which agree well with the theoretical predictions. The inset in Fig. 4 is a magnification of the region in the red pane. Error bars are due to Poissonian counting statistics. The experimental states and steering radius in the case of two-measurement settings are discussed further in the Supplementary Material [21].

**Conclusion.**—In our work, we construct a class of states that are only steerable from Alice to Bob, even for infinite-measurement settings. By measuring the steering radius, the asymmetric steerability of the prepared states is clearly shown. Compared with the previous experiments, our work provides a more essential and intuitive way to understand the asymmetric characteristic of EPR steering. Our experimental results for the simplest bipartite system, with a smaller requirement of quantum resources, can yield potential applications in future one-way quantum information tasks.

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