LETTERS
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Observation of one-way Einstein–Podolsky–Rosen steering

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The distinctive non-classical features of quantum physics were first discussed in the seminal paper[1] by A. Einstein, B. Podolsky and N. Rosen (EPR) in 1935. In his immediate response[2], E. Schrödinger introduced the notion of entanglement, now seen as the essential resource in quantum information[3–5] as well as in quantum metrology[6–8]. Furthermore, he showed that at the core of the EPR argument is a phenomenon that he called steering. In contrast to entanglement and violations of Bell's inequalities, steering implies a direction between the parties involved. Recent theoretical works have precisely defined this property, but the question arose as to whether there are bipartite states showing steering only in one direction[9,10]. Here, we present an experimental realization of two entangled Gaussian modes of light that in fact shows the steering effect in one direction but not in the other. The generated one-way steering gives a new insight into quantum physics and may open a new field of applications in quantum information.

The steering effect can be described by considering two remote observers, Alice and Bob, who share a bipartite quantum state. Their local systems are in a mixed state and therefore permit a decomposition into pure states. Schrödinger found that within quantum mechanics certain states do not allow such a decomposition locally. Depending on the observable Alice chooses to measure, Bob's local state is decomposed into incompatible mixtures of conditional states. So, if pure states were a local complete description of Bob's system, this would require some interaction from Alice to Bob. This is what Schrödinger named steering and Einstein later called the 'spooky action at a distance'. The first experimental demonstration of this effect was achieved by Ou *et al.*[11], and was followed by a great number of experiments[12–15].

Steering is strictly stronger than entanglement and strictly weaker than the violation of a Bell inequality; that is, steering does not imply the violation of any Bell inequality, while the violation of at least one Bell inequality immediately implies steering in both directions[16], as shown in Fig. 1. In contrast to entanglement and Bell tests, Alice and Bob have certain roles in the steering scenario that are not interchangeable. This intrinsic asymmetry raises the question[9] of whether there are physical states certifying steering only in one direction for arbitrary observables. This *one-way* steering would lead to the peculiar situation that two experimenters measuring the same observables on their subsystems would describe the same shared state in qualitatively different ways. Whereas, in general, this question cannot as yet be answered, in the Gaussian regime (that is, for Gaussian state preparation and Gaussian measurements) the answer is yes. In a pioneering paper by H.-A. Bachor and co-workers, two-way steering with an asymmetry in the steering strengths was observed[17]. Their theoretical analysis proposes a possible extension of their set-up with a view to observing one-way steering. In a more recent theoretical work, an intracavity nonlinear coupler was proposed to generate Gaussian one-way steering[18].

Here, we propose and experimentally certify the realization of Gaussian one-way steering with two-mode squeezed states. Our states were generated by first superimposing a squeezed mode with a vacuum mode at a balanced beamsplitter. By introducing additional amounts of vacuum to Bob's mode, the overall state's asymmetry was stepwise driven through the one-way regime, finally losing all steering properties. The most significant one-way states were qualified by the Reid criterion, giving 0.908 ± 0.003 for the direction from Alice to Bob and 1.206 ± 0.004 for the reverse direction, where the normalization was chosen such that below 1, steering is certified.

To analyse the steering scenario, we start with the bipartite situation in which Alice sends quantum states to Bob. If Bob locally observes a mixed state, this can be decomposed into convex combinations of purer states. These decompositions can be seen as more precise descriptions of his system. Indeed, any information that Alice has about the state will give a decomposition into conditional states that are purer than Bob's mixed state. This can be seen in the upper panels of Fig. 2 for the case of a Gaussian system and quadrature measurements. Two exemplary measurement results X_1 and P_1, which Alice obtains on her system, are depicted by the green and blue lines. The related conditional states on Bob's side are shown by the accordingly coloured ellipses. For all measurement results Alice can obtain, these ellipses will have the same shape; only their positions in phase space will be different. So Alice's X and P results give two different decompositions of Bob's system.

The argument by Einstein, Podolsky and Rosen (EPR) and Schrödinger is now that measurements on Alice's side should not influence Bob's system. So, the decomposition of Bob's state should be independent of Alice's choice of observable. This implies that the conditional decompositions, which depend on Alice's choice, should have a common finer-grained decomposition that does not depend on Alice's choice. Such a refinement should show an X uncertainty that is, at most, as large as that of Bob's X conditional state (green arrow). At the same time, it should show a P uncertainty that is, at most, as large as that of Bob's P conditional state (blue arrow). We have depicted this hypothetical state in the inset as a red ellipse. However, this state would clearly violate the Heisenberg uncertainty relation, depicted by the black dotted ellipse, and is therefore forbidden within quantum mechanics.

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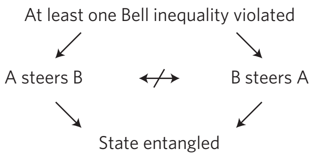

Figure 1 | Implications of inseparability criteria. A violation of at least one Bell inequality implies steering in both directions. If steering is only present in one direction, no Bell inequality can be violated. However, any certification of steering implies that the state is entangled. The converse implications are not true: entangled states are not necessarily steering states and steering does not imply the violation of a Bell inequality.

The absence of a common refinement leads to the conclusion that Alice's choice of observable somehow changes the states of Bob's system, which Schrödinger called steering. More formally, we define a bipartite state to be steerable with respect to Alice's observables, if the resulting conditional-state decompositions of Bob's state do not allow a common refinement. We say that the state is steerable from Alice to Bob if there are some observables for which it is steerable. This description of steering is close to Schrödinger's original presentation. It is equivalent to a modern definition based on the existence of certain classical models as given in the seminal paper of ref. 9.

As we consider the Gaussian regime, our description of steering is equivalent to a definition by M. Reid[10,19]. Her definition is based on Heisenberg Uncertainty Relations for conditional measurements of the amplitude and phase quadrature X and P of light fields. A state is steerable from Alice to Bob if the following conditional Heisenberg Uncertainty Relation is violated:

$$\mathrm{V}_{B|A}(X_B)\cdot \mathrm{V}_{B|A}(P_B)\geq 1 \tag{1}$$

Here, $\mathrm{V}_{B|A}(X_B)$ denotes the conditional variance of X_B, that is, the variance of Bob's measurements conditioned on Alice's results. We have chosen the units such that the right-hand side is 1. A violation of this inequality is exactly what is shown in the upper inset of Fig. 2 where the red ellipse is smaller than the black.

Conversely, steering from Bob to Alice is certified if the following inequality is violated:

$$\mathrm{V}_{A|B}(X_A)\cdot \mathrm{V}_{A|B}(P_A)\geq 1 \tag{2}$$

This converse scenario is shown in the lower panels of Fig. 2 for the same quantum state as in the upper panels. The two measurement results obtained by Bob give related conditional states on Alice's side and permit two different decompositions. However, this time, these conditional decompositions do have a common refinement that does not violate the uncertainty relation. So, in terms of Schrödinger, Bob's measurements do not steer Alice's system, as an underlying description with pure states is possible. Therefore, the state analysed in Fig. 2 shows one-way steering in the Gaussian regime.

The experimental set-up we used to generate these one-way steering states is shown schematically in Fig. 3. The continuous-wave 10.2 dB squeezed state at 1,550 nm was generated by type I parametric downconversion in a half-monolithic cavity. After superposition with vacuum on a first balanced beamsplitter, output mode B was sent through a half-wave plate and a polarizing beamsplitter. This set-up allowed the preparation of mode B with an adjustable contribution of a second vacuum mode. The measurements at A and B were performed by balanced homodyne detection. Both detectors could independently choose the measured quadrature by adjusting the phase of their local oscillators. The signals of the homodyne detectors were simultaneously recorded with a data acquisition system. A more detailed description of the squeezed-light source, the homodyne measurement set-up and the locking scheme is given in ref. 20.

Figure 4 presents the main result of this work. The conditional variance products from inequalities (1) and (2) for Alice's ability to steer Bob (lower line, red) and Bob's ability to steer Alice (upper line, blue) are plotted against the contribution of the second vacuum mode. For values between 0% and 95% we performed a partial tomographic measurement. The uncertainties of the contributed vacuum result from the adjustment accuracy of the half-wave plate. A bootstrapping method was used to determine the means and standard deviations of the conditional variance products. For 10^4 times we randomly chose 10^6 data points from a total of 5×10^6 points. From these we calculated the two conditional variance products for each data set. Histograms of these values for a 50% vacuum contribution are shown in the insets in Fig. 4. This is the setting where the observed one-way steering effect becomes most obvious. For Alice (left box) the mean of 0.908 is 31 standard deviations below 1, whereas for Bob (right box) the mean of 1.206 is 53 standard deviations above 1. Furthermore, we verified the Gaussianity of the states using a Q-Q-plot method as in ref. 21.

The two solid lines in Fig. 4 are theory curves taking into account the optical detection efficiencies and parameters of the squeezed-light source. For a vacuum contribution smaller than 39%, both

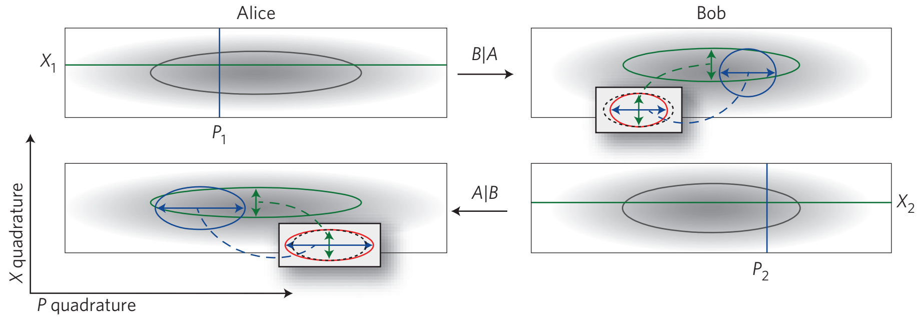

Figure 2 | Gaussian one-way EPR steering visualized in phase space. The local Wigner functions of a bipartite quantum state, as presented in this work, are represented by the grey ellipses as well as by the background clouds. The axes are not to scale. The upper panels show steering from Alice to Bob. Two exemplary measurement results, X_1 and P_1, are depicted by the green and blue lines, respectively. The appertaining conditional states at Bob's system are depicted by the accordingly coloured ellipses, with their uncertainties in the respective quadratures given by the arrows. Any hypothetical common refinement, depicted by the red ellipse in the inset, may not exceed these uncertainties. This is, however, not possible without violating the Heisenberg Uncertainty Relation, shown in black. The lower panels show a non-steering situation from Bob to Alice. In this case, a common refinement is possible; that is, the uncertainty relation is not violated.

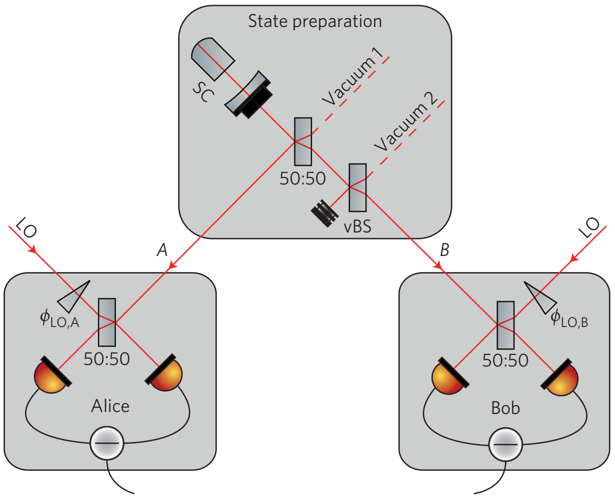

Figure 3 | Schematic of the experimental set-up. A squeezed-light field at 1,550 nm, produced by a squeezing cavity (SC), is superimposed at a balanced beamsplitter with a vacuum mode. A variable beamsplitter (vBS) is implemented in one output mode to change the contribution of a second vacuum mode. Measurements are performed by balanced homodyne detection, where the measured quadrature is chosen by the phase ϕ_{LO} of the local oscillator (LO).

Alice and Bob can steer the respective remote subsystem, whereas for a contribution larger than 70% neither of them can. These values arise from the overall optical loss in the set-up and, for a perfectly lossless experiment, would be 50% and 100%, respectively. One-way steering is observed precisely between these two values in the white region in Fig. 4.

Although for our present experiment one of the output modes of the variable beamsplitter was dumped, a tripartite situation arises when, instead, a third party, Charlie, receives this mode. For symmetry reasons Alice would then also be able to steer Charlie, in fact, simultaneously to steering Bob. We can also say that Bob cannot steer Charlie, and Charlie cannot steer Bob, because the input of the second beamsplitter already has a vacuum mode contribution of 50% due to the first beamsplitter. Steering in the presence of just one squeezed mode is only possible for vacuum contributions less than 33% (ref. 22).

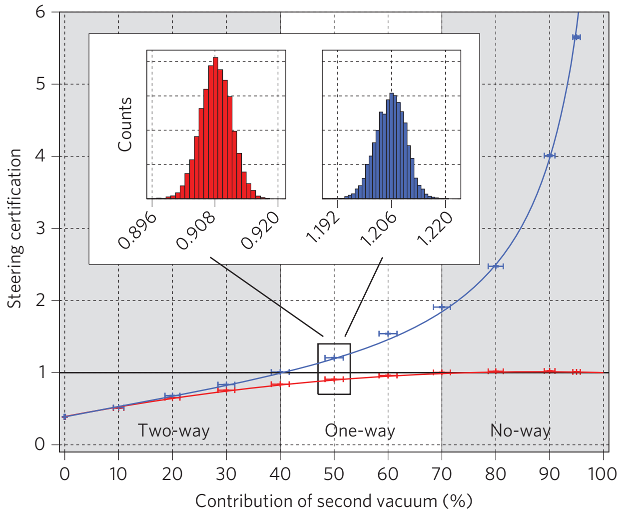

Figure 4 | Certification of one-way steering. Measurement results of the conditional variance products according to criteria (1) and (2) are shown versus an increasing contribution of the second vacuum mode in mode B. One-way steering is observed if the value for one steering direction is below unity, but the value for the other steering direction is above the unity benchmark. This is fulfilled in the white region and most significantly at a vacuum contribution of 50%, as shown by the measurement histograms.

In conclusion, our experimental scheme provided the generation of Gaussian one-way steering with high significance. Criterion (1) for steering from Alice to Bob was violated by more than 30 standard deviations, whereas criterion (2) for steering from Bob to Alice was *not* violated with a significance of more than 50 standard deviations. Hence, depending on whether Alice tries to steer Bob's system, or Bob tries to steer Alice's system, our prepared state provided two opposing answers. This one-way property of EPR steering gives a new insight into the counterintuitive nature of quantum physics. It may have applications in bipartite and multipartite quantum key distribution and in information science in general. Its full nature, however, remains essentially unexplored to date.

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Author contributions

V.H., T.E. and R.S. conceived the experiment. V.H. and T.E. conducted the experiment and performed all measurements with the help of S.S. and A.S. and under the supervision of R.S. Theoretical analysis was carried out by T.F. with supervision from R.F.W.

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Competing financial interests

The authors declare no competing financial interests.