ARTICLES

An experimental test of non-local realism

Simon Gröblacher[1,2], Tomasz Paterek[3,4], Rainer Kaltenbaek[1], Časlav Brukner[1,2], Marek Żukowski[1,3], Markus Aspelmeyer[1,2] & Anton Zeilinger[1,2]

Most working scientists hold fast to the concept of 'realism'—a viewpoint according to which an external reality exists independent of observation. But quantum physics has shattered some of our cornerstone beliefs. According to Bell's theorem, any theory that is based on the joint assumption of realism and locality (meaning that local events cannot be affected by actions in space-like separated regions) is at variance with certain quantum predictions. Experiments with entangled pairs of particles have amply confirmed these quantum predictions, thus rendering local realistic theories untenable. Maintaining realism as a fundamental concept would therefore necessitate the introduction of 'spooky' actions that defy locality. Here we show by both theory and experiment that a broad and rather reasonable class of such non-local realistic theories is incompatible with experimentally observable quantum correlations. In the experiment, we measure previously untested correlations between two entangled photons, and show that these correlations violate an inequality proposed by Leggett for non-local realistic theories. Our result suggests that giving up the concept of locality is not sufficient to be consistent with quantum experiments, unless certain intuitive features of realism are abandoned.

Physical realism suggests that the results of observations are a consequence of properties carried by physical systems. It remains surprising that this tenet is very little challenged, as its significance goes far beyond science. Quantum physics, however, questions this concept in a very deep way. To maintain a realistic description of nature, non-local hidden-variable theories are being discussed as a possible completion of quantum theory. They offer to explain intrinsic quantum phenomena—above all, quantum entanglement[1]—by non-local influences. Up to now, however, it has not been possible to test such theories in experiments. We present an inequality, similar in spirit to the seminal one given by Clauser, Horne, Shimony and Holt[2] on local hidden variables, that allows us to test an important class of non-local hidden-variable theories against quantum theory. The theories under test provide an explanation of all existing two-qubit Bell-type experiments. Our derivation is based on a recent incompatibility theorem by Leggett[3], which we extend so as to make it applicable to real experimental situations and also to allow simultaneous tests of all local hidden-variable models. Finally, we perform an experiment that violates the new inequality and hence excludes for the first time a broad class of non-local hidden-variable theories.

Quantum theory gives only probabilistic predictions for individual events. Can one go beyond this? Einstein's view[4,5] was that quantum theory does not provide a complete description of physical reality: "While we have thus shown that the wavefunction does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe, however, that such a theory is possible."[4]. It remained an open question whether the theory could be completed in Einstein's sense[6]. If so, more complete theories based on objective properties of physical systems should be possible. Such models are referred to as hidden-variable theories.

Bell's theorem[7] proves that all hidden-variable theories based on the joint assumption of locality and realism are at variance with the predictions of quantum physics. Locality prohibits any influences between events in space-like separated regions, while realism claims that all measurement outcomes depend on pre-existing properties of objects that are independent of the measurement. The more refined versions of Bell's theorem by Clauser, Horne, Shimony and Holt[2] and by Clauser and Horne[8,9] start from the assumptions of local realism and result in inequalities for a set of statistical correlations (expectation values), which must be satisfied by all local realistic hidden-variable theories. The inequalities are violated by quantum mechanical predictions. Greenberger, Horne and Zeilinger[10,11] showed that already perfect correlations of systems with at least three particles are inconsistent with these assumptions. So far, all experiments motivated by these theorems are in full agreement with quantum predictions[12–17]. For some time, loopholes existed that allowed the observed correlations to be explained within local realistic theories. In particular, an ideal Bell experiment has to be performed with detectors of sufficiently high efficiency (to close the 'detection loophole') and with experimental settings that are randomly chosen in space-like separated regions (to close the 'locality loophole'). Since the first successful Bell experiment by Freedman and Clauser[12], later implementations have continuously converged to closing both the locality loophole[14,15,18,19] on the one hand and the detection loophole[16,20] on the other hand. Therefore it is reasonable to consider the violation of local realism a well established fact.

The logical conclusion one can draw from the violation of local realism is that at least one of its assumptions fails. Specifically, either locality or realism or both cannot provide a foundational basis for quantum theory. Each of the resulting possible positions has strong supporters and opponents in the scientific community. However, Bell's theorem is unbiased with respect to these views: on the basis of this theorem, one cannot, even in principle, favour one over the other. It is therefore important to ask whether incompatibility theorems similar to Bell's can be found in which at least one of these concepts is relaxed. Our work addresses a broad class of non-local hidden-variable theories that are based on a very plausible type of realism and that provide an explanation for all existing Bell-type experiments. Nevertheless we demonstrate, both in theory and experiment, their conflict with quantum predictions and observed

[1]Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria. [2]Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria. [3]Institute of Theoretical Physics and Astrophysics, University of Gdansk, ul. Wita Stwosza 57, PL-08-952 Gdansk, Poland. [4]The Erwin Schrödinger International Institute for Mathematical Physics (ESI), Boltzmanngasse 9, A-1090 Vienna, Austria.

measurement data. Following the recent approach of Leggett[3], who introduced the class of non-local models and formulated an incompatibility theorem, we have analysed its assumptions and derived an inequality valid for such theories that can be experimentally tested. In addition, the experiments allow for a simultaneous test of all local hidden-variable models—that is, the measurement data can neither be explained by a local realistic model nor by the considered class of non-local models.

The theories under investigation describe experiments on pairs of particles. It is sufficient for our purposes to discuss two-dimensional quantum systems. We will hence focus our description on the polarization degree of freedom of photons. The theories are based on the following assumptions: (1) all measurement outcomes are determined by pre-existing properties of particles independent of the measurement (realism); (2) physical states are statistical mixtures of subensembles with definite polarization, where (3) polarization is defined such that expectation values taken for each subensemble obey Malus' law (that is, the well-known cosine dependence of the intensity of a polarized beam after an ideal polarizer).

These assumptions are in a way appealing, because they provide a natural explanation of quantum mechanically separable states (polarization states indeed obey Malus' law). In addition, they do not explicitly demand locality; that is, measurement outcomes may very well depend on parameters in space-like separated regions. As a consequence, such theories can explain important features of quantum mechanically entangled (non-separable) states of two particles (a specific model can be found in Supplementary Information): first, they do not allow information to be transmitted faster than the speed of light; second, they reproduce perfect correlations for all measurements in the same bases, which is a fundamental feature of the Bell singlet state; and third, they provide a model for all thus far performed experiments in which the Clauser, Horne, Shimony and Holt (CHSH) inequality was violated. Nevertheless, we will show that all models based on assumptions (1)–(3) are at variance with other quantum predictions.

A general framework of such models is the following: assumption (1) requires that an individual binary measurement outcome A for a polarization measurement along direction $\mathbf{a}$ (that is, whether a single photon is transmitted or absorbed by a polarizer set at a specific angle) is predetermined by some set of hidden variables λ, and a three-dimensional vector $\mathbf{u}$, as well as by some set of other possibly non-local parameters η (for example, measurement settings in space-like separated regions)—that is, $A = A(\lambda,\mathbf{u},\mathbf{a},\eta)$. According to assumption (3), particles with the same $\mathbf{u}$ but with different λ build up subensembles of 'definite polarization' described by a probability distribution $\rho_{\mathbf{u}}(\lambda)$. The expectation value $\bar{A}(\mathbf{u})$, obtained by averaging over λ, fulfils Malus' law, that is, $\bar{A}(\mathbf{u}) = \int \mathrm{d}\lambda\rho_{\mathbf{u}}(\lambda)A(\lambda,\mathbf{u},\mathbf{a},\eta) = \mathbf{u}\cdot\mathbf{a}$. Finally, with assumption (2), the measured expectation value for a general physical state is given by averaging over the distribution $F(\mathbf{u})$ of subensembles, that is, $\langle A\rangle = \int \mathrm{d}\mathbf{u}F(\mathbf{u})\bar{A}(\mathbf{u})$.

Let us consider a specific source, which emits pairs of photons with well-defined polarizations $\mathbf{u}$ and $\mathbf{v}$ to laboratories of Alice and Bob, respectively. The local polarization measurement outcomes A and B are fully determined by the polarization vector, by an additional set of hidden variables λ specific to the source and by any set of parameters η outside the source. For reasons of clarity, we choose an explicit non-local dependence of the outcomes on the settings $\mathbf{a}$ and $\mathbf{b}$ of the measurement devices. Note, however, that this is just an example of a possible non-local dependence, and that one can choose any other set out of η. Each emitted pair is fully defined by the subensemble distribution $\rho_{\mathbf{u},\mathbf{v}}(\lambda)$. In agreement with assumption (3) we impose the following conditions on the predictions for local averages of such measurements (all polarizations and measurement directions are represented as vectors on the Poincaré sphere[21]):

$$\bar{A}(\mathbf{u}) = \int \mathrm{d}\lambda\rho_{\mathbf{u},\mathbf{v}}(\lambda)A(\mathbf{a},\mathbf{b},\lambda) = \mathbf{u}\cdot\mathbf{a} \quad (1)$$

$$\bar{B}(\mathbf{v}) = \int \mathrm{d}\lambda\rho_{\mathbf{u},\mathbf{v}}(\lambda)B(\mathbf{b},\mathbf{a},\lambda) = \mathbf{v}\cdot\mathbf{b} \quad (2)$$

It is important to note that the validity of Malus' law imposes the non-signalling condition on the investigated non-local models, as the local expectation values do only depend on local parameters. The correlation function of measurement results for a source emitting well-polarized photons is defined as the average of the products of the individual measurement outcomes:

$$\overline{AB}(\mathbf{u},\mathbf{v}) = \int \mathrm{d}\lambda\rho_{\mathbf{u},\mathbf{v}}(\lambda)A(\mathbf{a},\mathbf{b},\lambda)B(\mathbf{b},\mathbf{a},\lambda) \quad (3)$$

For a general source producing mixtures of polarized photons the observable correlations are averaged over a distribution of the polarizations $F(\mathbf{u},\mathbf{v})$, and the general correlation function E is given by:

$$E = \langle AB\rangle = \int \mathrm{d}\mathbf{u}\mathrm{d}\mathbf{v}F(\mathbf{u},\mathbf{v})\overline{AB}(\mathbf{u},\mathbf{v}) \quad (4)$$

It is a very important trait of this model that there exist subensembles of definite polarizations (independent of measurements) and that the predictions for the subensembles agree with Malus' law. It is clear that other classes of non-local theories, possibly even fully compliant with all quantum mechanical predictions, might exist that do not have this property when reproducing entangled states. Such theories may, for example, include additional communication[22] or dimensions[23]. A specific case deserving comment is Bohm's theory[24]. There the non-local correlations are a consequence of the non-local quantum potential, which exerts suitable torque on the particles leading to experimental results compliant with quantum mechanics. In that theory, neither of the two particles in a maximally entangled state carries any angular momentum at all when emerging from the source[25]. In contrast, in the Leggett model, it is the total ensemble emitted by the source that carries no angular momentum, which is a consequence of averaging over the individual particles' well defined angular momenta (polarization).

The theories described here are incompatible with quantum theory. The basic idea of the incompatibility theorem[3] uses the following identity, which holds for any numbers $A = \pm 1$ and $B = \pm 1$:

$$-1 + |A + B| = AB = 1 - |A - B| \quad (5)$$

One can apply this identity to the dichotomic measurement results $A = A(\mathbf{a},\mathbf{b},\lambda) = \pm 1$ and $B = B(\mathbf{b},\mathbf{a},\lambda) = \pm 1$. The identity holds even if the values of A and B mutually depend on each other. For example, the value of a specific outcome A can depend on the value of an actually obtained result B. In contrast, in the derivation of the CHSH inequality it is necessary to assume that A and B do not depend on each other. Therefore, any kind of non-local dependencies used in the present class of theories are allowed. Taking the average over the subensembles with definite polarizations we obtain:

$$-1 + \int \mathrm{d}\lambda\rho_{\mathbf{u},\mathbf{v}}(\lambda)|A + B| = \int \mathrm{d}\lambda\rho_{\mathbf{u},\mathbf{v}}(\lambda)AB = 1 - \int \mathrm{d}\lambda\rho_{\mathbf{u},\mathbf{v}}(\lambda)|A - B| \quad (6)$$

Denoting these averages by bars, one arrives at the shorter expression:

$$-1 + \overline{|A + B|} = \overline{AB} = 1 - \overline{|A - B|} \quad (7)$$

As the average of the modulus is greater than or equal to the modulus of the averages, one gets the set of inequalities:

$$-1 + |\bar{A} + \bar{B}| \leq \overline{AB} \leq 1 - |\bar{A} - \bar{B}| \quad (8)$$

By inserting Malus' law, equations (1) and (2), in equation (8), and by using expression (4), one arrives at a set of inequalities for experimentally accessible correlation functions (for a detailed derivation, see the Supplementary Information). In particular, if we let Alice

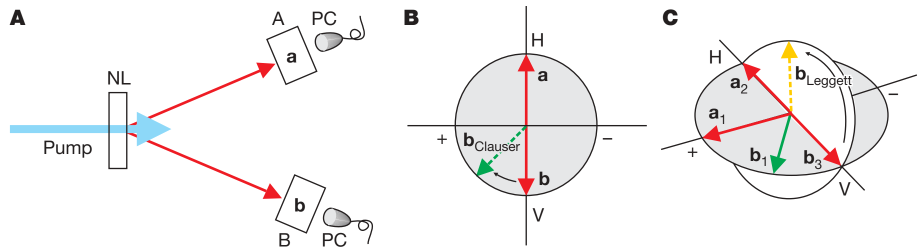

Figure 1 | Testing non-local hidden-variable theories. A, Diagram of a standard two-photon experiment to test for hidden-variable theories. When pumping a nonlinear crystal (NL) with a strong pump field, photon pairs are created via SPDC and their polarization is detected with single-photon counters (PC). Local measurements at A and B are performed along directions **a** and **b** on the Poincaré sphere, respectively. Depending on the measurement directions, the obtained correlations can be used to test Bell inequalities (**B**) or Leggett-type inequalities (**C**). **B**, Correlations in one plane. Shown are measurements along directions in the linear plane of the Poincaré sphere (H (V) denotes horizontal (vertical) polarization). The original experiments by Wu and Shaknov[26] and Kocher and Commins[27], designed to test quantum predictions for correlated photon pairs, measured perfect correlations (solid lines). Measurements along the dashed line allow a Bell test, as was first performed by Freedman and Clauser[12]. **C**, Correlations in orthogonal planes. All current experimental tests to violate Bell's inequality (CHSH) are performed within the shaded plane. Out-of plane measurements are required for a direct test of the class of non-local hidden-variable theories, as was first suggested by Leggett.

choose her observable from the set of two settings $\mathbf{a}_1$ and $\mathbf{a}_2$, and Bob from the set of three settings $\mathbf{b}_1$, $\mathbf{b}_2$ and $\mathbf{b}_3 = \mathbf{a}_2$, the following generalized Leggett-type inequality is obtained:

$$S_{\mathrm{NLHV}} = |E_{11}(\varphi) + E_{23}(0)| + |E_{22}(\varphi) + E_{23}(0)| \leq 4 - \frac{4}{\pi}\left|\sin\frac{\varphi}{2}\right| \quad (9)$$

where $E_{kl}(\varphi)$ is a uniform average of all correlation functions, defined in the plane of $\mathbf{a}_k$ and $\mathbf{b}_l$, with the same relative angle φ; the subscript NLHV stands for 'non-local hidden variables'. For the inequality to be applied, vectors $\mathbf{a}_1$ and $\mathbf{b}_1$ necessarily have to lie in a plane orthogonal to the one defined by $\mathbf{a}_2$ and $\mathbf{b}_2$. This contrasts with the standard experimental configuration used to test the CHSH inequality, which is maximally violated for settings in one plane.

The situation resembles in a way the status of the Einstein, Podolsky and Rosen (EPR) paradox before the advent of Bell's theorem and its first experimental tests. The experiments of Wu and Shaknov[26] and of Kocher and Commins[27] were designed to demonstrate the validity of a quantum description of photon-pair correlations. As this task only required the testing of correlations along the same polarization direction, their results could not provide experimental data for the newly derived Bell inequalities (Fig. 1A, B). Curiously, as was shown by Clauser, Horne, Shimony and Holt, only a small modification of the measurement directions, such that non-perfect correlations of an entangled state are probed, was sufficient to test Bell's inequalities. The seminal experiment by Freedman and Clauser[12] was the first direct and successful test[28]. Today, all Bell tests—that is, tests of local realism—are performed by testing correlations of measurements along directions that lie in the same plane of the Poincaré sphere. Similar to the previous case, violation of the Leggett-type inequality requires only small modifications to that arrangement: To test the inequality, correlations of measurements along two orthogonal planes have to be probed (Fig. 1C). Therefore the existing data of all Bell tests cannot be used to test the class of non-local theories considered here.

Quantum theory violates inequality (9). Consider the quantum predictions for the polarization singlet state of two photons,

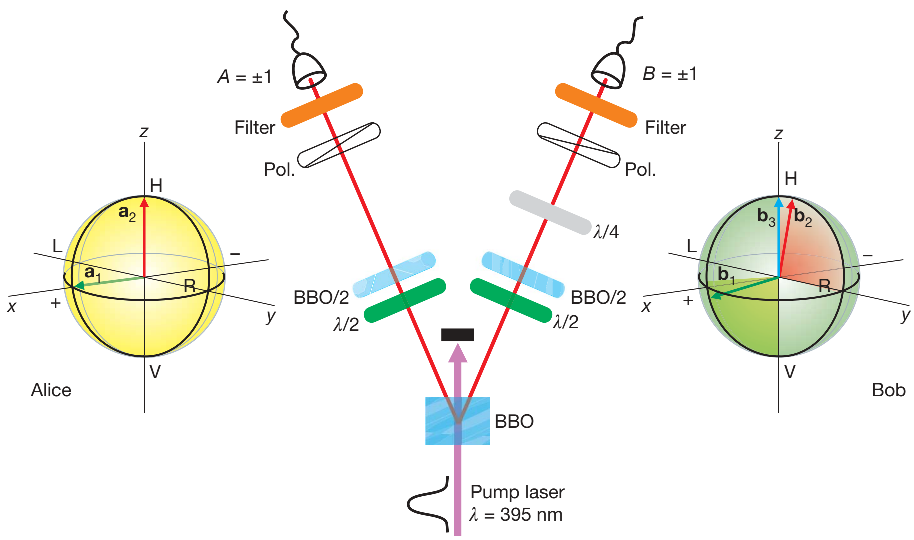

Figure 2 | Experimental set-up. A 2-mm-thick type-II β-barium-borate (BBO) crystal is pumped with a pulsed frequency-doubled Ti:sapphire laser (180 fs) at $\lambda = 395$ nm wavelength and ~150 mW optical c.w. power. The crystal is aligned to produce the polarization-entangled singlet state $|\Psi^-\rangle_{\mathrm{AB}} = \frac{1}{\sqrt{2}}[|H\rangle_{\mathrm{A}}|V\rangle_{\mathrm{B}} - |V\rangle_{\mathrm{A}}|H\rangle_{\mathrm{B}}]$. Spatial and temporal distinguishability of the produced photons (induced by birefringence in the BBO) are compensated by a combination of half-wave plates ($\lambda/2$) and additional BBO crystals (BBO/2), while spectral distinguishability (due to the broad spectrum of the pulsed pump) is eliminated by narrow spectral filtering of 1 nm bandwidth in front of each detector. In addition, the reduced pump power diminishes higher-order SPDC emissions of multiple photon pairs. This allows us to achieve a two-photon visibility of about 99%, which is well beyond the required threshold of 97.4%. The arrows in the Poincaré spheres indicate the measurement settings of Alice's and Bob's polarizers for the maximal violation of inequality (9). Note that setting $\mathbf{b}_2$ lies in the y–z plane and therefore a quarter-wave plate has to be introduced on Bob's side. The coloured planes indicate the measurement directions for various difference angles φ for both inequalities.

$|\Psi^-\rangle_{AB} = \frac{1}{\sqrt{2}}[|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B]$, where, for example, $|H\rangle_A$ denotes a horizontally polarized photon propagating to Alice. The quantum correlation function for the measurements $\mathbf{a}_k$ and $\mathbf{b}_l$ performed on photons depends only on the relative angles between these vectors, and therefore $E_{kl} = -\mathbf{a}_k \cdot \mathbf{b}_l = -\cos\varphi$. Thus the left hand side of inequality (9), for quantum predictions, reads $|2(\cos\varphi + 1)|$. The maximal violation of inequality (9) is for $\varphi_{max} = 18.8°$. For this difference angle, the bound given by inequality (9) equals 3.792 and the quantum value is 3.893.

Although this excludes the non-local models, it might still be possible that the obtained correlations could be explained by a local realistic model. In order to avoid that, we have to exclude both local realistic and non-local realistic hidden-variable theories. Note however that such local realistic theories need not be constrained by assumptions (1)–(3). The violation of the CHSH inequality invalidates all local realistic models. If one takes

$$S_{CHSH} = |E_{11} + E_{12} - E_{21} + E_{22}| \leq 2 \qquad (10)$$

the quantum value of the left hand side for the settings used to maximally violate inequality (9) is 2.2156.

The correlation function determined in an actual experiment is typically reduced by a visibility factor V to $E^{exp} = -V\cos\varphi$ owing to noise and imperfections. Thus to observe violations of inequality (9) (and inequality (10)) in the experiment, one must have a sufficiently high experimental visibility of the observed interference. For the optimal difference angle $\varphi_{max} = 18.8°$, the minimum required visibility is given by the ratio of the bound (3.792) and the quantum value (3.893) of inequality (9), or ~97.4%. We note that in standard Bell-type experiments, a minimum visibility of only ~71% is sufficient to violate the CHSH inequality, inequality (10), at the optimal settings. For the settings used here, the critical visibility reads $2/2.2156 \approx 90.3\%$, which is much lower than 97.4%.

In the experiment (see Fig. 2), we generate pairs of polarization entangled photons via spontaneous parametric down-conversion (SPDC). The photon source is aligned to produce pairs in the polarization singlet state. We observed maximal coincidence count rates (per 10 s), in the *H*/*V* basis, of around 3,500 with single count rates of 95,000 (Alice) and 105,000 (Bob), 3,300 coincidences in the ±45° basis (75,000 singles at Alice and 90,000 at Bob), and 2,400 coincidences in the *R*/*L* basis (70,000 singles at Alice and 70,000 at Bob). The reduced count rates in the *R*/*L* basis are due to additional retarding elements in the beam path. The two-photon visibilities are approximately 99.0 ± 1.2% in the *H*/*V* basis, 99.2 ± 1.6% in the ±45° basis and 98.9 ± 1.7% in the *R*/*L* basis, which—to our knowledge—is the highest reported visibility for a pulsed SPDC scheme. So far, no experimental evidence against the rotational invariance of the singlet state exists. We therefore replace the rotation averaged correlation functions in inequality (9) with their values measured for one pair of settings (in the given plane).

In terms of experimental count rates, the correlation function $E(\mathbf{a},\mathbf{b})$ for a given pair of general measurement settings is defined by

$$E(\mathbf{a},\mathbf{b}) = \frac{N_{++} + N_{--} - N_{+-} - N_{-+}}{N_{++} + N_{--} + N_{+-} + N_{-+}} \qquad (11)$$

where N_{AB} denotes the number of coincident detection events between Alice's and Bob's measurements within the integration time. We ascribe the number +1, if Alice (Bob) detects a photon polarized along $\mathbf{a}$ ($\mathbf{b}$), and −1 for the orthogonal direction $\mathbf{a}^\perp$ ($\mathbf{b}^\perp$). For example, N_{+-} denotes the number of coincidences in which Alice obtains $\mathbf{a}$ and Bob $\mathbf{b}^\perp$. Note that $E(\mathbf{a}_k,\mathbf{b}_l) = E_{kl}(\varphi)$, where φ is the difference angle between the vectors $\mathbf{a}$ and $\mathbf{b}$ on the Poincaré sphere.

To test inequality (9), three correlation functions ($E(\mathbf{a}_1,\mathbf{b}_1)$, $E(\mathbf{a}_2,\mathbf{b}_2)$, $E(\mathbf{a}_2,\mathbf{b}_3)$) have to be extracted from the measured data. We choose observables $\mathbf{a}_1$ and $\mathbf{b}_1$ as linear polarization measurements (in the *x*–*z* plane on the Poincaré sphere; see Fig. 2) and $\mathbf{a}_2$ and $\mathbf{b}_2$ as elliptical polarization measurements in the *y*–*z* plane. Two further correlation functions ($E(\mathbf{a}_2,\mathbf{b}_1)$ and $E(\mathbf{a}_1,\mathbf{b}_2)$) are extracted to test the CHSH inequality, inequality (10).

The first set of correlations, in the *x*–*z* plane, is obtained by using linear polarizers set to α_1 and β_1 (relative to the *z* axis) at Alice's and Bob's location, respectively. In particular, $\alpha_1 = \pm 45°$, while β_1 is chosen to lie between 45° and 160° (green arrows in Fig. 2). The second set of correlations (necessary for CHSH) is obtained in the same plane for $\alpha_2 = 0°/90°$ and β_1 between 45° and 160°. The set of correlations for measurements in the *y*–*z* plane is obtained by introducing a quarter-wave plate with the fast axis aligned along the (horizontal) 0°-direction at Bob's site, which effectively rotates the polarization state by 90° around the *z*-axis on the Poincaré sphere (red arrows in Fig. 2). The polarizer angles are then set to $\alpha_2 = 0°/90°$ and β_2 is scanned between 0° and 115°. With the same β_2 and $\alpha_1 = \pm 45°$, the expectation values specific only for the CHSH case are measured. The remaining measurement for inequality (9) is the check of perfect correlations, for which we choose $\alpha_2 = \beta_3 = 0°$, that

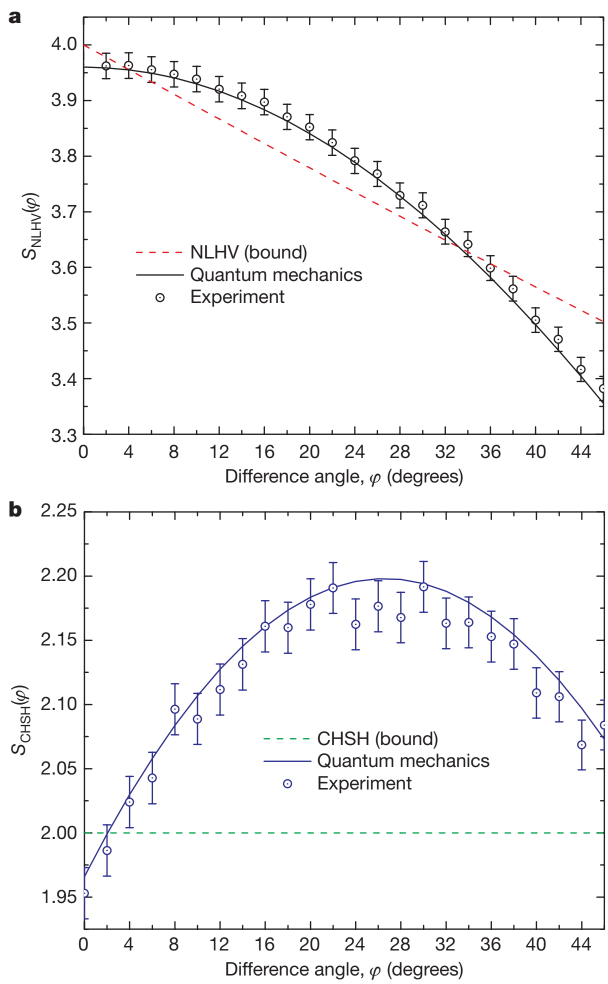

Figure 3 | Experimental violation of the inequalities for non-local hidden-variable theories (NLHV) and for local realistic theories (CHSH). a, Dashed line indicates the bound of inequality (9) for the investigated class of non-local hidden-variable theories (see text). The solid line is the quantum theoretical prediction reduced by the experimental visibility. The shown experimental data were taken for various difference angles φ (on the Poincaré sphere) of local measurement settings. The bound is clearly violated for $4° < \varphi < 36°$. Maximum violation is observed for $\varphi_{max} \approx 20°$. **b,** At the same time, no local realistic theory can model the correlations for the investigated settings as the same set of data also violates the CHSH inequality (10). The bound (dashed line) is overcome for all values φ around φ_{max}, and hence excludes any local realistic explanation of the observed correlations in **a.** Again, the solid line is the quantum prediction for the observed experimental visibility. Error bars indicate s.d.

is, the intersection of the two orthogonal planes. Figure 3 shows the experimental violation of inequalities (9) and (10) for various difference angles. Maximum violation of inequality (9) is achieved, for example, for the settings $\{\alpha_1,\alpha_2,\beta_1,\beta_2,\beta_3\} = \{45^\circ,0^\circ,55^\circ,10^\circ,0^\circ\}$.

We finally obtain the following expectation values for the optimal settings for a test of inequality (9) (the errors are calculated assuming that the counts follow a poissonian distribution): $E(\mathbf{a}_1,\mathbf{b}_1) = -0.9298 \pm 0.0105$, $E(\mathbf{a}_2,\mathbf{b}_2) = -0.942 \pm 0.0112$, $E(\mathbf{a}_2,\mathbf{b}_3) = -0.9902 \pm 0.0118$. This results in $S_{\mathrm{NLHV}} = 3.8521 \pm 0.0227$, which violates inequality (9) by 3.2 standard deviations (see Fig. 3). At the same time, we can extract the additional correlation functions $E(\mathbf{a}_2,\mathbf{b}_1) = 0.3436 \pm 0.0088$, $E(\mathbf{a}_1,\mathbf{b}_2) = 0.0374 \pm 0.0091$ required for the CHSH inequality. We obtain $S_{\mathrm{CHSH}} = 2.178 \pm 0.0199$, which is a violation by $\sim$9 standard deviations. The stronger violation of inequality (10) is due to the relaxed visibility requirements on the probed entangled state.

We have experimentally excluded a class of important non-local hidden-variable theories. In an attempt to model quantum correlations of entangled states, the theories under consideration assume realism, a source emitting classical mixtures of polarized particles (for which Malus' law is valid) and arbitrary non-local dependencies via the measurement devices. Besides their natural assumptions, the main appealing feature of these theories is that they allow us both to model perfect correlations of entangled states and to explain all existing Bell-type experiments. We believe that the experimental exclusion of this particular class indicates that any non-local extension of quantum theory has to be highly counterintuitive. For example, the concept of ensembles of particles carrying definite polarization could fail. Furthermore, one could consider the breakdown of other assumptions that are implicit in our reasoning leading to the inequality. These include Aristotelian logic, counterfactual definiteness, absence of actions into the past or a world that is not completely deterministic[29]. We believe that our results lend strong support to the view that any future extension of quantum theory that is in agreement with experiments must abandon certain features of realistic descriptions.

Received 22 December 2006; accepted 13 February 2007.

1. Schrödinger, E. Die gegenwärtige Situation in der Quantenmechanik. *Naturwissenschaften* **23**, 807–812; 823–828; 844–849 (1935).
2. Clauser, J. F., Horne, M. A., Shimony, A. & Holt, R. A. Proposed experiment to test local hidden-variable theories. *Phys. Rev. Lett.* **23**, 880–884 (1969).
3. Leggett, A. J. Nonlocal hidden-variable theories and quantum mechanics: An incompatibility theorem. *Found. Phys.* **33**, 1469–1493 (2003).
4. Einstein, A., Podolsky, B. & Rosen, N. Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **47**, 777–780 (1935).
5. Einstein, A. to Erwin Schrödinger, 19 June 1935 (Albert Einstein Archives, Jewish National and University Library, The Hebrew University of Jerusalem)
6. Bohr, N. in *Albert Einstein: Philosopher-Scientist* Vol. 7 (ed. Schilpp, P. A.) 201–241 (Library of Living Philosophers, Evanston, 1949).
7. Bell, J. S. On the Einstein Podolsky Rosen paradox. *Physics* **1**, 195–200 (1964).
8. Clauser, J. F. & Horne, M. D. Experimental consequences of objective local theories. *Phys. Rev. D* **10**, 526–535 (1974).
9. Clauser, J. F. in *Quantum [Un]speakables: From Bell to Quantum Information* (eds Bertlmann, R. A. & Zeilinger, A.) 61–98 (Springer, Heidelberg, 2002).
10. Greenberger, D. M., Horne, M. A. & Zeilinger, A. in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe* (ed. Kafatos, M.) 69–72 (Kluwer, Dordrecht, 1989).
11. Greenberger, D. M., Horne, M. A., Shimony, A. & Zeilinger, A. Bell's theorem without inequalities. *Am. J. Phys.* **58**, 1131–1143 (1990).
12. Freedman, S. J. & Clauser, J. F. Experimental test of local hidden-variable theories. *Phys. Rev. Lett.* **28**, 938–941 (1972).
13. Aspect, A., Grangier, P. & Roger, G. Experimental tests of realistic local theories via Bell's theorem. *Phys. Rev. Lett.* **47**, 460–463 (1981).
14. Aspect, A., Dalibard, J. & Roger, G. Experimental test of Bell's inequalities using time-varying analyzers. *Phys. Rev. Lett.* **49**, 1804–1807 (1982).
15. Weihs, G., Jennewein, T., Simon, C., Weinfurter, H. & Zeilinger, A. Violation of Bell's inequality under strict Einstein locality conditions. *Phys. Rev. Lett.* **81**, 5039–5043 (1998).
16. Rowe, M. A. *et al.* Experimental violation of a Bell's inequality with efficient detection. *Nature* **409**, 791–794 (2001).
17. Pan, J.-W., Bouwmeester, D., Daniell, M., Weinfurter, H. & Zeilinger, A. Experimental test of quantum nonlocality in three-photon Greenberger-Horne-Zeilinger entanglement. *Nature* **403**, 515–519 (2000).
18. Zeilinger, A. Testing Bell's inequalities with periodic switching. *Phys. Lett. A* **118**, 1–2 (1986).
19. Aspect, A. Bell's inequality test: more ideal than ever. *Nature* **398**, 189–190 (1999).
20. Grangier, P. Count them all. *Nature* **409**, 774–775 (2001).
21. Born, M. & Wolf, E. *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light* 2nd edn (Pergamon, Oxford, 1964).
22. Bacon, D. & Toner, B. F. Bell inequalities with auxiliary communication. *Phys. Rev. Lett.* **90**, 157904 (2003).
23. Ne'eman, Y. The problems in quantum foundations in the light of gauge theories. *Found. Phys.* **16**, 361–377 (1986).
24. Bohm, D. A suggested interpretation of the quantum theory in terms of "hidden" variables. I and II. *Phys. Rev.* **85**, 166–193 (1952).
25. Dewdney, C., Holland, P. R. & Kyprianidis, A. A causal account of non-local Einstein-Podolsky-Rosen spin correlations. *J. Phys. Math. Gen.* **20**, 4717–4732 (1987).
26. Wu, C. S. & Shaknov, I. The angular correlation of scattered annihilation radiation. *Phys. Rev.* **77**, 136 (1950).
27. Kocher, C. A. & Commins, E. D. Polarization correlation of photons emitted in an atomic cascade. *Phys. Rev. Lett.* **18**, 575–577 (1967).
28. Clauser, J. F. & Shimony, A. Bell's theorem. Experimental tests and implications. *Rep. Prog. Phys.* **41**, 1881–1927 (1978).
29. Bell, J. S. Free variables and local causality. *Dialectica* **39**, 103–106 (1985).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We are grateful to A. J. Leggett for stimulating this work and for discussions. We also thank D. Greenberger, M. A. Horne, T. Jennewein, J. Kofler, S. Malin and A. Shimony for their comments. T.P. is grateful for the hospitality of the IQOQI, Vienna. M.A. thanks L. Gohlike for his hospitality at the Seven Pines VIII. We acknowledge support from the Austrian Science Fund (FWF), the European Commission, the Austrian Exchange Service (ÖAD), the Foundation for Polish Science (FNP), the Polish Ministry of Higher Education and Science, the City of Vienna and the Foundational Questions Institute (FQXi).

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to M.A. (markus.aspelmeyer@quantum.at) or A.Z. (zeilinger-office@quantum.at).

CORRIGENDUM

doi:10.1038/nature06190

An experimental test of non-local realism

S. Gröblacher, T. Paterek, R. Kaltenbaek, Č. Brukner, M. Żukowski, M. Aspelmeyer & A. Zeilinger

Nature 446, 871–875 (2007)

The experimental values of correlation functions were measured at the difference angle $\varphi = 20^\circ$ (on the Poincaré sphere), rather than 18.8° as was stated in the original paper. The reported violation of 3.2 standard deviations refers to $\varphi = 20^\circ$. In Supplementary Information II of the original paper the boundaries of all integrals over variables χ and ψ should be the following: χ varies from -2π to 2π; ψ varies from $|\chi|/2$ to $2\pi - |\chi|/2$. Also, in equation (35) and what follows, $F(\vartheta_u,\vartheta_v)$ should be replaced by $\int_{-2\pi}^{2\pi} \mathrm{d}\chi \int_{|\chi|/2}^{2\pi - |\chi|/2} \mathrm{d}\psi F(\vartheta_u,\vartheta_v,\psi,\chi)$. The final inequality of the paper and all its conclusions do not change. The errors arose from our attempt for a more concise notation, but were never used in our actual calculations. We thank Stephen Parrott for pointing out these errors.