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Testing quantum theory in a photon pair experiment

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A new set of measurements provides the tightest ever constraint for the Bell parameter, which constitutes the closest ever approach to the Tsirelson bound.

It has been shown[1] that the results of spin measurements on quantum systems cannot be explained with local theories. This is because these theories violate certain inequalities in the correlations between the measurement outcomes from two distant locations (A and B). The simplest of these 'Bell inequalities' is that proposed by Clauser, Horne, Shimony, and Holt (CHSH Bell inequality).[2] This can be expressed as $|S| \leq 2$, where S (the Bell parameter) is a combination of correlations, $E(a_i, b_j)$, defined by equation 1.

$$S = E(a_0, b_0) - E(a_0, b_1) + E(a_1, b_0) + E(a_1, b_1) \quad (1)$$

In this equation, $a_{0,1}$ and $b_{0,1}$ are the measurement settings at A and B, respectively. Each spin measurement has two possible outcomes, $+1$ or -1. The correlations $E(a_i, b_j)$ are thus defined from the joint probabilities (P) of four different outcomes, i.e., positive and positive spins ($++$), positive and negative spins ($+-$), negative and positive spins ($-+$), and negative and negative spins ($--$), or by equation 2.

$$E(a_i, b_j) = P(++) - P(+-) - P(-+) + P(--) \quad (2)$$

In previous work, Boris Tsirelson[3] has also shown that, according to quantum theory, $|S|$ has an upper bound of $2\sqrt{2}$ (i.e., about 2.82843). Alexei Grinbaum,[4] however, predicted that the violation of the Bell CHSH inequality has a different upper bound, of 2.82537(2), i.e., slightly smaller than the Tsirelson bound. This alternative estimate arises from an attempt to address issues associated with the cut between the observer and the observed system[5] in quantum theory. If Grinbaum's limit cannot be exceeded, this would support the idea that quantum theory is only an effective description of a more fundamental theory.[4] It would thus have a deep impact within physics and the field of quantum information processing. Highly accurate experiments are therefore required to investigate potential violations of the Bell CHSH inequality.

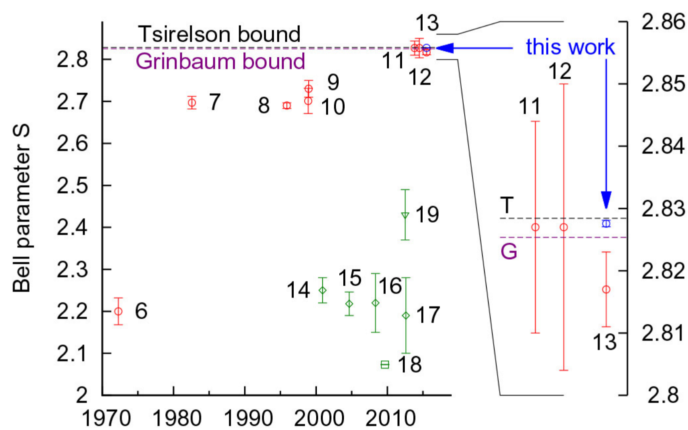

Figure 1. Selected results from experimental tests of the Clauser, Horne, Shimony, and Holt (CHSH) Bell inequality. Results that are close to the Tsirelson (T) and Grinbaum (G) bounds in photonic systems (circles), atoms and ions (diamonds), Josephson junctions (squares), and nitrogen-vacancy centers in diamond (triangles) are shown. Numbers denote the relevant references. The x-axis shows the year of the experiments. Figure is adapted from a previous publication.[20]

The violation of Bell's inequality has previously been observed in several experiments. Many of these tests were based on the generation—from cascade decay in atoms[6,7] or from the exploitation of non-linear optical processes[8–12]—of correlated photon pairs. Other successful demonstrations of the inequality violation have been based on the internal degrees of freedom of ions[13–15] and neutral atoms,[16] Josephson junctions,[17] and nitrogen-vacancy centers in diamond.[18] The different results obtained for the Bell parameter, together with the corresponding uncertainties, are summarized in Figure 1. All the available experimental results are consistent with the Grinbaum bound.[6–19]

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Motivated by this status quo, we have attempted to approach the Tsirelson bound experimentally.[20] We are therefore able to make direct observations that can be compared with the prediction of the Grinbaum model. This kind of experimental search for the maximum violation of a Bell inequality[1] also allows us to test the principles that are used to predict the Tsirelson bound[21–23], i.e., to test them as possible explanations of all natural limits of the correlations.

Our experimental setup is shown in Figure 2. We used the output of a laser diode (central wavelength of 405nm) to pump a barium borate crystal that was cut for type-II phase-matching. Spontaneous parametric down-conversion in the slightly non-collinear configuration generated photon pairs. These pairs consisted of a horizontally (H) and vertically (V) polarized photon, at a wavelength of 810nm. To optimize photon collection, we used two single-mode fibers to define two spatial modes that were matched to the pump mode.[24] We also used a half-wave plate and a pair of compensation crystals (CCs) to deal with the temporal and transversal walk-off.[8] These also allowed us to adjust the phase between the two decay components and thus obtain the singlet state. We used film polarizers to perform the basis choice and polarization projection. Photons were detected by avalanche photodiodes, and the corresponding detection events from the same pair were identified with a coincidence unit. To obtain a very clean singlet state, we had to carefully align the photon pair collection so that the contributions of $|HV\rangle$ and $|VH\rangle$ were balanced. We were able to adjust their relative positions with the CC. We minimized higher-order parametric conversion processes[25] by restricting the pump power. As expected, the rate of coincidence events depended on the orientation of the polarizers. In our experiments this rate ranged from 26–217s^{-1}.

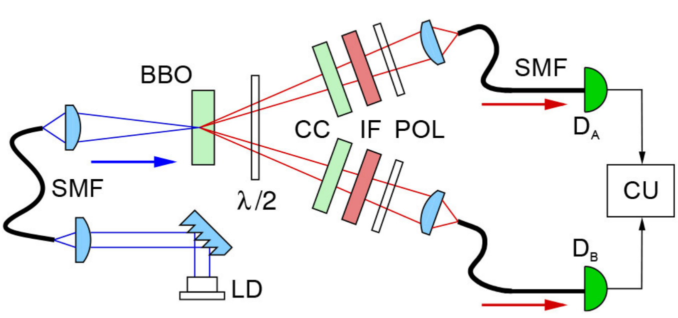

Figure 2. *Schematic diagram of the experimental setup. The polarization correlations of entangled photon pairs are measured with the use of film polarizers (POL) placed in front of the collection optics. All photons are detected by the silicon avalanche photodetectors (D_A and D_B), and are registered with a coincidence unit (CU). LD: Laser diode. SMF: single-mode fiber. BBO: Barium borate crystal. λ/2: Half-wave plate. CC: Compensation crystal.*

We measured high visibilities (99.9±0.1%) in both the ±45° and the natural H/V linear polarization basis for the polarization correlations. Our results therefore indicated a high quality of polarization entanglement. Furthermore, to compensate for imperfections in the state generation and errors in the setting of the polarizers, we optimized the angular settings of the polarizers. We could thus observe the largest possible violation. We estimated the correlations (E)—see equation 2—from the coincidence counts (N) between A and B for the settings of the polarizers as:

$$E = \frac{N_{++} - N_{+-} - N_{-+} + N_{--}}{N_{++} + N_{+-} + N_{-+} + N_{--}} \quad (3)$$

To acquire sufficient statistics, we collected coincidence events for each of the 16 settings that were required to evaluate S for 1 minute. We then repeated each set of measurements 312 times, and registered a total of 33,184,329 pair events. From our experiments—via equations 1 and 3—we thus obtained a value for S of 2.82759±0.00051 (see Figure 1). This can also be expressed as a separation of $2\sqrt{2} - S$ (or 0.00084±0.00051) from the Tsirelson bound.

Our result violates Grinbaum's bound by 4.3 standard deviations and constitutes the tightest experimental test of Tsirelson's bound that has ever been reported. We have therefore falsified the thesis that quantum theory is only an effective version of a deeper theory. We have also reinforced the concepts that quantum theory is fundamental and that the Tsirelson bound is a natural limit. In addition, our conclusion strengthens the potential value of principles in which the Tsirelson bound[21–23] is used to explain the natural limits of correlations in all scenarios.

In summary, we have conducted an experimental test of the CHSH Bell inequality, to try and approach the Tsirelson bound. Through these experiments we have achieved a new value for the Bell inequality and the closest ever test of the Tsirelson bound. Our work therefore demonstrates the possibility of experimentally reaching this bound, which has important consequences for quantum information and the certification of a variety of physical properties.

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