Exploring the Limits of Non-Locality with Pairs of Photons

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Bell inequalities are a powerful tool in discriminating whether Nature is better described by classical theories or non-local ones. We present our efforts in experimentally test Bell inequalities and the predictions of standard quantum mechanics using a source of polarization entangled photon pairs, in particular our most recent two works. In the first, we attempt to saturate the Tsirelson bound, the well known $2\sqrt{2}$ predicted by standard quantum mechanics. This attempt allowed us to exclude some of the alternative, non-local theories [1]. In the second, I present an approach to discriminate between classical and non-classical system based on the computational complexity of the output, as opposed to the statistical nature of the standard Bell tests [2].

Theory

With local realism, the Bell inequality (CHSH inequality [3]) $|S| \leq 2$ is not violated. Tsirelson [4] showed that, according to quantum theory, $|S|$ has an upper bound of $2\sqrt{2} \approx 2.82843$. Other non-local theories predict other upper bounds. One of such theories, proposed by Grinbaum [5], tries to address the cut between the observer and the observed system in quantum mechanics. His theory predicts an upper bound of the violation of the CHSH inequality to be 2.82537(2) (Grinbaum bound), slightly smaller than the Tsirelson bound. This lower bound is so far consistent with all the available experimental results supporting the hypothesis that quantum theory is only an effective description of a more fundamental theory. However any violations would suggest contrary.

Bell tests are based on the statistical inference of correlations between measurements. However it is possible to adopt an algorithmic approach where we consider the Kolmogorov complexity [6] of the output of a long sequence of measurements. Under such an approach, the typical bipartite Bell-type experiment can be thought of as having two spatially separated universal Turing machines (UTMs): UTM$_A$ and UTM$_B$, with the corresponding outputs, x and y. A local hidden variable theory that describes the outputs two machines can be encoded in a common input program Λ, and additional programs for each UTM encoding the sequence of local measurement settings a_j and b_k $(j, k = 0, 1)$. An experimental result that cannot be simulated by the UTMs would therefore falsify any local realistic description of that process.

This algorithmic Bell inequality given by:

$$S_A = NCD(x_0, y_1) - NCD(x_0, y_0) - NCD(x_1, y_0) - NCD(x_1, y_1) \leq 0. \qquad (1)$$

A violation of the local realism hypothesis occurs if S_A is positive. The normalized compression distance (NCD), tells us how similar the two strings x and y are, is defined as

$$NCD(x, y) = \frac{C(x, y) - \min\{C(x), C(y)\}}{\max\{C(x), C(y)\}}, \qquad (2)$$

where $C(x, y)$, the resulting file size after compression with a commercial compression software, gives the estimate of its Kolmogorov complexity which in general cannot be evaluated.

Experimental Setup

In our experiment (see figure 2), we implemented a typical polarization-entangled photon pair source in a crossed-ring configuration at 810 nm. The source is adjusted to generated the polarization state $|\psi\rangle = 1/\sqrt{2}\,(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B)$.

In the first experiment, polarization analysis is being perform by means of film polarizers placed in front of the collection optics. This is to eliminate any unwanted polarization state transformations due to the fiber neutralization. In the second experiment, photons from SPDC are projected onto arbitrary linear polarization by $\lambda/2$ plates and polarization beam splitter in each analyzer (inset of figure 2). For both experiments, photons are detected by APDs, and corresponding detection events from the same pair identified by a coincidence unit if they arrive within $\approx \pm 1.2$ ns of each other.

To arrive at a very clean singlet state, we carefully align the photon pair collection to balance the two photon pair contributions $|HV\rangle$ and $|VH\rangle$, and adjust their relative phase with the CC. Furthermore, we minimize contributions from higher order parametric conversion processes by restricting the pump power to $7/$,mW. We observed both in the natural H/V and complementary $\pm 45°$ basis, high visibility of $V = 99.9 \pm 0.1\%$, indicating a high quality of polarization entanglement.

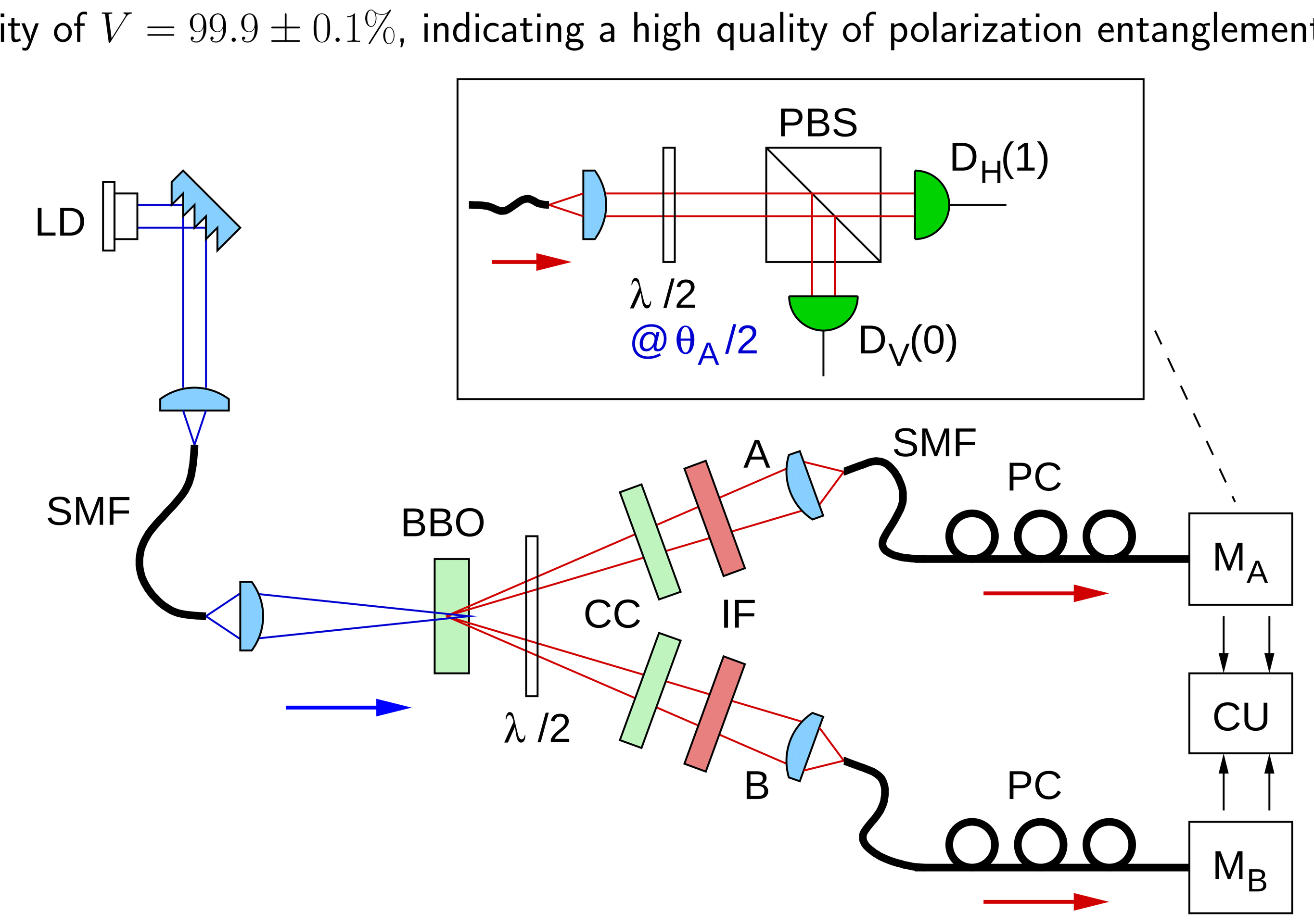

Figure 1: Schematic of the experimental set-up. Polarization correlations of entangled-photon pairs are measured by the polarization analyzers M$_A$ and M$_B$, each consisting of a half wave plate ($\lambda/2$) followed by a polarization beam splitter (PBS). All photons are detected by Avalanche photodetectors D$_H$ and D$_V$, and registered in a coincidence unit (CU).

Results

For the first experiment, the violation of the CHSH inequality, we collect coincidence events for each of the 16 settings required to evaluate S for 1 minute, and then repeat again the whole set. Within 312 such complete sets, we registered a total of 33,184,329 pair events. As a result, we obtain in this experiment, a value of $S = 2.82759 \pm 0.00051$, or a separation of $2\sqrt{2} - S = 0.00084 \pm 0.00051$ from the Tsirelson bound. This violation of the Grinbaum bound suggests that quantum mechanics is not just an effective description of a more fundamental theory but a fundamental theory in itself.

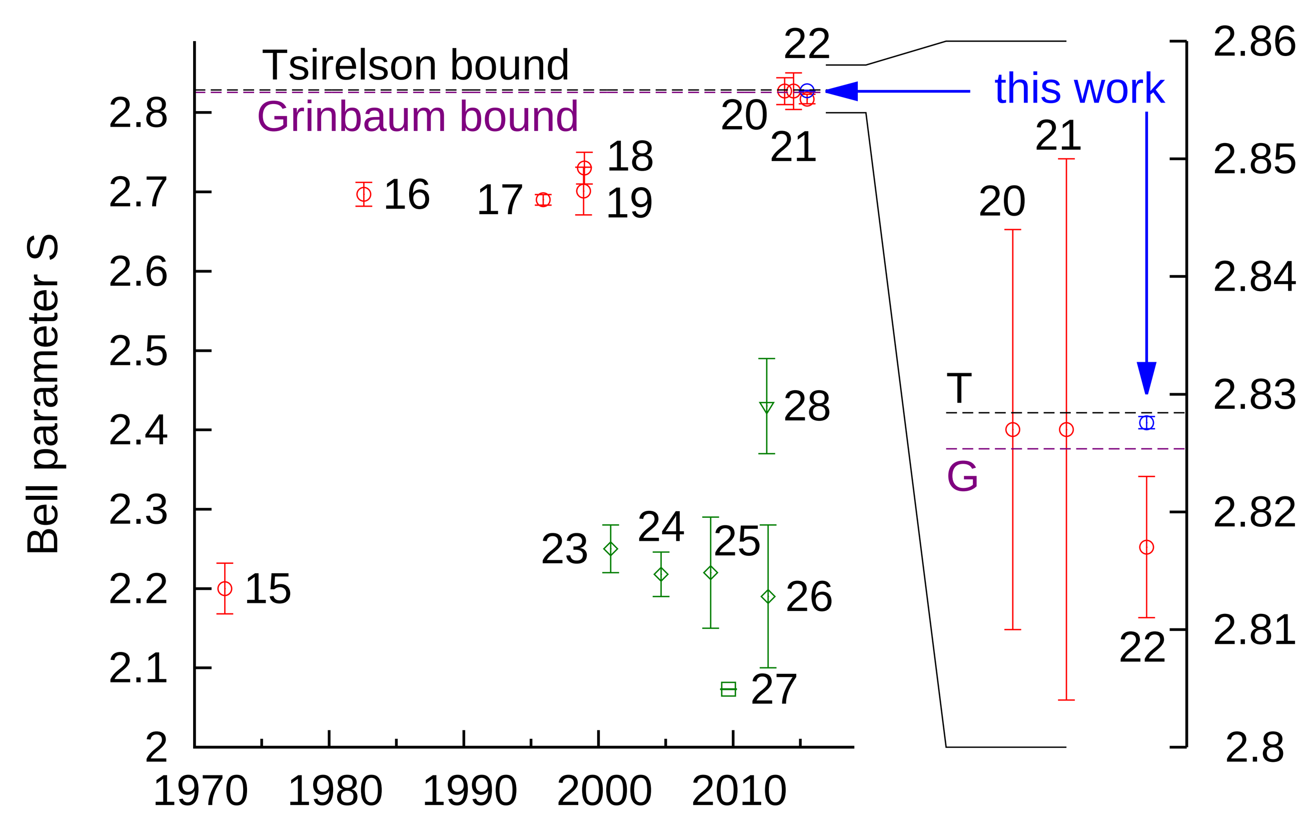

Figure 2: Selected experimental tests of the CHSH Bell inequality with results close to the Tsirelson (T) and Grinbaum (G) bounds in photonic systems (circles), atoms and ions (diamonds), Josephson junctions (square), and nitrogen-vacancy centers in diamond (triangle). See [1] for details.

For the second experiment, violation of the algorithmic Bell inequality, the inequality is experimentally tested by evaluating S_A in Eq. (1) for a range of angle θ between each of the four settings; the results [points (c), (d) in figure 4] are consistently lower than the trace (a) calculated via entropy, and than a simulation with the same compressor (b). This is because the compression software we used (LZMA Utility) is not working exactly at the Shannon limit, and also due to imperfect state generation and detection.

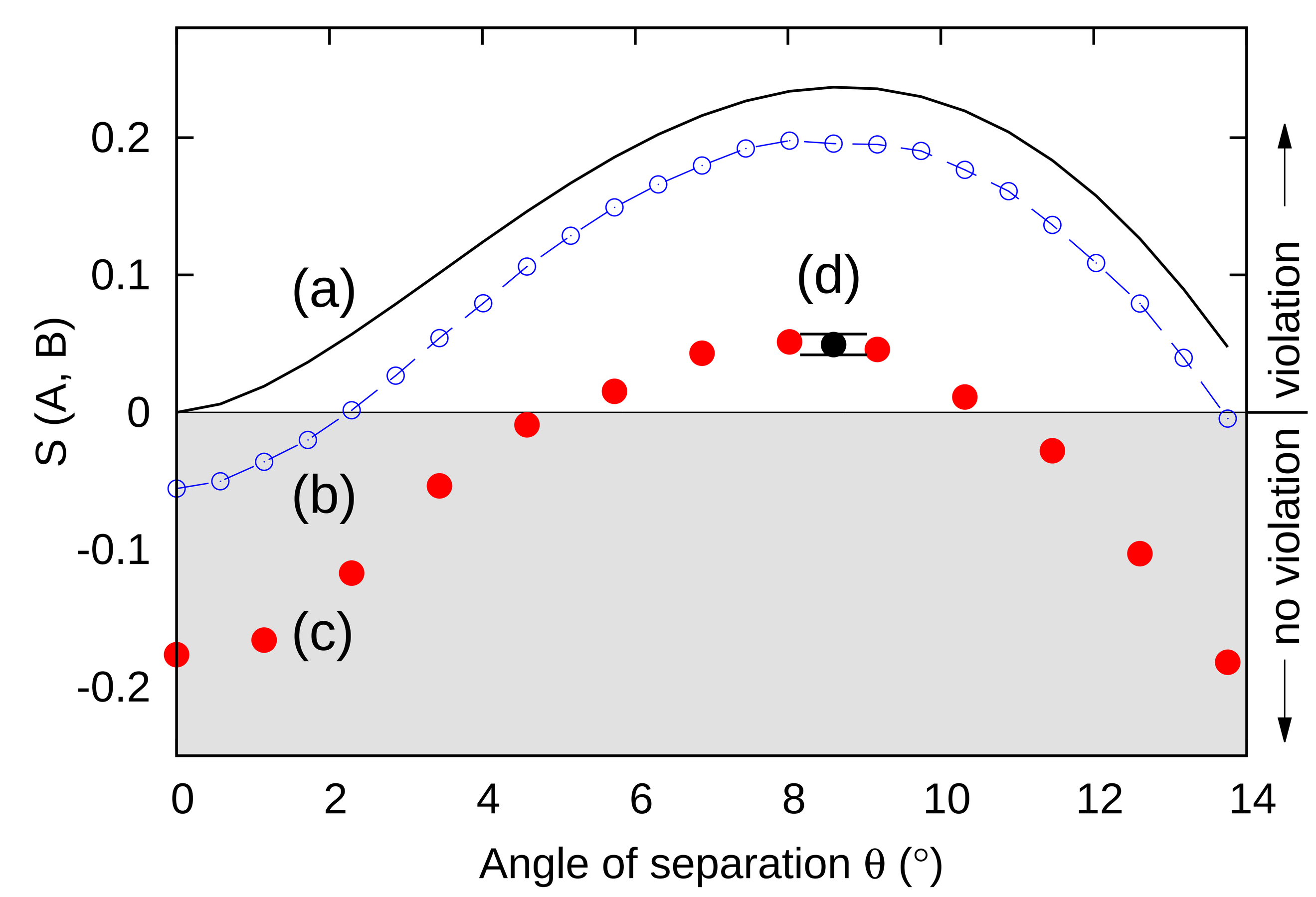

Figure 3: Plots of S_A versus angle of separation θ. (a) Result obtained from Eq. (??), (b) result obtained from using the LZMA compressor on numerically generated data, c) measurement of S in the experiment shown in figure ??,and (d) longer measurement at the optimal angle $\theta = 8.6°$.

To estimate an uncertainty of the experimentally obtained values for S_A, we set $\theta = 8.6°$, for which we expect the maximum violation, and collected results from a larger number of photon pairs. We then repeated the measurement of S, as described in the previous section, 8 times, and considered the average value and standard deviation of this set obtaining the final result of $S(\theta = 8.6°) = 0.0494 \pm 0.0076$. This demonstrates that the algorithmic approach is complementary to the orthodox Bell inequality approach to quantum nonlocality that is statistical in its nature.

References

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