Testing the reality of Wigner's friend's experience

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Quantum mechanics is a robust theory which produces highly accurate predictions. Despite its successes, it is still plagued with controversies like the measurement problem. In short, the measurement problem is the conflict between the evolution of the wavefunction described by Schrödinger's equation and the apparent collapse of the wavefunction after a measurement is done. The Wigner's friend paradox illustrates the conflict between the two rules [1]. In the thought experiment, we consider an observer (Wigner's friend) who is able to perform measurement on the quantum system and assign a quantum state. Wigner is a super-observer who is able to measure the laboratory his friend is in and also assign a quantum state. This process, however, leads to a quantum state that does not ascribe a well-defined value to the outcome of the friend's observation, in apparent contradiction with the friend's perspective.

Brukner proposed a no-go theorem to demonstrate that the assumptions of *observer-independent facts*, *locality* and *freedom of choice* are in contradiction with the predictions of quantum mechanics for an extended version of the Wigner's friend scenario [2], where we now have two superobservers, Alice and Bob, and their respective friends, Charlie and Debbie. Alice and Bob perform measurements on the entire contents of the labs containing Charlie and Debbie respectively. Charlie and Debbie measure a pair of particles prepared in an entangled state. Brukner's claim that the assumption mentioned leads to a local hidden variable (LHV) correlations and thereby to Bell's inequality. He then proceeds to show that we are able to violate the inequalities and concludes that the assumptions are in contradiction with each other. A recent 4-photon experiment, where the role of each friend is played by a single photon, demonstrated the violation of a Bell inequality proposed by Brunker [3]. Yet, recent work by Healey [4] showed Brukner's no-go theorem has an additional implicit assumption related to the equal treatment of performed and unperformed measurements. The extra assumption weakens the conclusion made by Brukner.

We formalised the assumptions in the no-go theorem and improved it by replacing it with a weaker version. The conjunction of the three assumptions is coined *Local Friendliness* (LF). From the formalised LF assumptions, they have derived a LF correlation. For the case when there are two measurement settings, we are able to derive the LHV correlations. Proving that the LHV correlation is a subset of the LF correlation, and thus violation of a Bell inequality does not imply a violation of a LF inequality. We were also able to find specific states and measurements that show that quantum theory is able to predict the violation of LF inequalities, which we were able to test experimentally with polarization entangled photon pairs.

Bell non-LF	$\langle A_2B_2\rangle - \langle A_2B_3\rangle - \langle A_3B_2\rangle - \langle A_3B_3\rangle - 2 \leq 0$
Brukner	$-\langle A_1B_2\rangle + \langle A_1B_3\rangle - \langle A_3B_2\rangle - \langle A_3B_3\rangle - 2 \leq 0$
Semi-Brukner	$\langle A_1B_1\rangle - \langle A_1B_2\rangle - \langle A_1B_3\rangle$ $-\langle A_2B_1\rangle + \langle A_2B_2\rangle - \langle A_2B_3\rangle$ $-\langle A_3B_1\rangle - \langle A_3B_2\rangle$ $-\langle A_1\rangle + \langle A_2\rangle + \langle B_1\rangle - \langle B_2\rangle - 4 \leq 0$
I3322	$\langle A_1B_1\rangle - \langle A_1B_2\rangle - \langle A_1B_3\rangle$ $-\langle A_2B_1\rangle + \langle A_2B_2\rangle - \langle A_2B_3\rangle$ $-\langle A_3B_1\rangle - \langle A_3B_2\rangle$ $-\langle A_1\rangle + \langle A_2\rangle + \langle B_1\rangle - \langle B_2\rangle - 4 \leq 0$
Genuine LF	$-\langle A_1B_1\rangle - 2\langle A_1B_2\rangle$ $-2\langle A_2B_1\rangle + 2\langle A_2B_2\rangle - \langle A_2B_3\rangle$ $-\langle A_3B_2\rangle - \langle A_3B_3\rangle$ $-\langle A_1\rangle - \langle A_2\rangle - \langle B_1\rangle - \langle B_2\rangle - 6 \leq 0$

Table I. Categorization of Bell and LF inequalities from 9 inequivalent classes to 5 shown in the table above, according to the measurement settings involved, and whether they are Bell facets. Each category represents inequalities with the same form up to arbitrary relabelling of measurement settings, outcomes and parties.

The desired quantum state is generated via type-I spontaneous parametric down-conversion using two orthogonally oriented BiBO crystals in Fig. 1. The crystals are pumped with a mixture of a diagonally polarized state, coming from the short arm of the interferometer, and a decohered state, coming from the long arm. The relative pump power in the long and short arm determines the μ parameter which controls the degree of mixture in the desired quantum state. In the measurement section, tomography can be performed when the motorized mirrors are removed such that the photon-pairs pass through the beam displacer (BD) interferometers. The tomography stages also transform into the projective

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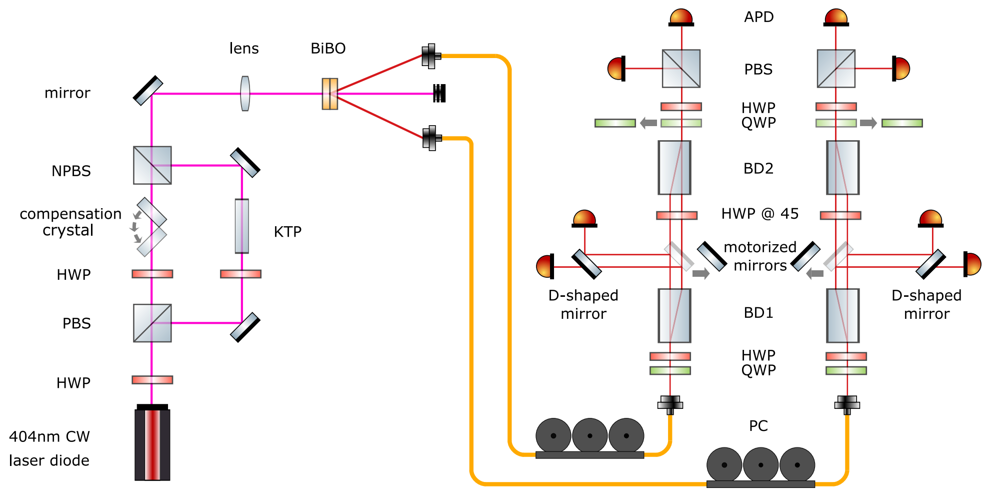

Figure 1. Experimental setup.

measurement stages of Alice and Bob when the quarter-wave plates (QWP) are removed. Charlie and Debbie's projective measurements correspond to the beam paths within the interferometers, so that Alice and Bob can ask their respective friends for their measurement outcomes by inserting the motorized mirrors.

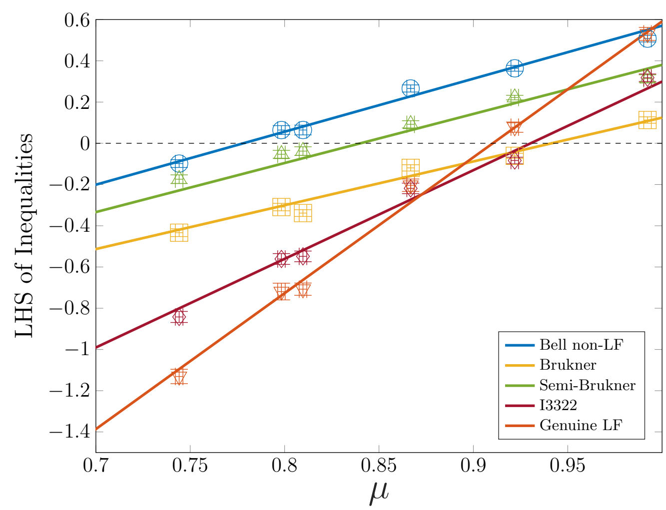

Figure 2. Experimental results of the left-hand sides of various Bell and LF inequalities in Table I. The dashed line in the plot represents the bound above which a violation occurs. The uncertainties for the data points are calculated from a Monte Carlo simulation using 100 samples of Poisson distributed photon counts. The solid lines are theory and the points are experimental data

The results of the experiment are shown in Fig. 2. The μ values cover the full range of interest, from none of the inequalities being violated to the violation of all inequalities. The experimental data demonstrate the sequential violations of the Bell non-LF, semi-Brukner, and genuine LF inequalities. The data points corresponding to $\mu = 0.79$ and $\mu = 0.81$ are of particular significance, as they demonstrate that it is possible to violate Bell inequalities without violating any LF inequalities. This means that the correlations allowed by an LHV model are a subset of the correlations allowed by LF assumptions. Finally, the two highest μ values show that genuine LF inequality can also be violated.

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