Experimental amplification of an entangled photon: what if the detection loophole is ignored?

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Abstract. The experimental verification of quantum features, such as entanglement, at large scales is extremely challenging because of environment-induced decoherence. Indeed, measurement techniques for demonstrating the quantumness of multiparticle systems in the presence of losses are difficult to define, and if they are not sufficiently accurate they can provide wrong conclusions. We present a Bell test where one photon of an entangled pair is amplified and then detected by threshold detectors, whose signals undergo postselection. The amplification is performed by a classical machine, which produces a fully separable micro–macro state. However, by adopting such a technique one can surprisingly observe a violation of the Clauser–Horne–Shimony–Holt inequality. This is due to the fact that ignoring the detection loophole opened by the postselection and the system losses can lead to misinterpretations, such as claiming micro–macro entanglement in a setup where evidently it is not present. By using threshold detectors and postselection, one can only infer the entanglement of the initial pair of photons, and so micro–micro entanglement, as is further confirmed by the violation of a nonseparability criterion for bipartite systems. How to detect photonic micro–macro entanglement in the presence of losses with the currently available technology remains an open question.

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1. Introduction

Typically, quantum effects such as superposition and entanglement can be observed exclusively in the microscopic regime. This limitation prevents quantum mechanics from easily accessing our everyday experience and from becoming intuitive. Investigating quantum features at larger scales is a fundamentally relevant step, because it allows one to test the limits of quantum theory and to fully solve the conceptual difficulties of the quantum-to-classical transition, pointed out, for example, by the famous ‘Schrödinger’s cat’ paradox [1].

In recent years, some quantum effects at mesoscopic scales have been observed. Schrödinger cat states have been generated by making Rydberg atoms interact with a coherent field trapped in a high-$Q$ cavity [2], by superposing localized wave packets of a single trapped $^{9}$Be$^{+}$ ion with distinct internal electronic states [3, 4] or macroscopically distinct current states in superconducting quantum interference devices (SQUID) [5] and by subtracting photons to squeezed states [6]. Interference patterns for massive molecules, such as spherical fullerenes $C_{60}$, have also been reported [7].

Recently, the entanglement between a photon and a macroscopic field containing $\approx 10^{4}$ photons was tested for the first time [8]. Photonic micro–macro entanglement can be created in principle by amplifying one photon initially belonging to an entangled pair via a phase covariant cloner, a unitary transformation that can be implemented with an optical parametric amplifier. This remarkable experiment also stimulated the idea of performing Bell tests with human eyes as detectors [9], in order to explore ways of bringing entanglement close to the realm of human experience.

Nonetheless, the experimental exploration of quantum mechanics in the macroscopic domain is extremely challenging because multiparticle systems are more susceptible to interactions with the environment and can easily and quickly lose their quantum coherence [10]. Experimental losses (including finite detector efficiency) can be seen as an interaction between the system and the environment and make the task of revealing the entanglement of multiparticle systems highly nontrivial. In [8], the nonseparability of the photonic micro–macro entangled state is claimed by violating an entanglement witness criterion for a bipartite system, where
the macro state is conceived as a qubit, and by adopting a postselection of the detected events based on a threshold condition, called the orthogonality filter. However, in [11] we have shown that decoherence results in a large increase in the dimension of the Hilbert space in which the macroscopic state is defined, moving it far from its theoretical model of a qubit. Therefore, verifying the existence of micro–macro entanglement after losses requires measurements that are able to explore this Hilbert space, and needs an extremely efficient photon number resolution. Coarse-grained techniques, such as threshold detectors of finite efficiency and postselection, are not sufficiently accurate and can lead to wrong conclusions.

In this paper, we illustrate experimentally some issues arising when the entanglement between a photon and a macroscopic field is investigated [11]. We describe an experiment where one photon of an entangled pair is amplified inside a black box and then detected by threshold detectors, whose signals undergo a postselection that is independent of the measurement bases. At first, the entanglement in the system can be tested by measuring a Clauser–Horne–Shimony–Holt (CHSH) inequality that, within the frame of quantum mechanics, can be considered as an entanglement witness.

In a standard CHSH test [12] the choice of the measurement basis is made before the photon is amplified, usually by an avalanche photodiode. Interestingly, in our setup the measurement basis can be chosen after the optical amplification. We show that, even if the final micro–macro state is fully separable, a violation of the Bell inequality is surprisingly possible and drives one to claim micro–macro entanglement, although we prove that it is clearly not present. This result highlights the relevance of the detection loophole, opened by system losses and postselection: indeed, if it is not taken into account, misinterpretations can result from similar experiments. By violating a second test of nonseparability for bipartite systems, similar to the one measured in [8], we confirm that with threshold detectors and postselection, one can only demonstrate the initial entanglement between the two photons, prior to amplification. A fascinating aspect of the experiment described in this paper is that it can even be carried out using a human observer as a detector, as we show at the end of the paper.

2. A Clauser–Horne–Shimony–Holt (CHSH)–Bell test with the amplification of an entangled photon

2.1. The experimental concept

Let us consider the following experiment. Photon pairs entangled in polarization are distributed to two separate locations A and B, as schematically illustrated in figure 1. The polarization of the photon on side A is analyzed by a two-channel polarizer, measuring at an angle $\alpha$ with
Figure 2. Setup of the CHSH–Bell test with artificial threshold detectors made with photodiodes on side B.

respect to the horizontal direction. As in standard optical Bell tests, two single-photon detectors are placed at the two outputs of the measuring device, labeled ‘+’ and ‘−’.

The other photon of the pair is sent to a black box on side B. For the moment we assume no knowledge of the internal functioning of the box, except for the fact that for an incoming photon it sends a macroscopic pulse, thus performing an optical amplification.

Now, we would like to measure the CHSH inequality. Actually, this is a rather unusual configuration for such a test. Indeed, in standard CHSH–Bell tests [12], each photon of the entangled pair is measured in a specific measurement basis and then the result of the measurement is amplified (electrically in a single-photon detector) in order to be accessible to the experimenter. Here, the amplification is performed before the choice of the measurement basis. By keeping the analogy with the CHSH test, the pulse coming from the box is analyzed by a two-channel polarizer as well, measuring at angle $\beta$ with respect to the horizontal direction. The outputs are labeled ‘+’ and ‘−’.

The two orthogonally polarized pulses at the outputs of the polarizer have variable intensities. Each of the two orthogonal polarization components of this macroscopic pulse is incident on a threshold detector, which fires if the light is sufficiently intense. A postselection technique is applied to the detected signals: if only one threshold detector fires, a conclusive result is produced. When both or neither of them fire, the result is inconclusive and the event is rejected. In order to perform a CHSH test, the correlations between the results on the two sides for some specific measurement bases have to be measured.

2.2. The experimental implementation and the violation of the CHSH inequality

Photon pairs at 810 nm entangled in polarization are produced by a spontaneous parametric down conversion with a nonlinear $\beta$-barium borate (BBO) crystal cut for a type II phase matching and pumped by a diode laser at 405 nm, as shown in figure 2. The pairs are generated in the singlet state $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$, where $|H(V)\rangle$ represents a single-photon state of horizontal (vertical) polarization. The photons pass interference filters with a 10 nm bandwidth and are coupled into single-mode fibers passing through polarization controllers. The photon on side A is analyzed in polarization with a system composed of a half-wave plate (HWP) and a polarizing beam splitter (PBS), which allows one to project into a linear polarization at an angle $\alpha$ with respect to the horizontal direction and to its orthogonal one at $\alpha^\perp$. The photons at the two
outputs of the polarizer are detected by avalanche photodiode single-photon detectors, labeled A_1 and A_2.

The photon on side B is sent to the black box. The pulses emitted by the box are at 635 nm and are similarly analyzed in polarization by an HWP and PBS, projecting into the polarizations at angles \( \beta \) and \( \beta^\perp \) with respect to the horizontal direction. Two linear photodiodes, labeled B_1 and B_2, are used to detect the flashes at the two outputs of the PBS. We record the analogue output of these diodes and set, in software, a threshold voltage value on the detected signals; then the postselection technique described in the previous section is applied. When only one of the signals overcomes the threshold, a conclusive result is produced. The outcome is inconclusive and rejected when the signals are both above or both below the threshold value.

To measure the CHSH inequality, we determine the correlations of the results on the two sides using the following measurement bases. On side A we measure the polarizations at the angles \((\alpha_1 = 22.5^\circ, \alpha_1^\perp = 112.5^\circ)\) for the first basis \(a_1\) or \((\alpha_2 = 67.5^\circ, \alpha_2^\perp = 157.5^\circ)\) for the second basis \(a_2\). On side B we measure at the angles \((\beta_1 = 0^\circ, \beta_1^\perp = 90^\circ)\) for the \((H, V)\) basis \(b_1\) or \((\beta_2 = 45^\circ, \beta_2^\perp = 135^\circ)\) for the \((+, -)\) one \(b_2\). For each correlation term, we take into account, in a total of 5000 trials, the coincidences between the single-photon detectors on side A and the conclusive answers provided by the threshold detectors on side B. Each trial corresponds to the emission of a flash by the box. The way in which coincidences are measured will be detailed in the following sections. Our goal is to estimate the Bell parameter

\[
S = |E(a_1, b_1) - E(a_1, b_2) + E(a_2, b_1) + E(a_2, b_2)| \leq 2, \tag{1}
\]

where \(E(a_i, b_j)\) with \(i, j = 1, 2\) is the correlation term in the basis \(a_i\) and \(b_j\), and 2 represents the local bound.

By fixing a low threshold value such that we postselect 20% of the detected events, a value of \(2.45 \pm 0.08\), which violates the local bound 2, is measured for the Bell parameter. Note that the 20% ratio of detected events is independent of the choices of the measurement bases on sides A and B. Now, we know from textbooks on quantum mechanics that a violation of a Bell inequality indicates the presence of entanglement. But what exactly is entangled with what? Is it the pulse at the output of the black box that is entangled with the single photon on the other side?

3. The opening of the box

The observed violation of the CHSH inequality could be explained if we assume having a phase covariant cloner \([13]\) in the black box. A phase covariant cloner is an optimal quantum cloning machine for qubits on the equatorial plane of the Poincaré sphere. Indeed, assuming a classical pump field, this cloner represents a unitary process that thus preserves the entanglement of the initial pair of photons \([11]\).

However, when the box is opened a much simpler machine is found. As shown in figure 3, the incoming photons are focused onto a single-photon detector by a converging lens placed behind a linear polarizer. The single-photon detector (ID Quantique 101) has 7% efficiency and low noise (0.7 Hz). The polarizer is continuously rotated by an external motor, so the photons are measured in random linear polarizations. When the detector fires, a pulse is emitted by a diode laser, which is also rotated by the motor. The polarization of the pulse is aligned with the direction of the polarizer. As one photon of the pairs in the singlet state is unpolarized, a flash is sent at the output of the box with a random polarization and a constant probability
corresponding to the efficiency of the detector. This amplifying machine, which is a measure and prepare cloner, is absolutely classical: the state of the photon entering the black box is projected onto a random basis on a great circle of the Poincaré sphere and, if the detector clicks, the measured state is amplified.

The measure and prepare cloner is very similar to the phase covariant one because the amplification is limited to the great circle of the Poincaré sphere and both machines clone one qubit of the plane into a large number of qubits with a fidelity of $\frac{3}{4}$ \cite{14}. Moreover, the measure and prepare cloner can be designed to emit photon states providing the same measurement statistics as the phase covariant cloner. Hence, it can be considered a sort of classical simulation of the quantum cloner. However, the two devices, beyond their practical implementation, differ strongly in one fundamental point. The phase covariant cloner performs a unitary transformation on the initial quantum state and thus can in principle transfer the entanglement of two initial photons to the micro–macro regime. In contrast, the measure and prepare cloner installed in the black box performs a detection; it therefore entirely breaks the entanglement between the two initially entangled photons.

Therefore, observing a violation of the CHSH inequality using a measure and prepare cloner, as reported in the previous section, and a detection system based on threshold detectors and postselection, indicates that one cannot distinguish between a phase covariant and a measure and prepare cloner. It is clear that the violation we reported in the previous section does not reveal any kind of micro–macro entanglement.

### 3.1. The importance of the detection loophole

We repeat the Bell test by varying the threshold value on the signal recorded by the photodiodes on side B. In figure 4, the values of the Bell parameter are reported as a function of different thresholds. The local bound at 2 for the CHSH inequality is represented by a horizontal line.

A violation of the local bound is evident only for small and large values of the threshold. The two electrical signals are often above the threshold in the case of small thresholds, and below the threshold in the case of large ones. In these cases many events are rejected and so a large amount of postselection is used. For small or large thresholds the error in the...
Bell parameter increases because of the more restricted sample of data with which it has been evaluated. The values shown in figure 4 are in good agreement with what we expect by taking into account the working principle of the measure and prepare cloner and the fact that the entangled state after the transmission of the photons in the fibers, which degrades the quality of the entanglement, can be roughly thought of as a Werner state with density matrix

$$\rho = p|\Psi^\perp\rangle\langle \Psi^\perp| + (1 - p)\frac{1}{4}$$

with the visibility \( p \approx 0.89 \). Note that \( p \) is the average of the visibilities in the two bases \((H, V)\) and \((+, -)\).

We quantify the postselection in terms of the success probability \( P_s \), i.e. the probability of a conclusive result, which can be calculated as the ratio between the overall number of conclusive events and the total number of trials. In figure 4, the values of the success probability as a function of the threshold values are also reported and represented by the red dashed line. The violation of the CHSH inequality is large for small values of the success probability, i.e. for a strong postselection. This effect is related to the fact that a conclusive result is obtained when the polarization measured in the measure and prepare cloner is parallel to that measured on side B. Therefore, increasing the amount of postselection means being more restrictive on this condition and accepting only the cases in which the two polarizations are more and more parallel. Note that the postselection efficiency is, on average, the same for all polarization measurement bases of side B and is independent of the basis set on side A.

The results reported in this section show that the detection loophole has a crucial role in the interpretation of the violation of the CHSH inequality in our experiment. Losses before the choice of the measurement settings, such as the low efficiency of the measure and prepare cloner, have no effect on the detection loophole. In contrast, what opens the detection loophole in our test is the postselection and the threshold detection system after the choice of the measurement settings. From our experiment it emerges that if the detection loophole is ignored, one can easily come to false conclusions. For instance, one could claim that the macroscopic state produced by the black box is entangled with the single photon, although it is clearly not the
case because the measure and prepare cloner gives rise to a completely separable state. The result highlighted in this section can be applied to general micro–macro entanglement witness criteria. When losses are present, micro–macro entanglement deteriorates and, if it is still present, is extremely difficult to detect. Indeed, coarse-grained measurement techniques, such as threshold detectors and postselection, are not able to capture the complexity of the Hilbert space in which the macrostate lives and the possible entangled nature of the photonic micro–macro system.

3.2. Micro–micro entanglement

In the previous sections we have proved that threshold detectors and postselection turn out to be inappropriate to detect micro–macro entanglement. But does the measured violation of the Bell inequality in the presence of postselection provide other useful information? In the context of quantum mechanics, a Bell inequality can be considered an entanglement witness even in the presence of losses. Indeed, entanglement is a concept defined within Hilbert space quantum mechanics. Thus, an entanglement witness assumes a specific Hilbert space and can rely on hypotheses accepted by quantum physics, such as the fact that inefficient detectors or, in general, losses independent of the measurement settings, do not modify the conclusions of an entanglement test [11]. Therefore, the Bell inequality in the presence of postselection can be used to detect the entanglement of a system composed of two qubits, so in a Hilbert space of dimension $2 \otimes 2$ and, in our case, its measured violation shows the entanglement of the initial pair of photons.

In order to further confirm the micro–micro entanglement, we can consider the optical amplification performed by the measure and prepare cloner as a part of the detection system and measure an entanglement witness similar to the one measured in [8].

According to this criterion for a separable state, the following condition is obtained:

$$|V_{a,a_\perp} + V_{a',a'_\perp}| \leq 1,$$

(2)

where $V_{a,a_\perp}$ and $V_{a',a'_\perp}$ are the correlation visibilities in two orthogonal bases in a great circle of the Poincaré sphere $(a, a_\perp)$ and $(a', a'_\perp)$. In the appendix, a derivation of this entanglement witness can be found. The correlation visibility in the basis $(a, a_\perp)$ can be measured by fixing the basis $(a, a_\perp)$ for both sides A and B and calculating the quantity

$$V_{a,a_\perp} = \frac{N_{A_1,B_1} + N_{A_2,B_2} - N_{A_1,B_2} - N_{A_2,B_1}}{N_{A_1,B_1} + N_{A_2,B_2} + N_{A_1,B_2} + N_{A_2,B_1}},$$

(3)

where $N_{i,j}$ are the coincidences between the detector $i = A_1$ ($A_2$) measuring the state $a$ ($a_\perp$) and the conclusive results provided by the photodiodes $j = B_1$ ($B_2$) measuring similarly the states $a$ ($a_\perp$). The measure and prepare cloner acts on the great circle of the Poincaré sphere corresponding to the linear polarizations; therefore two orthogonal bases such as $(H, V)$ and $(+, -)$ can give nonzero contributions to the total correlation visibility. In this case the bound in equation (2) reads

$$|V_{H,V} + V_{\mp,-}| \leq 1.$$

(4)

In order to measure the visibility in the basis $(a, a_\perp)$, we set this basis on side B and continuously change the phase $\alpha$ on the photon on side A. By using a threshold value of 1.2 $V$, at which no postselection is performed, we observe interference fringes (figure 5) with visibilities of
Figure 5. Coincidence counts in 1000 trials between the detector $A_1$ and all the results given by the photodiode $B_1$ for the bases $(H, V)$ (blue squares data with a continuous fitting curve) and $(+, -)$ (green circles with a dashed fitting curve). The fitting curves together with those of the coincidences between $A_1$ and $B_2$ are used to estimate the correlation visibilities.

$0.536 \pm 0.019$ for the $(H, V)$ basis and $0.602 \pm 0.018$ for the $(+, -)$ basis. The difference between these two correlation visibilities is already present in the state of the two initially entangled photons, prior to the amplification. The reported values give $|V_{H,V} + V_{+, -}| = 1.138 \pm 0.026$, which violates the bound in equation (2).

We observe that the entanglement witness is violated in a more consistent way if postselection is performed. However, it is important to note that, even if postselection of the detected signals is not necessary, the detected events are in any case only a part of the events generated by the entanglement source because of the inefficiency of the detectors, so the detection loophole is still open.

The confirmation of the existence of micro–micro entanglement makes evident another interesting result. The measure and prepare cloner breaks the entanglement but, in some sense, not the information about it. Indeed, it is able to preserve the symmetry of the initial photon pair state after the amplification. If the measurement basis is chosen prior to the amplification, the information carried by the macroscopic state is simply the result of the measurement. In contrast, when the amplification is performed before the measurement, the macroscopic state still carries the answers to all possible questions.

4. Replacing artificial detectors with a human observer

The CHSH–Bell test described in this paper can be in general carried out by adopting any kind of threshold detectors on side B. Since the measure and prepare cloner optically amplifies the result of the measurement on a single photon to the classical regime, visible with the naked eye, threshold detection criteria based on the human visual system can be used.

Indeed, we perform a Bell test with a human observer on side B, replacing artificial detectors in a way that will be clarified below. Similarly to the test described in section 2.2,
one photon of the entangled pair is amplified by the measure and prepare cloner and analyzed by a two-channel polarizer. The two pulses at the output of the polarizer are sent to a screen and the observer looks at the two spots (see the inset of figure 6). Since the polarization of the pulses is always changing, the intensity of the two spots varies. When the intensities of the two spots are quite different, the observer is asked to decide which spot is brighter by pushing a button corresponding to the left or to the right one. The labels ‘+’ and ‘−’ are associated with the two possibilities, respectively. However, he often cannot perceive differences between the two spots in intensity. In this case he is not able to give a conclusive answer, so he rejects the trial and waits for the following one. In other words, he performs a postselection of the events in a way similar to what was done previously by software on the electrical signals of the photodiodes. The experiment is performed in a darkened room with a constant low-level luminosity and lasts for approximately 2 h. The pulses have a duration of 200 ms and a maximum peak power of approximately 1 μW before the screen.

Data acquisition is carried out in the following way. Once the detector inside the cloner fires, the pulse is emitted, a sound alerts the observer to answer and the answers are registered by software, together with the time-stamp of the detection inside the cloner.

We measure the CHSH inequality by setting the measurement bases as described in section 2.2. For each of the four correlation terms, we take into account the coincidences in 1000 trials between the single-photon detectors A\textsubscript{1} and A\textsubscript{2} and the conclusive answers provided by the observer. Note that the use of two single-photon detectors on side A guarantees that the observer does not know which coincidence term of the correlation term he is measuring for each trial, avoiding any kind of arbitrary choice in the results. The measurement bases for the four correlation terms are also varied after every 250 trials in order to average the fluctuations in time of the threshold criterion of the observer.
Table 1. Coincidence values collected for the measurement of the CHSH inequality with one human observer on side B of the experiment.

| $\alpha_1$ | $\alpha_1^\perp$ | $\alpha_2$ | $\alpha_2^\perp$ |
|------------|-----------------|------------|-----------------|
| $\beta_1$  | 15 ± 4          | 134 ± 12   | 112 ± 11        | 44 ± 7          |
| $\beta_1^\perp$ | 144 ± 12      | 26 ± 5     | 46 ± 7          | 135 ± 12        |
| $\beta_2$  | 35 ± 6          | 132 ± 11   | 29 ± 5          | 155 ± 12        |
| $\beta_2^\perp$ | 118 ± 11      | 59 ± 8     | 150 ± 12        | 27 ± 5          |

Table 1 reports the values of the coincidences collected for the measurement of the CHSH inequality in this new configuration, providing the following values for the correlation terms:

$$E(a_1, b_1) = -0.743 \pm 0.038,$$
$$E(a_1, b_2) = 0.466 \pm 0.048,$$
$$E(a_2, b_1) = -0.453 \pm 0.048,$$
$$E(a_2, b_2) = -0.672 \pm 0.040.$$

These results give for the Bell parameter the value $2.334 \pm 0.087$, providing a violation of the local bound 2. The average amount of postselection used in the experiment corresponds to a success probability of 33.5%. The violation is in good agreement with the results given by the artificial threshold detectors, as shown in figure 6.\(^2\)

It is important to stress again that in this kind of Bell test, the human observer does not look at anything entangled but is just witnessing the micro–micro entanglement already present in the system. Adopting the human visual system for the detection of a quantum phenomenon is fascinating and can be of interest for public demonstrations or for highlighting the importance of the detection loophole in undergraduate laboratory courses.

5. Discussion and conclusions

In this paper, we discuss some of the difficulties and limitations encountered in the experimental investigation of the entanglement between a photon and a macroscopic field. We describe a CHSH–Bell test where one photon of an entangled pair is amplified by a measure and prepare cloner and detected by using threshold detectors and a postselection technique of the detected events. This is an unusual configuration for a Bell test, where the amplification is performed before the choice of the measurement basis. A violation of the CHSH inequality is observed, although the final micro–macro state is completely separable. This result emphasizes

\(^2\) We also performed the same Bell test by using, instead of artificial detectors, two observers at each output of the PBS on side B and by attenuating the pulses to a peak power of approximately 1 nW before the screen. This attenuation ensured that the amount of light was at the threshold vision level, roughly a few thousands of photons scattered from the screen and impinging on the observers’ corneas. As for artificial threshold detectors, the events were conclusive only when one of the two observers saw the spot. We repeated these experiments with different pairs of observers, but the CHSH inequality was not systematically violated. In our opinion this was due to the fact that the visual detection thresholds of the two observers, related to individual states of concentration and light adaptation, vary in an independent way during a rather long experiment.
the importance of the detection loophole, which is opened by the postselection and the system losses, and is a serious problem that cannot be ignored. This result is quite general. Detecting micro–macro entanglement in the presence of losses is extremely difficult: coarse-grained measurement techniques, such as threshold detectors and postselection, are not sufficient. Extremely efficient photon-number-resolving detectors should be used, together with appropriate entanglement witness criteria.

However, the experiment reported in this paper can show the entanglement of the two initial photons: the micro–micro entanglement. This has been shown by observing the violation of a nonseparability criterion for bipartite systems, defined in [11]. We have also shown that the violation of the CHSH inequality can even be obtained by replacing artificial threshold detectors with a human observer. Furthermore, adopting the human visual system for the detection of a quantum phenomenon could be of interest for highlighting in undergraduate laboratory courses the importance of the detection loophole.

Detecting micro–macro entanglement in the presence of losses is an open issue that needs fundamental investigation, and where new and appropriate criteria have to be formulated [15, 16] to answer important questions such as the following. What amount of decoherence can be tolerated for a genuine micro–macro entanglement test? Can one really detect photonic micro–macro entanglement with currently available technologies?

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Appendix. Derivation of the micro–micro entanglement witness

In [11], an entanglement witness criterion has been defined, according to which for a separable state,

$$|V_x + V_y + V_z| \leq 1,$$

where $V_x$, $V_y$ and $V_z$ are the components of the correlation visibility of the state in three orthogonal bases on the Poincaré sphere. It can be derived by taking into account the quantity $|\langle \tilde{J}_A \cdot \tilde{J}_B \rangle|$, where $J_A = a^\dagger a - a_\perp^\dagger a_\perp$ and $J_B = b^\dagger b - b_\perp^\dagger b_\perp$, which for a separable state $\rho_A \otimes \rho_B$ gives $|\langle \tilde{J}_A \rangle_{\rho_A} \cdot \langle \tilde{J}_B \rangle_{\rho_B}|$. An upper bound of this term can be found by observing that $\langle \tilde{J}_A \rangle_{\rho_A} \cdot \langle \tilde{J}_B \rangle_{\rho_B}$ is a ‘classical’ vector and the scalar product between two vectors is smaller than the product of their lengths:

$$|\langle \tilde{J}_A \rangle_{\rho_A} \cdot \langle \tilde{J}_B \rangle_{\rho_B}| \leq |\langle \tilde{J}_A \rangle_{\rho_A}| |\langle \tilde{J}_B \rangle_{\rho_B}| \leq \langle N_A \rangle \langle N_B \rangle.$$  \hspace{1cm} (A.1)

This is a basic proof of the entanglement witness in [11].

In the same fashion we can derive a witness for only two visibility components. Let us consider the term $|\langle J_A^x \tilde{J}_B^x + J_A^y \tilde{J}_B^y \rangle|$, where $x$ and $y$ refer to two arbitrary orthogonal measurement settings ($J_A^x = a_\parallel^\dagger a_x - a_\parallel^\dagger a_x \perp$), which gives $|\langle \tilde{J}_A \rangle_{\rho_A} \langle \tilde{J}_B \rangle_{\rho_B} + \langle J_A^x \rangle_{\rho_A} \langle J_B^x \rangle_{\rho_B}|$ for a separable state $\rho_A \otimes \rho_B$. Now, this quantity can be seen as the scalar product $|P_{xy} \langle \tilde{J}_A \rangle \cdot P_{xy} \langle \tilde{J}_B \rangle|$, with
$P_{xy} \langle \vec{J}_{A(B)} \rangle$ being the projection of $\langle \vec{J}_{A(B)} \rangle$ on the $x$–$y$-plane. These projected vectors clearly have a smaller length with respect to the initial vectors, thus we have

$$\langle J^x_A \rangle_{\rho_A} \langle J^y_B \rangle_{\rho_B} + \langle J^y_A \rangle_{\rho_A} \langle J^x_B \rangle_{\rho_B} \leqslant |P_{xy} \langle \vec{J}_A \rangle||P_{xy} \langle \vec{J}_B \rangle| \leqslant |\langle \vec{J}_A \rangle||\langle \vec{J}_B \rangle| \leqslant \langle N_A \rangle \langle N_B \rangle.$$ (A.2)

Using this entanglement witness, we only need to measure two components of the correlation visibility without any assumption on a third one.

References

[1] Schrödinger E 1935 Naturwissenschaften 23 807
[2] Brune M, Hagley E, Dreyer J, Maître X, Maali A, Wunderlich C, Raimond J M and Haroche S 1996 Phys. Rev. Lett. 77 4887
[3] Monroe C, Meekhof D M, King B E and Wineland D J 1996 Science 272 1131
[4] Myatt C J, King B E, Turchette Q A, Sackett C A, Kielpinski D, W M, Itano Monroe C and Wineland D J 2000 Nature 403 269
[5] Friedman J R, Patel V, Chen W, Tolpygo S K and Lukens J E 2000 Nature 406 43
[6] Ourjoumtsev A, Tualle-Brouri R, Laurat J and Grangier P 2006 Science 312 83
[7] Arndt M, Nairz O, Vos-Andreae J, Keller C, van der Zouw G and Zeilinger A 1999 Nature 401 680
[8] De Martini F, Sciarrino F and Vitelli C 2008 Phys. Rev. Lett. 100 253601
[9] Sekatski P, Brunner N, Branciard C, Gisin N and Simon C 2009 Phys. Rev. Lett. 103 113601
[10] Zurek W H 2003 Rev. Mod. Phys. 75 715
[11] Sekatski P, Sanguinetti B, Pomarico E, Gisin N and Simon C 2010 Phys. Rev. A 82 053814
[12] Clauser J F, Horne M A, Shimony A and Holt R A 1969 Phys. Rev. Lett. 23 880
[13] Scarani V, Iblisdir S, Gisin N and Acin A 2005 Rev. Mod. Phys. 77 1225
[14] Bae J and Acin A 2006 Phys. Rev. Lett. 97 030402
[15] Spagnolo N, Vitelli C, Sciarrino F and De Martini F 2010 Phys. Rev. A 82 052101
[16] Spagnolo N, Vitelli C, Paternostro M, De F and Martini Sciarrino F 2010 arXiv:1012.3660v1