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Towards a test of non-locality without "supplementary assumptions"

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Abstract

We have experimentally tested the non-local properties of the two-photon states generated by a high brilliance source of entanglement which virtually allows the direct measurement of the full set of photon pairs created by the basic QED process implied by the parametric quantum scattering. Standard Bell measurements and Bell's inequality violation test have been realized over the entire cone of emission of the degenerate pairs. By the same source we have verified Hardy's ladder theory up to the 20th step and the contradiction between the standard quantum theory and the local realism has been tested for 41% of entangled pairs.

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Entanglement, "*the characteristic trait of quantum mechanics*" according to Erwin Schroedinger, is playing an increasing role in nowadays physics [1]. Since the EPR discovery in 1935 followed by a many decades long endeavour ending with the emergence of the Bell's inequalities and with the experiment by Alain Aspect, entanglement is considered as the irrevocable signature of quantum non-locality, i.e., the scientific paradigm recognized as the fundamental cornerstone of our yet uncertain understanding of the Universe [2–4]. In recent years the violation of these inequalities has been successfully tested many times by optical experiments, mostly involving polarization entangled photons generated by spontaneous parametric down conversion (SPDC) in a non-linear (NL) crystal [5]. In addition, an other non-locality test not involving inequalities was proposed years ago by Lucien Hardy's [6] and soon realized experimentally by a SPDC process [7].

The present work reports yet another non-locality test both of the standard Bell configuration and of Hardy's no-inequality scheme. The novelty of this experiment consists of the peculiar spatial properties of the output **k**-vector distribution generated by the

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SPDC source implied by the present scheme [8,9]. As shown in the Letter, this source allows, at least in principle, the coupling to the output detectors of the full set of optical modes carrying the particle pairs involved in the EPR measurement. In other words, all entangled pairs created over the entire set of wavevectors allowed by phase matching can virtually be detected. Since then the detected emission process is entirely "quantum", i.e., not affected by any previous "classical" manipulation, such as wavelength (λ) of wavevector ($\mathbf{k}$) filtering, e.g., by filters and/or limiting pinholes, the new scheme allows in principle the realization of the necessary premises underlying the original formulation of the "EPR paradox" [10]. Indeed all non-locality tests performed so far were affected by a quantum efficiency (QE) "loophole" expressing the overall lack of detection of all couples of entangled photons generated by the EPR source [11]. This effect is ascribable either to the limited QE of the detectors ("*detection QE*": dQE) [12] and to the loss of the pairs that, created by the underlying QED quantum process, could not reach the detectors for geometrical reasons ("*collection QE*": cQE). Note that, while dQE can be of the order of 10^{-1} for normal detectors in the visible range, the cQE contribution has been always typically less than 10^{-5}. As shown later, this filtering truncation of the distribution of the emitted entangled pairs necessarily results in a mixed character of the detected state, at variance with the original EPR assumptions [10]. The efforts for realizing experiments relieving the need for "supplementary assumptions" [3,11,12] were mostly devoted in obtaining a high value of dQE [13]. In the present Letter we present a scheme that allows to achieve, at least in principle, values of $cQE \simeq 1$, a condition long advocated by John Bell himself and never realized in practice [14]. The same idealization is possible for the source described in Ref. [15].

A detailed description of the high brilliance source of entanglement was already given in previous papers [8,9]. Pairs of horizontally (H) polarized SPDC photons are emitted at wavelength λ over the surface of the phase matching cone of a thin (0.5 mm) type I BBO crystal which is excited by a cw vertically (V) polarized Ar^+ laser beam ($\lambda_p = \lambda/2$) (see Fig. 1). A spherical mirror M with radius R, placed at a distance $d = R$ from the crystal, reflects back both the pump and the photons. By a zero-order $\lambda/4$ waveplate (wp) placed between M and the BBO the $H \to V$ transformation for the λ photons polarization is performed while the pump beam is left in its original polarization state. This excites an identical SPDC process over a new radiation cone which is spatially and temporally indistinguishable from the previous one. The state of the overall radiation is then expressed by the entangled state:

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\big(|HH\rangle + e^{i\phi}|VV\rangle\big), \tag{1}$$

with phase ϕ ($0 \leqslant \phi \leqslant \pi$) reliably controlled by micrometric displacements of M. By a positive lens the overall conical emission distribution is transformed into a cylindrical one whose transverse circular section, spatially selected by an annular mask, identifies the entanglement-ring (E-ring) (Fig. 1). After division of the ring along a vertical axis, the two resulting equal portions are detected at sites $\mathcal{A}$ and $\mathcal{B}$ within a bandwidth $\Delta\lambda = 6$ nm. More than $4 \times 10^3\ s^{-1}$ coincidences are measured at a pump power $P \simeq 100$ mW over the entire E-ring.

We may analyze the structural characteristics of the quantum state of any photon pair generated by our source by accounting first for the excited elec-

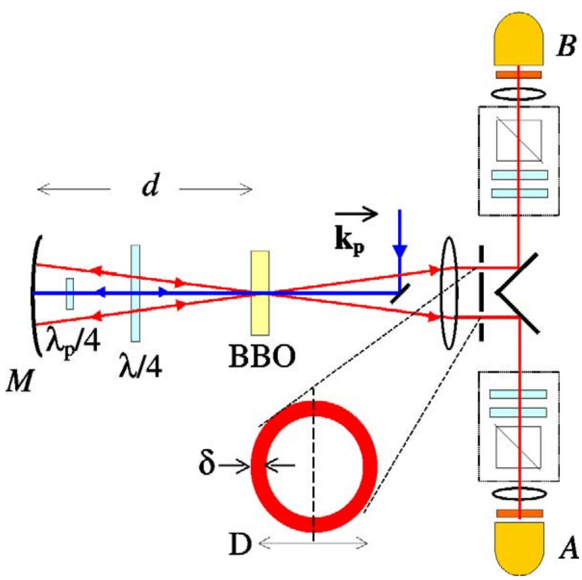

Fig. 1. Layout of the high brilliance source of polarization entanglement. The dimension of the annular mask are $D = 1.5$ cm, $\delta = 0.07$ cm.

tromagnetic modes which, in our case are grouped in correlated pairs by the three-wave SPDC interaction. Assume that each SPDC $\mathbf{k}$-cone is represented by a linear superposition of correlated pairs of e.m. modes $(\mathbf{k}_1, \mathbf{k}_2)$. Since only one pair of photons is detected at the output of the source, each mode corresponds to a Fock two-mode product state that can be either $|0, 0\rangle$ or $|1_H, 1_H\rangle$ or $|1_V, 1_V\rangle$. Accordingly, we can express the overall entangled-state by the quantum superposition:

$$|\Phi\rangle = \int d\mathbf{k}_1\, d\mathbf{k}_2 \big(|1_H, 1_H\rangle_{\mathbf{k}_1\mathbf{k}_2} |0_V, 0_V\rangle_{\mathbf{k}_1\mathbf{k}_2} + e^{i\phi}|0_H, 0_H\rangle_{\mathbf{k}_1\mathbf{k}_2} |1_V, 1_V\rangle_{\mathbf{k}_1\mathbf{k}_2}\big) \bigotimes_{(\mathbf{k}'_1\mathbf{k}'_2)\neq(\mathbf{k}_1\mathbf{k}_2)} |0_H, 0_H\rangle_{\mathbf{k}'_1\mathbf{k}'_2} |0_V, 0_V\rangle_{\mathbf{k}'_1\mathbf{k}'_2}. \tag{2}$$

This state should indeed express the exact form of the single photon-pair output state of the source if the full set of mode pairs could be coupled to the detectors $\mathcal{A}$ and $\mathcal{B}$. Indeed, it is not difficult to conceive an ideal experiment (an approximate one is in fact in progress in our laboratory) by which the full set of modes at any wavelength, either degenerate or non-degenerate can be coupled to the detectors without any geometrical or frequency constraint, i.e., without any spatial or λ-filtering. In practice, in this case limitations for an overall full particle detection should come from the limited λ-extension of the photocathode *dQE*s and of the performance of the optical components (mirrors, lenses, etc.). Nevertheless, this should not affect *in principle* the structural character of the output entangled-state.

A typical SPDC based experiment uses a type II phase matching crystal to generate polarization entangled photons [16], which are emitted over two well defined correlated $\mathbf{k}$-vectors. Henceforth, the set of mode pairs coupled to the detectors is drastically reduced by the use of very narrow pinholes [16] or single mode fibers [17]. However, this operation cannot be realized but within a mode uncertainty $\Delta\mathbf{k}$ because of the inescapable effect of diffraction. In these conditions there is a definite probability that only one photon in a pair passes through the spatial filter while the other one is intercepted. A similar effect can be ascribed to any frequency filtering operation as well. More recently, a high brightness parametric source has been realized exploiting the superposition of two orthogonally polarized type I emissions [15]. In this case, any pair of photons over correlated $\mathbf{k}$-vectors is polarization entangled. Nevertheless, in all the non-locality tests realized so far by this source, single mode selection was performed. As a consequence, this drastic truncation implies necessarily a *mixed character* of the output entangled state [18].

These considerations lead to the quasi-purity of the generated output state. The state purity condition may be simply analyzed as follows. The well-known unitary character of the SPDC quantum operator $\hat{S}$ assures that the purity of the input state implies also the purity of the output state: $|\Phi\rangle_{\text{out}} = \hat{S}|\Phi\rangle_{\text{in}}$ [19]. Adopting the common hypothesis of a undepleted “classical” pump beam, the input pure state is expressed by the overall vacuum-state character of the full set of input modes acted upon by the SPDC process: $|\Phi\rangle_{\text{in}} \equiv |\text{vac}\rangle$. Within the single-pair emission approximation, the output pure state is found: $|\Phi\rangle_{\text{out}} \simeq |\Phi\rangle + |\text{vac}\rangle$, viz. consists of the sum of the state given by Eq. (2) and of the vacuum-state expressing the non-realization of the QED scattering process. As a consequence, $|\Phi\rangle$ given by Eq. (2) is not, strictu sensu, a pure state but one out of a two components mixture. However, in the common case of a conditional experiment where the overall registration system is activated by a trigger pulse elicited by the source itself, the output state $|\Phi\rangle$ may be considered a “post-selected” pure state. This last condition is often referred to as expressing the “conditional purity” of the output state.

It is worth noting that single photon events due to the above described spatial and frequency filtering, cannot be discarded by coincidence post-selection. In fact, in this case, one cannot distinguish among these two events: (1) Only one photon of the pair is transmitted by the filters and is detected. (2) Both photons of the pair are transmitted but only one is detected because of the limited value of *dQE*. Post-selection in presence of $|0, 1\rangle$ and $|1, 0\rangle$ Fock state contributions is legitimate in the ideal condition $dQE = 1$. On the other hand, a loophole-free test can be carried out also with real detectors in the limit condition $cQE = 1$. In the general case, this purpose can be accomplished if $cQE \cdot dQE \geqslant 2/3$ [20].

The experimental interference pattern, with coincidence visibility $V \geqslant 94\%$, shown in Fig. 2(a) gives a strong indication of the entangled nature of the Bell state $|\Phi^-\rangle$, $(\phi = \pi)$ over the entire emission cone at

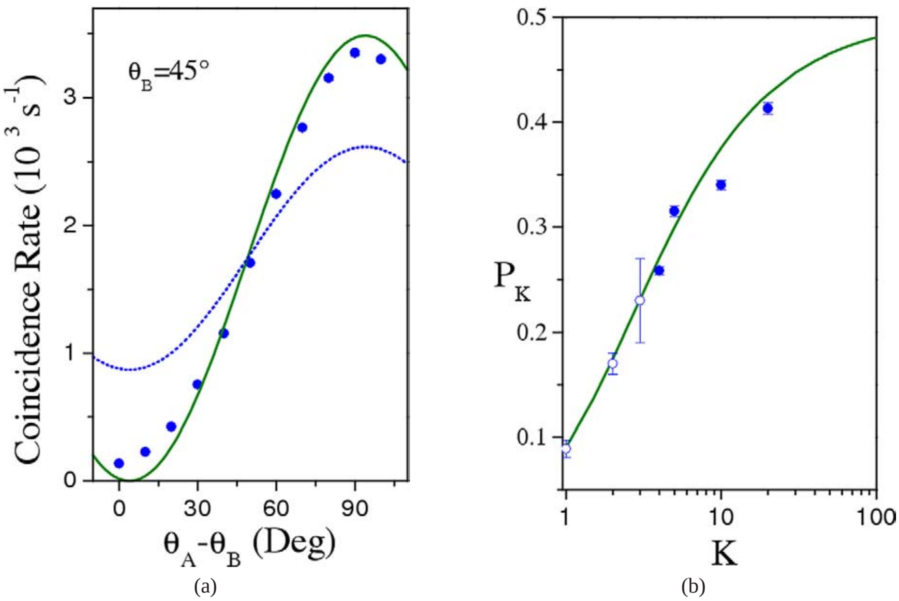

Fig. 2. (a) Measurement of the polarization entanglement for the state $|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|H,H\rangle - |V,V\rangle)$ obtained by varying the angle θ_A on site $\mathcal{A}$ in the range (45°–135°), having kept fixed the angle $\theta_B = 45°$ on site $\mathcal{B}$. (b) Plot of P_K against K. Black circles: experimental results for $K = 4, 5, 10, 20$ (error bars are lower than the dimension of the corresponding experimental points). White circles: experimental results obtained in Ref. [7].

$\lambda = 2\lambda_p$. In this condition it is possible to evaluate that *cQE* is enhanced of a factor $\geqq 70$ with respect the standard pinhole configuration. The dotted line corresponds to the limit boundary between the quantum and the classical regimes [21] while the theoretical continuous curve expresses the ideal interferometric pattern with maximum visibility: $V = 1$. By performing the standard Bell-inequality test we have evaluated the non-locality parameter S [3]. The measured value $S = 2.5564 \pm 0.0026$ [8], obtained by integrating the data over 180 s, corresponds to a violation as large as 213 standard deviations respect to the limit value $S = 2$ implied by local realistic theories.

Hardy's theorem represents an alternative proof of non-locality [6,7]. It is obtained in the case of non-maximally entangled states of two spin 1/2 particles:

$$|\Phi\rangle = \alpha|H,H\rangle - \beta|V,V\rangle, \quad (0 \leqslant \alpha \leqslant \beta;\ \alpha^2 + \beta^2 = 1). \tag{3}$$

We have realized these states by inserting a zero-order $\lambda_p/4$ wp between M and the BBO, intercepting only the UV beam (Fig. 1). In our system, by rotating the UV wp by an angle θ_p, the back-reflected UV pump beam experiences a polarization rotation of $2\theta_p$ respect to the optical axes of the NL crystal slab. As a consequence, the emission efficiency of the $|H,H\rangle$ cone is decreased by a coefficient $\propto \cos^2 2\theta_p$. By adjusting θ_p in the range $0 - \pi/4$, the degree of entanglement $\gamma = \alpha/\beta$ can be continuously tuned between 0 and 1.

A full presentation of Hardy's theorem can be found in Ref. [7]. For two photons in the state (3), the polarization measurements performed along $K+1$ possible directions at sites $\mathcal{A}$ and $\mathcal{B}$ of Fig. 1 give a corresponding set of propositions $\mathbf{A}_k$, $k = 0, \ldots, K$ which imply $\mathbf{A}_0 \Rightarrow \mathbf{A}_1 \Rightarrow \cdots \Rightarrow \mathbf{A}_K$, with the further condition $\mathbf{A}_0 \nRightarrow \mathbf{A}_K$. It can be demonstrated that the fraction of pairs P_K with non-local properties increases with K and is a function of the entanglement degree γ. For each value of K, a proper γ exists which maximizes P_K. Hardy's ladder proof is purely logical and does not involve inequalities. However, inequalities are necessary as a quantitative test in a real experiment in order to avoid the conceptual problems associated to the realization of a *nullum experiment* [7]. A proper inequality, violated by quantum theory, can be derived by combining Hardy's theorem

Table 1
Experimental joint probabilities for $K = 20$

θ_A	θ_B	$P(\theta_A,\theta_B)$	θ_A	θ_B	$P(\theta_A,\theta_B)$	θ_A	θ_B	$P(\theta_A,\theta_B)$	θ_A	θ_B	$P(\theta_A,\theta_B)$
θ_{20}	θ_{20}	0.4132 ± 0.0053	θ_{15}	$\theta_{14}^{\perp}$	0.00699 ± 0.00033	$\theta_9^{\perp}$	θ_{10}	0.01036 ± 0.00040	$\theta_4^{\perp}$	θ_5	0.00933 ± 0.00038
θ_{20}	$\theta_{19}^{\perp}$	0.00104 ± 0.00012	$\theta_{14}^{\perp}$	θ_{15}	0.01114 ± 0.00042	θ_9	$\theta_8^{\perp}$	0.00440 ± 0.00026	θ_4	$\theta_3^{\perp}$	0.00622 ± 0.00031
$\theta_{19}^{\perp}$	θ_{20}	0.00298 ± 0.00021	θ_{14}	$\theta_{13}^{\perp}$	0.00311 ± 0.00021	$\theta_8^{\perp}$	θ_9	0.00984 ± 0.00039	$\theta_3^{\perp}$	θ_4	0.01010 ± 0.00040
θ_{19}	$\theta_{18}^{\perp}$	0.00311 ± 0.00021	$\theta_{13}^{\perp}$	θ_{14}	0.00907 ± 0.00038	θ_8	$\theta_7^{\perp}$	0.00415 ± 0.00025	θ_3	$\theta_2^{\perp}$	0.00531 ± 0.00028
$\theta_{18}^{\perp}$	θ_{19}	0.01166 ± 0.00043	θ_{13}	$\theta_{12}^{\perp}$	0.00363 ± 0.00023	$\theta_7^{\perp}$	θ_8	0.01075 ± 0.00041	$\theta_2^{\perp}$	θ_3	0.00855 ± 0.00036
θ_{18}	$\theta_{17}^{\perp}$	0.00207 ± 0.00017	$\theta_{12}^{\perp}$	θ_{13}	0.01218 ± 0.00044	θ_7	$\theta_6^{\perp}$	0.00389 ± 0.00024	θ_2	$\theta_1^{\perp}$	0.00699 ± 0.00033
$\theta_{17}^{\perp}$	θ_{18}	0.01917 ± 0.00057	θ_{12}	$\theta_{11}^{\perp}$	0.00285 ± 0.00021	$\theta_6^{\perp}$	θ_7	0.00751 ± 0.00034	$\theta_1^{\perp}$	θ_2	0.00933 ± 0.00038
θ_{17}	$\theta_{16}^{\perp}$	0.00363 ± 0.00023	$\theta_{11}^{\perp}$	θ_{12}	0.01088 ± 0.00041	θ_6	$\theta_5^{\perp}$	0.00363 ± 0.00023	θ_1	$\theta_0^{\perp}$	0.00674 ± 0.00032
$\theta_{16}^{\perp}$	θ_{17}	0.01010 ± 0.00040	θ_{11}	$\theta_{10}^{\perp}$	0.00440 ± 0.00026	$\theta_5^{\perp}$	θ_6	0.01218 ± 0.00044	$\theta_0^{\perp}$	θ_1	0.00855 ± 0.00036
θ_{16}	$\theta_{15}^{\perp}$	0.00311 ± 0.00021	$\theta_{10}^{\perp}$	θ_{11}	0.00984 ± 0.00039	θ_5	$\theta_4^{\perp}$	0.00492 ± 0.00027	θ_0	θ_0	0.00699 ± 0.00033
$\theta_{15}^{\perp}$	θ_{16}	0.01036 ± 0.00040	θ_{10}	$\theta_9^{\perp}$	0.00285 ± 0.00021						

with Clauser–Horne inequality [2,3]. It consists of the measurement of $2K + 2$ joint detection probabilities $P(\theta_A, \theta_B)$, where θ_A, θ_B are the angular settings of polarizers on sites $\mathcal{A}$ and $\mathcal{B}$ in Fig. 1:

$$P(\theta_K,\theta_K) \leqslant P(\theta_0,\theta_0) + \sum_{k=1}^{K} \left[P\left(\theta_k, \theta_{k-1}^{\perp}\right) + P\left(\theta_{k-1}^{\perp}, \theta_k\right) \right] = \mathcal{P}, \tag{4}$$

where $\theta_k = (-1)^k \arctan(\gamma^{k+1/2})$, $\theta_k^{\perp} = \theta_k + \pi/2$, with $k = 0, \ldots, K$, and $P(\theta_K, \theta_K) = P_K$.

The experimental observation of the inequality violation becomes more and more difficult as K increases because of an eventually imperfect definition of the state and of the experimental uncertainties associated to all the $2K + 2$ measurements. The experiments realized so far were performed only for low values of K, in particular for $K \leqslant 3$ [7,22,23]. The above described source possesses unique characteristics for this experiment. In fact, it allows the direct generation of non-maximally entangled states without post-selection. Moreover, the particular configuration of "single arm" interferometer guarantees a very high phase stability for long periods (> 1 hr). Finally, the high brilliance character of the source allows to accumulate large sets of statistical data in a short measurement time ΔT also with a relatively low UV pump power. By taking advantage from all these properties of our source, we could successfully test Hardy's ladder proof for large values of K.

The experiment, realized for $K = 4, 5, 10, 20$, has given the following violations of the inequality (4):

$K = 4$ ($\Delta T = 60$ s): $P_4 = 0.2586 \pm 0.0041$; $\mathcal{P} = 0.1213 \pm 0.0022$. Inequality violated for 30σ.

$K = 5$ ($\Delta T = 60$ s): $P_5 = 0.3152 \pm 0.0050$; $\mathcal{P} = 0.1184 \pm 0.0022$. Inequality violated for 37σ.

$K = 10$ ($\Delta T = 120$ s): $P_{10} = 0.3402 \pm 0.0045$; $\mathcal{P} = 0.2288 \pm 0.0015$. Inequality violated for 26σ.

$K = 20$ ($\Delta T = 180$ s): $P_{20} = 0.4132 \pm 0.0053$; $\mathcal{P} = 0.2439 \pm 0.0016$. Inequality violated for 21σ.

The probabilities of each outcome for all the 42 polarization settings of $K = 20$ are reported in Table 1. These have been obtained by normalizing the coincidence measurements to the sum of coincidence rates measured in the basis $|HH\rangle$ and $|VV\rangle$.

The count rates for each value of P_K are plotted in Fig. 2(b) as a function of K. We report for comparison the results obtained in the experiment of Ref. [7]. The theoretical curve shown in the same figure indicates a very slow convergence to the asymptotic value $P_K = 0.5$.

Finally, additional measurements of P_K are plotted as a function of γ for $K = 4, 5, 10, 20$ in Fig. 3. The angle θ_K has been calculated for each value of γ by using the above given expression. The agreement with the theory appears very good.

In summary, we have presented two different experimental tests of quantum non-locality realized by a high brilliance source of polarization entanglement.

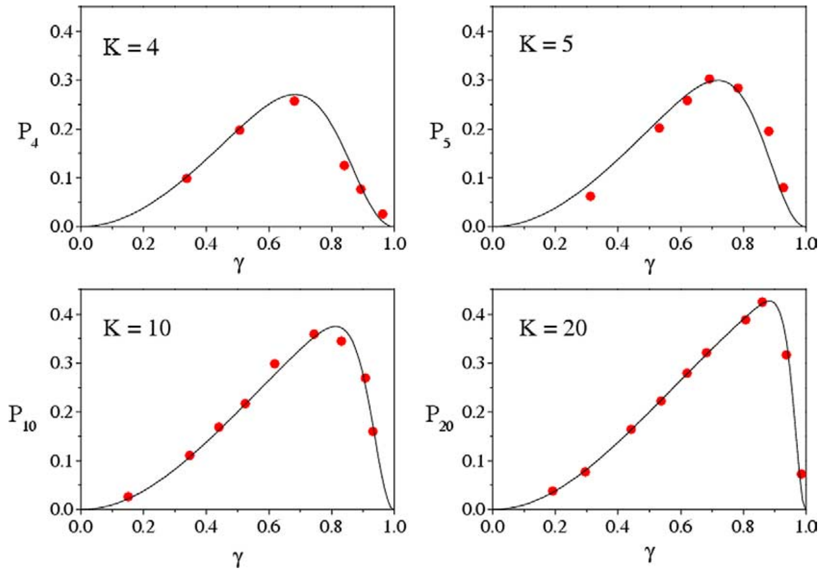

Fig. 3. Plots of P_4, P_5, P_{10}, P_{20} as a function of γ. The solid curves represent the theoretical predictions. The error bars are lower than the dimension of the corresponding experimental points.

The value of the *collection quantum efficiency* (cQE) realized by the present system is about 2 order of magnitude larger than for all previous experiments. We have obtained in these conditions a 213σ Bell inequality violation. Furthermore, in virtue of the very large overall efficiency of the source, within the framework of Hardy's ladder theory, a contradiction between standard quantum theory and local realism has been attained by for a fraction as large as 41% of the entangled photon pairs and as many as 20 steps of the ladder have been realized.

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