Experimental multilocation remote state preparation

Magnus Rådmark,[1] Marcin Wieśniak,[2] Marek Żukowski,[2] and Mohamed Bourennane[1]
[1]*Department of Physics, Stockholm University, S-10691 Stockholm, Sweden*
[2]*Instytut Fizyki Teoretycznej i Astrofizyki, Uniwersytet Gdański, PL-80-952 Gdańsk, Poland*
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Transmission of quantum states is a central task in quantum information science. Remote state preparation (RSP) has the same goal as teleportation, i.e., transferring quantum information without sending physically the information carrier, but in RSP the sender knows the state which is to be transmitted. We present experimental demonstrations of RSP for two and three locations. In our experimental scheme Alice (the preparer) and her three partners share four and six photon polarization entangled singlets. This allows us to perform RSP of two or three copies of a single-qubit state, a two-qubit Bell state, and a three-qubit W, or $\overline{W}$ state. A possibility to prepare two-qubit nonmaximally entangled and GHZ states is also discussed. The ability to remotely prepare an entangled states by local projections at Alice is a distinguishing feature of our scheme.

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I. INTRODUCTION

Theoretical studies in quantum information predict existence of various types of entangled states, which could be useful in many communication situations and information processing, for example, quantum key distribution [1], teleportation [2], etc. Correlations between entangled systems are so strong that they cannot be modeled by any classical means [3]. In theory we can study entangled states of very many qubits and complicated quantum protocols. But experimental practice shows that protocols involving many qubits are very difficult to demonstrate in the laboratory. In order to see to what extent theoretical quantum information science talks about experimentally controllable phenomena, one has to keep testing the limits of the range of feasibility of such schemes, and keep extending such limits. With this in mind, we present realizations of several remote state preparation (RSP) protocols [4–7], using tools of advanced multiphoton quantum interferometry [8].

The aim of teleportation and RSP is to take the advantage of entanglement to prepare a desired state at a distant location. In teleportation protocol, Alice's task is to prepare an unknown, given to her, quantum state at Bob's location. In the case of RSP Alice knows which state she wants to prepare at Bob's location. The most elementary scheme runs as follows. Alice and Bob share a maximally entangled state of two qubits, say, a singlet. Alice performs a projective measurement in a basis which contains the state which is to be remotely prepared. If her measurement locally projects onto the state orthogonal to the one she wants to prepare, Bob's subsystem collapses into the required state. She sends a single bit [4] announcing whether or not her projection measurement was successful. Such an experiment was realized with polarization qubits [9] and with an photon-atom system [10]. Note that such a protocol must be probabilistic. Alice has a probability of $\frac{1}{2}$ of projecting onto the required state. In the case of failure Bob obtains a state orthogonal to the intended one. Because of the impossibility of a universal NOT gate, such a state cannot be corrected without the knowledge of the basis to which belongs. Nevertheless, if Alice is choice restricted to, e.g., states from the equator of the Bloch sphere, the protocol becomes deterministic. Simply, given the bit from Alice, Bob may perform the σ_z operation, which acts as the NOT gate on the equatorial plane.

In this contribution, we present an experimental demonstration of a more general scheme, allowing Alice to remotely prepare a large class of symmetric states, including entangled ones. For this purpose we will utilize rotationally invariant multiqubit singlet states. The scheme presented here has thus two important features. One is a possibility to prepare entangled states at one side by local projections on the other. This simplifies preparation of otherwise complicated states. The other highlight is the universality due to rotational invariance of the singlet states used. One can remotely prepare the same set of states in any coordinate system.

We begin with a brief description of the experimental setup, which allows us to prepare such generalized singlet states, using methods of multiphoton interferometry. The setup consists of a nonlinear crystal allows an efficient down-conversion process (noncollinear type II PDC). Photons from a pulsed laser pumping field can spontaneously, with a low probability, fission into a pair of photons with orthogonal polarizations, in two conjugate propagation modes. If the pumping is strong enough, one can observe multifold emissions of such kind form a single pulse. The state can be expressed as

$$|\mathrm{PDC}\rangle = \frac{1}{\cosh^2 K}\sum_{p=0}^{\infty}\tanh^p K\sum_{m=0}^{p}(-1)^p \times |mH_a,(p-m)V_a,(p-m)H_b,mV_b\rangle, \qquad (1)$$

where $|nX_c\rangle$ denotes a Fock state with n photons, of polarization $X = H,V$ in mode $c = a,b$. k-photon components of the state then lead to singlet states $|\psi_k^-\rangle$ (see below). The parameter K is a function of the nonlinearity and length of the crystal, pump power, and filtering bandwidth, and ϕ is the possible phase difference between horizontal and vertical polarization due to birefringence in the crystal [11]. The nth-order PDC emission corresponds to terms with $p = n$. The trick is to place $n-1$ consecutive beam splitters in each of the two emission spacial modes and observe $2n$-fold coincidences [12]. Correlations characteristic for four- and six- (polarization) qubit states ($|\Psi_k^-\rangle, k = 2,3$) can be observed in this way, see formulas (2) below.

II. THEORY OF EXPERIMENT

The four-qubit state was reported in Ref. [13], while Rådmark *et al.* [14] observed the six-qubit one. The states are generalizations of singlets, that is, they have the same form irrespective of which pair of orthogonal polarizations is used to express the polarization of *each and every* qubit. This implies rotational symmetry: if each qubit is rotated by the same unitary transformation U, such that $\det U = 1$, the states do not change, $U^{\otimes k}|\Psi_k^-\rangle = |\Psi_k^-\rangle$ just like the two-qubit singlet $|\Psi_2^-\rangle$. This property can be used to circumvent some forms decoherence [15]. If the interaction with the environment is symmetric under an exchange of systems, one can process information within a so-called decoherence-free subspace [16,17]. For random rotations acting of all qubits in the same way, such a space is spanned by singlet states. For four qubits such a decoherence-free subspace is spanned by two orthogonal four-qubit states invariant under such transformations. One of them describes the product of two two-qubit singlets $|\psi_2^-\rangle \otimes |\psi_2^-\rangle$, and the other one is $|\psi_4^-\rangle$. A decoherence-free operation in this subspace has been demonstrated experimentally in Ref. [18].

Using such states Alice can, by projecting her half of the qubits, efficiently change the state of remote qubits (see Fig. 1). Here we consider remote state preparation with $|\Psi_2^-\rangle$, $|\Psi_4^-\rangle$, and $|\Psi_6^-\rangle$.

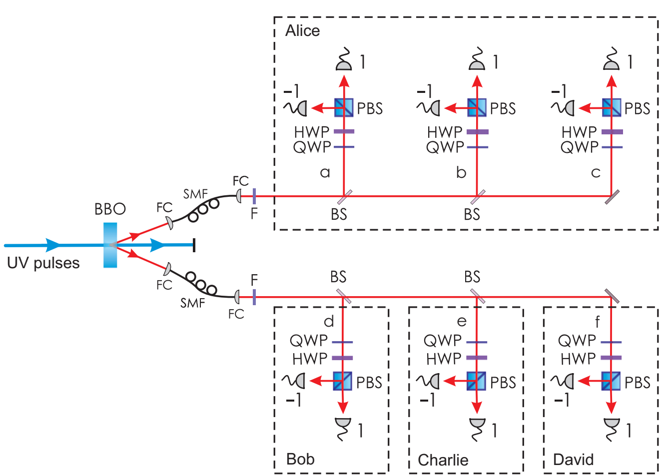

FIG. 1. (Color online) Experimental setup for generating and analyzing the six-photon polarization-entangled state. The six photons are created in third-order PDC processes in a 2 mm thick BBO pumped by UV pulses. The emitted photons are coupled to single-mode fibers (SMFs). Narrow band ($\Delta\lambda = 3$ nm) interference filters (Fs) serve to remove spectral distinguishability. The coupled spatial modes are divided into six exit modes by two pairs of 50%–50% beam splitters (BSs). Each exit mode can be analyzed in arbitrary basis using half- and quarter-wave plates (HWP and QWP) and a polarizing beam splitter (PBS), and two single-photon detectors for each mode (the measurement station). The exit modes a, b, and c are controlled by Alice, and d, e, and f by Bob, Charlie, and David, respectively.

To make our discussion more transparent, we can put $|\Psi_2^-\rangle$, $|\Psi_4^-\rangle$ and $|\Psi_6^-\rangle$ as

$$
\begin{aligned}
|\Psi_2^-\rangle &= \frac{1}{\sqrt{2}}(|\psi\rangle|\overline{\psi}\rangle - |\overline{\psi}\rangle|\psi\rangle),\\
|\Psi_4^-\rangle &= \frac{1}{\sqrt{3}}(|\psi\psi\rangle|\overline{\psi\psi}\rangle + |\overline{\psi\psi}\rangle|\psi\psi\rangle)\\
&\quad + \frac{1}{\sqrt{6}}(|\psi\overline{\psi}\rangle + |\overline{\psi}\psi\rangle)|\Psi_2^+\rangle,\\
|\Psi_6^-\rangle &= \frac{1}{2}(|\psi\psi\psi\rangle|\overline{\psi\psi\psi}\rangle - |\overline{\psi\psi\psi}\rangle|\psi\psi\psi\rangle),\\
&\quad + \frac{1}{2\sqrt{3}}(|\psi\overline{\psi\psi}\rangle + |\overline{\psi}\psi\overline{\psi}\rangle + |\overline{\psi\psi}\psi\rangle)|W_3\rangle\\
&\quad - \frac{1}{2\sqrt{3}}(|\overline{\psi}\psi\psi\rangle + |\psi\overline{\psi}\psi\rangle + |\psi\overline{\psi\psi}\rangle)|\overline{W}_3\rangle, \qquad (2)
\end{aligned}
$$

where $|W_3\rangle = \frac{1}{\sqrt{3}}(|\psi\psi\overline{\psi}\rangle + |\psi\overline{\psi}\psi\rangle + |\overline{\psi}\psi\psi\rangle)$, while $|\overline{W}_3\rangle = \frac{1}{\sqrt{3}}(|\overline{\psi\psi}\psi\rangle + |\overline{\psi}\psi\overline{\psi}\rangle + |\psi\overline{\psi\psi}\rangle)$, and $|\Psi_2^+\rangle = (|\psi\psi\rangle + |\overline{\psi\psi}\rangle)$. Due to the rotational invariance ψ and $\overline{\psi}$ may denote any pair of orthogonal polarizations.

In order to have one universal setup for remote state preparation employing the above states, the pumping parameter must be such that the emission of a single pair is approximately by an order of magnitude more probable then for emission of two pairs. This automatically guarantees that probability of three-pair emission is lower by yet another order of magnitude. Such conditions allow high interferometric contrast (visibility) in two-, four-, and sixfold coincidence detections (the interference occurs while one changes the polarization settings at final analyzers at each of the exit arms of the beam-splitter system); see Ref. [11]. Note that lower pump rates could make the contrast higher, but the count rates of sixfold coincidence detections would become prohibitively low. Thus a proper tuning of the pump strength must be made.

Alice can conditionally prepare a three-qubit entangled state $|W_3\rangle$ or $|\overline{W}_3\rangle$ for her partners to share. Alice measures at all her stations in the basis $\{|\psi\rangle, |\overline{\psi}\rangle\}$. If she gets a count at each of her stations, consistent with three-qubit states $|\psi\overline{\psi\psi}\rangle$, $|\overline{\psi}\psi\overline{\psi}\rangle$ or $|\overline{\psi\psi}\psi\rangle$, the remote parties will be sharing W state, provided each of them received just one photon. If she registers $|\psi\psi\overline{\psi}\rangle$, $|\psi\overline{\psi}\psi\rangle$ or $|\overline{\psi}\psi\psi\rangle$, the $\overline{W}$ state is remotely prepared (under the same proviso).

Similarly, if we have a two-pair emission leading to the $|\Psi_4^-\rangle$ state, Alice can prepare the Bell state $|\Psi^+\rangle$, shared by a pair of her partners. It is so provided Alice measures $|\psi\overline{\psi}\rangle$ or $|\overline{\psi}\psi\rangle$ at a pair of her stations (and no counts at the third station), and two partners receive (register) photons.

It is important to notice that operating on $|\Psi_6^-\rangle$ Alice can prepare genuinely three-partite entangled pure states W and $\overline{W}$, by just using projections onto factorizable states. Interestingly, to prepare a Greenberger-Horne-Zeilinger state (GHZ), she needs to register one of her qubits in state $|\psi\rangle$, the second in state $\cos\theta|\psi\rangle + \sin\theta|\overline{\psi}\rangle$, and the third one in $\cos\theta|\psi\rangle - \sin\theta|\overline{\psi}\rangle$, where $\theta = \pm\frac{\pi}{3}$. A back of an envelope calculation shows that in such a case, state $|\Psi_6^-\rangle$ collapses in such a way that Bob, Charlie, and David share

TABLE I. Probabilities of RSP for emissions of $|\Psi_k^-\rangle$, for $k = 2,4,6$.

Shared state	No. qubits	Prepared state	Probability
$\lvert\Psi_2^-\rangle$	1	$\lvert\psi\rangle$	1/2
$\lvert\Psi_4^-\rangle$	2	$\lvert\psi\psi\rangle$	1/3
$\lvert\Psi_4^-\rangle$	2	$\lvert\Psi_2^+\rangle$	1/3
$\lvert\Psi_6^-\rangle$	3	$\lvert\psi\psi\psi\rangle$	1/4
$\lvert\Psi_6^-\rangle$	3	$\lvert W\rangle/\lvert\overline{W}\rangle$	1/4
$\lvert\Psi_6^-\rangle$	3	$\lvert\mathrm{GHZ}\rangle$	5/32

$\frac{1}{2}(|\overline{\psi\psi\psi}\rangle - |\overline{\psi}\psi\psi\rangle - |\psi\overline{\psi}\psi\rangle - |\psi\psi\overline{\psi}\rangle)$. This is a GHZ state in the diagonal-antidiagonal basis ($\frac{1}{\sqrt{2}}(|\psi\rangle \pm |\overline{\psi}\rangle)$).

In a similar fashion, Alice can prepare nonmaximally entangled state to two of her partners. She projects her two qubits on states $\cos\alpha|\psi\rangle \pm \sin\alpha|\overline{\psi}\rangle$ and $|\Psi_4^-\rangle$ collapses onto $(\cos^2\alpha|\overline{\psi\psi}\rangle - \sin^2\alpha|\psi\psi\rangle)/\sqrt{\cos^4\alpha + \sin^4\alpha}$.

In Table I we give the probabilities (in the ideal cases) of the remote preparations of specific states. The preparation probabilities in Table I can be doubled if the parties specify in advance that they want to remotely prepare qubit states on a specific great circle of the Bloch sphere. Then, if the remote qubits are $\bar{\psi}$, the receivers can rotate their qubits to ψ by applying σ_z operations.

Note that due to a permutation symmetry between Bob, Charlie, and David, the state of their qubits is in a symmetric subspace of the common Hilbert space. For this reason Alice cannot remotely prepare a maximally mixed state for each partner, as she is unable to remove the correlations arising from the symmetry. Yet she is able to prepare some mixtures, either by entangling her qubits with an ancilla, or by "tracing out" her qubits (that is, ignoring one of the actual results at one of her stations). For instance, if she traces out one of her particles and registers that the other ones are in $|\psi\rangle$, the other parties get an even mixture of $|\overline{\psi\psi\psi}\rangle\langle\overline{\psi\psi\psi}|$ and $|\overline{W}_3\rangle\langle\overline{W}_3|$. If she traces out one more qubit, the mixture shared by the other three observers is of $|\overline{\psi\psi\psi}\rangle\langle\overline{\psi\psi\psi}|$, $|\overline{W}_3\rangle\langle\overline{W}_3|$, and $|W_3\rangle\langle W_3|$, with respective weights $\frac{1}{4},\frac{1}{2},\frac{1}{4}$. Finally, if Alice simply sends the success signal without any measurement, her partners are left with the balanced mixture of $|\overline{\psi\psi\psi}\rangle\langle\overline{\psi\psi\psi}|$, $|\overline{W}_3\rangle\langle\overline{W}_3|$, $|W_3\rangle\langle W_3|$, $|\psi\psi\psi\rangle\langle\psi\psi\psi|$ (which is a separable state). All such processes are occur under the proviso that each partner receives a photon.

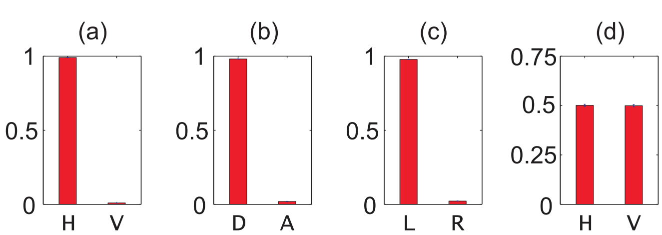

FIG. 2. (Color online) The single pair emission case $|\psi_2^-\rangle$: Renormalized observed detection probabilities for a photon in states (a) $|H\rangle$, (b) $|D\rangle$, (c) $|L\rangle$, and (d) a mixed state at one location for Bob, Charlie, or David (conditional on detection of only one photon by Alice in specific orthogonal states; see text).

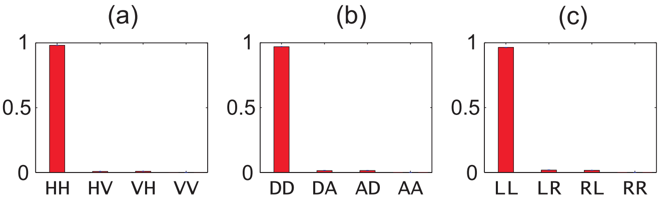

FIG. 3. (Color online) RSP of (a) $|\Psi_2^+\rangle$ and (b) a two-qubit mixed state. Renormalized detection probabilities for two-qubit detection events for Bob and Charlie, for the respective case of RSP.

III. EXPERIMENTAL SETUP AND RESULTS

We use a frequency-doubled Ti:sapphire laser (80 MHz repetition rate, 140 fs pulse length) yielding UV pulses of a central wavelength at 390 nm and an average power of 1300 mW. The pump beam is focused at a 160 μm waist in a 2 mm thick BBO (β-barium borate) crystal. Half-wave plates, and two 1 mm thick BBO crystals, compensate longitudinal and transversal walk-offs. The photons of noncollinear type II PDC are coupled to single mode fibers (SMFs), defining the two spatial modes at the crossings of two frequency down-conversion cones with light of half of the pump frequency. Upon exiting the fibers the PDC light passes narrow band ($\Delta\lambda = 3$ nm) interference filters (Fs) and is split into six spatial modes (a,b,c,d,e,f) by ordinary 50%–50% beam splitters (BSs), followed by birefringent optics compensating the phase shifts in the BSs. As the pump pulses are very short, narrow band filters, and single-mode fibers make the PDC photons temporally, spectrally, and spatially indistinguishable [8,12,19]; see Fig. 1. The polarization is kept by passive fiber polarization controllers. Polarization analysis stations, in each exit mode, are implemented by a half-wave plate (HWP), a quarter-wave plate (QWP), and a polarizing beam splitter (PBS). The outputs of the PBSs are lead to single-photon silicon avalanche photodiodes (APDs), via multimode fibers. The APDs' electronic responses, following photo detections, are counted by a multichannel coincidence counter, with a 3.3 ns time window. The coincidence counter registers any coincidence event between the 12 APDs, as well as single detection events.

The RSP protocol is implemented by projective measurements done by Alice on her qubits. The qubits in exit modes a, b, and c are given to Alice, and in each mode one has a polarization measuring station; see Fig. 1. The qubit in modes d, e, and f are given to Bob, Charlie, and David, respectively. For example, if Alice likes to prepare $|H\rangle$ for her three partners, she projects the state of her photons onto $|VVV\rangle$, which

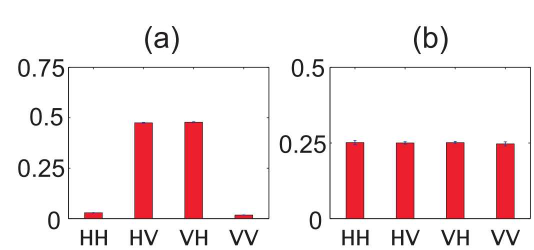

FIG. 4. (Color online) RSP of $|\Psi_2^+\rangle$ and a two-qubit mixed state. Renormalized detection probabilities for two-qubit detection events for Bob and Charlie, for the respective case of RSP.

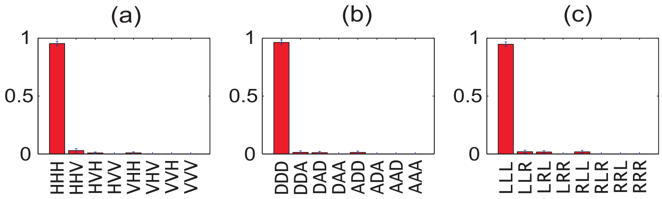

FIG. 5. (Color online) RSP of three identical qubit states ($|\psi_6^-\rangle$ emissions). Three photon detection probabilities for the case of $|H\rangle$, $|D\rangle$, and $|L\rangle$ at the three locations for Bob, Charlie, and David.

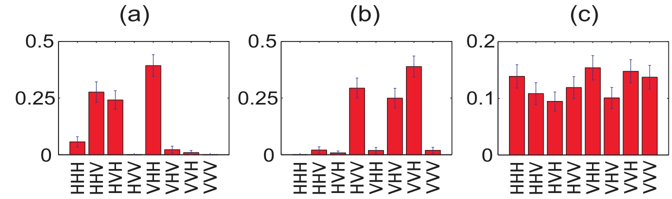

FIG. 6. (Color online) RSP of W states. Renormalized detection probabilities for three-qubit entangled states (a) $|W\rangle$, (b) $|\overline{W}\rangle$ shared between Bob, Charlie, and David after a successful RSP. (c) The mixed state defined in the text.

implies that the remaining three photons are all $|HHH\rangle$. Hence Alice can in this manner probabilistically prepare qubits in the $|HHH\rangle$ state for her three partners. Due to the probabilistic nature of projective measurements on $|\Psi_6^-\rangle$, Alice also needs to send classical information indicating the success to each of her partners, informing them that the intended state has been remotely prepared for them. In the experiment, we have tested a possibility to prepare horizontally, diagonally, and left circularly polarized photons, as well as the two-qubit maximally entangled states. For two-pair emissions the states which we prepared were $|HH\rangle$, $|DD\rangle$, $|LL\rangle$, $|\psi_2^+\rangle$, as well as $\frac{1}{4}(|HH\rangle\langle HH| + |VV\rangle\langle VV|) + \frac{1}{2}|\psi_2^+\rangle\langle\psi_2^+|$. Finally, for three-pair emissions we realized preparations of $|HHH\rangle$, $|DDD\rangle$, $|LLL\rangle$ and the mixture $\frac{1}{8}(|HHH\rangle\langle HHH| + |VVV\rangle\langle VVV|) + \frac{3}{8}(|W\rangle\langle W| + |\bar{W}\rangle\langle\bar{W}|)$.

In Fig. 2 we show experimental results of three-location RSP of horizontally H, diagonally D, left circularly L, and mixed polarized photons. The one-qubit fidelities are $F_H = 0.98 \pm 0.02$, $F_D = 0.97 \pm 0.04$, and $F_L = 0.97 \pm 0.05$, respectively. In Figs. 3 and 4 we show experimental results of two-location RSP of horizontally HH, diagonally DD, left circularly LL polarized photons, the two-qubit entangled state ψ_2^+, and the mixed state. The fidelities are $F_{HH} = 0.97 \pm 0.04$, $F_{DD} = 0.97 \pm 0.04$, $F_{LL} = 0.97 \pm 0.04$, and $F_{\psi_2^+} = 0.96 \pm 0.03$.

RSP of the three-qubit entangled W or $\overline{W}$ states has been demonstrated by projections at Alice's stations to $|HVV\rangle$, $|VHV\rangle$, or $|VVH\rangle$. Similarly, registrations of $|HHV\rangle$, $|HVH\rangle$, or $|VHH\rangle$ were used to prepare $\overline{W}$. RSP of three copies of one qubit is obtained by projection of Alice's qubits to $|VVV\rangle$. The results are given in Figs. 5 and 6. The three-qubit states fidelities are $F_{HHH} = 0.97 \pm 0.07$, $F_{DDD} = 0.97 \pm 0.07$, $F_{LLL} = 0.96 \pm 0.07$, $F_W = 0.90 \pm 0.09$, and $F_{\overline{W}} = 0.91 \pm 0.09$.

IV. SUMMARY OF RESULTS

The figures clearly show that we have demonstrated a method to remotely prepare several types of states of one, two, or three qubits (product, $|\psi^+\rangle$, W, and GHZ). The states are produced by projective measurements on one half of rotationally invariant multipartite states, which are readily available in laboratories, via a simple beam-splitting method (which by avoiding interferometric overlaps leads to a stable configuration). Our scheme involves multiphoton interferometry using a pulsed PDC based source of entangled photons. The experimental data confirm the high precision, with which RSP can work using such experimental methods. Interestingly, this scheme works as a kind of a symmetrizer of states. If Alice registers a projection on a product state, her partners obtain a symmetric superposition of the product of states orthogonal to ones, which she observed.

Finally, we wish to point out the relation of our scheme to the one recently presented in Ref. [20], where the authors demonstrate remote entanglement preparation. While their scheme is more universal, the one presented here is more efficient for special cases, since it takes six, rather than eight qubits, to prepare three-qubit W or GHZ states.

ACKNOWLEDGMENTS

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