Quantum Coherence and Decoherence - ISQM - Tokyo '98
Y.A. Ono and K. Fujikawa (Editors)

Three- and Four-Photon Correlations and Entanglement: Quantum Teleportation and Beyond

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Entanglement is at the root of many of the most fundamental quantum phenomena. Two-photon entangled states, which can readily be made with high quality in the laboratory, are a rich resource for producing quantum phenomena involving more particles. The general concept is to apply quantum erasure techniques jointly to some of the photons thus erasing their source information. This has been used successfully to achieve quantum teleportation, entanglement swapping and, most recently, to observe GHZ-states. While in all such schemes the desired *quantum state is obtained only conditioned* on its detection, this feature is of no significance in many quantum communication protocols.

1. INTRODUCTION

It has been known for a long time [1] that quantum entanglement is at the heart of fundamental phenomena such as the Einstein-Podolsky-Rosen paradox [2], Bell's theorem [3] or the measurement problem [4]. Most recently it turned out that entanglement also plays a key role in the discussion of quantum information and quantum computation procedures [5]. While sources of entangled pairs of particles are readily available, more advanced schemes involve more than two quanta. This is the case, for example, for quantum teleportation [6], entanglement swapping [7] and multiparticle phenomena involving so-called GHZ states [8]. It has turned out that one possible avenue to realize such phenomena in experiment is to use entangled photon pairs as a resource. The general concept involves sophisticated quantum erasure techniques. These are in general measurements of one or more photons which are performed in such a way that it is not possible to know, not even in principle, to which pair the measured photon(s) belong. The remaining photons then exhibit the desired phenomenon. A general feature of the existing schemes is that, so far, experimental confirmation necessitates detection of all photons involved. We will analyze this latter condition separately for each experiment performed up to now. This, we suggest, neither implies that the respective quantum phenomena have not been observed nor does it impart significant limitations on many possible quantum information protocols.

2. QUANTUM TELEPORTATION AND ENTNAGLEMENT SWAPPING

The aim of our experimental realization [9] of the original proposal [6] for quantum teleportation was to teleport the quantum state of a single photon. In the experiment shown in Fig. 1 we employed the double use of type II parametric down-conversion [10]. We will now analyze in detail the meaning of possible events that are to happen. First, we note that for most UV-pulses no photon pair was created. In fact, in our experiment the probability for an individual UV-pulse to create a photon pair was of the order of 10^{-4}. Secondly, even when a photon pair was created, in most cases it was not accompanied by a second pair. Yet, if we adopt a protocol which only accepts teleportation under the natural condition that a two-photon coincidence in the Bell-state analyzer occurred, these cases can readily be ruled out. We now turn to a careful analysis of those cases where such coincidences (between detectors $f1$ and $f2$) are observed. This necessitates that at least two down-conversion processes have occurred. We note that we can reasonably neglect the case of more than two down-conversions because such events are again sufficiently unlikely (the probability is again by a factor 10 smaller than the probability for a creation of two pairs).

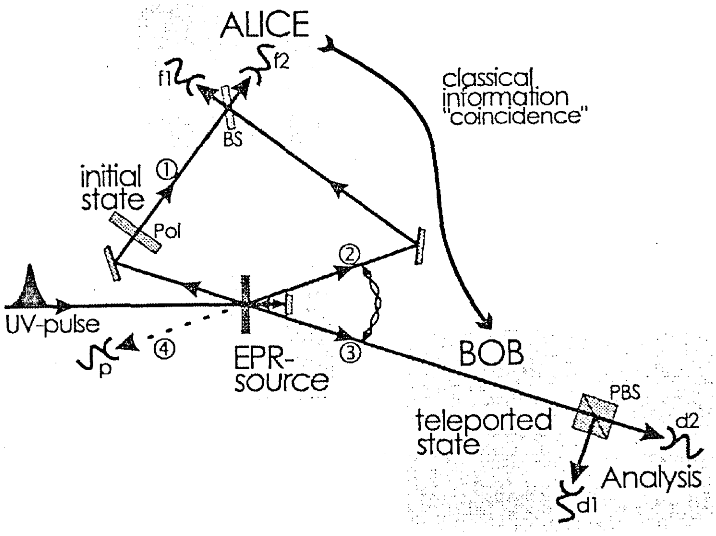

Fig. 1 Experimental Setup of Quantum Teleportation [9]. A UV-pulse creates a pair of entangled photons propagating to the right. One of these photons is directed to Alice while the other will become Bob's teleported photon. The pulse passes once more through the crystal creating another pair propagating to the left. One of those photons can either be prepared in any possible state or left undefined in entanglement swapping [11]. It is finally subject by Alice to a Bell-state measurement jointly with her entangled one. The other photon travelling to the left serves as a trigger.

Two pairs can be created in three different ways, either both during the first passage of the pulse, or both during the second, return passage of the pulse or one upon each passage. We note that the first case is irrelevant because it does not lead to a trigger event. The last case leads to the desired teleportation.

Finally, in the case of both down-conversions occuring on the return passage, one may obtain both a photon registration at the trigger and a coincidence event at both Bell state analyzer detectors.

As a detail we note that in the cases of successful teleportation the antisymmetric state

$$|\psi>_A=\frac{1}{\sqrt{2}}(|H>|V>- \quad |V>|H>) \tag{1}$$

was identified at Alice's Bell state analyzer [12]. Thus, even for perfect detections only one out of four possible Bell-state measurement results led to teleportation. This is just a limitation of the efficiency of the chosen procedure and it has no implications for the fact that in the successful cases the teleportation protocol has properly been realized.

Any state, pure or mixed, can be teleported with that procedure. Yet it is necessary to demonstrate that teleportation is successfully achieved. Thus one simply prepares the initial photon travelling to the Bell state analyzer in any arbitrary superposition state

$$|\psi>=\alpha|1>_H+\beta|1>_V \tag{2}$$

where $|1>_H$ ($|1>_V$) designs one photon in polarization mode $H(V)$ and $|\alpha|^2+|\beta|^2=1$. Bob then proves that his photon is in that state. In the experiment there was no need for Bob to apply a unitary transformation to his photon because the original entangled state created was also chosen to be $|\psi>_A$. Thus, implicitly, the necessary transformation would just be the identity operation.

We now turn to analyzing the case when both down-conversions happen on the return path of the pump pulse. In this case the trigger detector may certainly fire, this time indicating that two photons are on their way to the Bell-state analyzer. These two photons propagate to the two separate detectors of the Bell-state analyzer with a probability of 50%. The registration of these two detectors may falsely be interpreted by Alice as indicating projection on a Bell state and hence teleportation. Yet Bob does not in fact receive a photon and Braunstein and Kimble [13, 14] suggested the term "a posteriori" teleportation indicating that in the setup used the experimentalists only know that teleportation occurred if Bob's detector eventually registers. I will now argue that this feature is not a limitation of the procedure but actually underlines a significant advantage. Just consider the state after the polarizer

$$|\psi>'=\frac{1}{\sqrt{2}}(\alpha|2>_H+\beta|2>_V) \tag{3}$$

which in that case indicates that we now have a two-photon state. Evidently, this state is orthogonal to the state of Eq. (2). Now, since the purpose of the experiment is to teleport any general one-photon state, it is actually an advantage that in the case of the state of Eq. (2) teleportation does not occur. Thus, we arrive at the conclusion that the procedure itself acts as a powerful filter which enables only teleportation of the desired one-photon states as intended. This selectivity of the procedure, I suggest, may be of significant advantage in future quantum computation applications of teleportation.

In entanglement swapping [7],[11], one simply removes the polarizer in the setup of Fig. 1. Then, upon registration of two photons in the Bell-state analyzer, the outgoing two photons, the one propagating to the trigger detector and the one propagating to Bob, are entangled. Here too, it can happen that both photon pairs are created in one single passage. In that case, one registers two photons in the Bell state analyzer without one photon each in the outgoing beam for a certain fraction of all cases. An analogous interpretation problem arose in some early tests of Bell's inequality[15]. Yet, the cases where indeed one photon each is registered in each outgoing beam can be valid tests of quantum nonlocality and Bell's inequality if the probability for a photon to propagate to either detection station is independent of the parameter setting chosen at that detector [16, 17].

3. OBSERVATION OF GHZ STATES

It is well-known [8, 18, 19] that entangled states of three or more quanta can lead to stronger violations of local realism than two-quanta systems. Additionally, in recent years it turned out that such states play crucial roles in many quantum information schemes [20]. While the existence of such states was recently demonstrated experimentally for three nuclei in a single molecule using nuclear magnetic resonance (NMR) techniques [21], no experimental verification for spatially separated quanta existed hitherto. Very recently a first demonstration of GHZ states was obtained [22] for three photons.

The principle of the experiment [23] is to start again, as in the experiments discussed above, from two entangled pairs. One then subjects one photon to a measurement such that all information to which pair it belongs is completely erased. This projects the remaining three photons into the desired state.

The experimental principle is shown in Fig. 2. One again creates two pairs of photons by a sufficiently strong pump pulse.

The state of each pair created by the source is

$$|\psi>_A = \frac{1}{\sqrt{2}}(|H>_1 |V>_2 + e^{i\chi}|V>_1 |H>_2) \tag{4}$$

where the internal phase χ depends on the specific details of the experiment.

Restricting ourselves to four-fold coincidences at all four detectors T, D_1, D_2 and D_3, we obtain a GHZ-state through the following reasoning. The photon at T is always horizontally (H) polarized and therefore one of the photons in beam b must be vertically (V) polarized. If this photon ends up in detector D_2 then the one registered in D_1 must also be vertically polarized resulting in the photon at D_3 being horizontally polarized (H). Thus we obtain the first term in our quantum state

$$|H>_T |V>_1 |V>_2 |H>_3 \quad . \tag{5}$$

On the other hand, if the vertical photon of beam b is registered in detector D_3 then the photons registered in D_1 and D_2 must both carry H polarization resulting in the term

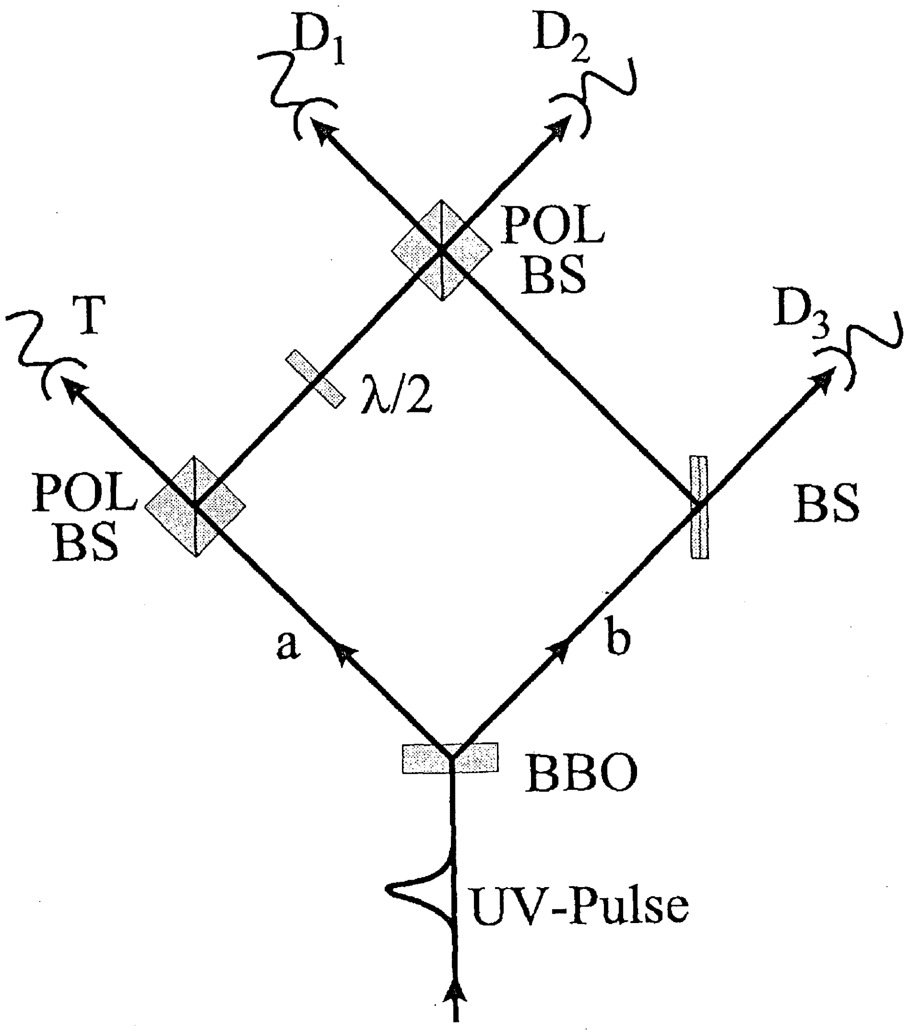

Fig. 2 Principle of the experimental observation of 3-photon GHZ-states [22]. A nonlinear BBO crystal is pumped by a strong UV-pulse. In beam *a* the photons encounter a two-channel polarizer which reflects vertical (V) polarization and transmits horizontal (H) polarization, the latter being registered by the trigger detector T. The vertical polarization is then rotated by 45° by a $\lambda/2$ plate oriented at 22.5°. In the *b* beam the photons encounter a standard 50/50 semireflecting beam splitter, with one of the outgoing beams heading towards detector D_3. Finally, detectors D_1 and D_2 observe the outputs of the final polarizer.

$$|H>_T |H>_1 |H>_2 |V>_3 \quad . \tag{6}$$

If the experimental arrangement is such that these two cases are coherent, the state

$$\frac{1}{\sqrt{2}}(|H>_T (|V>_1 |V>_2 |H>_3 + |H>_1 |H>_2 |V>_3) \tag{7}$$

results, exhibiting for photons 1 and 2 the desired GHZ correlations. The specific internal phase in Eq. (7) is a consequence of the two down-conversions being identical.

In the experiment, verification of the state (7) was done by measuring one of the photons at 45° linear polarization. Such a measurement results in an entangled two-photon state of the two remaining photons, as predicted by the concept of entangled entanglement [24]. This is because the GHZ part of state (7) can be rewritten as

$$\begin{aligned}&\tfrac{1}{2}\ \ |+45^\circ >_1 (|H >_2 |V >_3 +|V >_2 |H >_3) + \\ &\tfrac{1}{2}\ \ |-45^\circ >_1 (|H >_2 (V >_3 -|V >_2 |H >_3)\end{aligned} \tag{8}$$

Demonstration of the resulting entanglement of photons 2 and 3 is straightforward. It just entails the use of the specific rotational properties of two-particle entangled states which can be observed for example by measuring photons 2 and 3 in a basis that is also rotated by 45°.

We note that here too, it can happen that only one down-conversion occurs. That situation is readily identified by the fact that together with the trigger detector T only one of the other detectors fires. This also holds for the case of two photons heading towards any of the detectors. We note again that, as in the cases of teleportation and of entanglement swapping, this in no way restricts the usefulness of the scheme for tests of quantum nonlocality. The basic reason for that fact is that one can, as is well known, base a nonlocality argument just on an analysis of the events observed. No reference to the underlying quantum state is necessary. Such an analysis was recently performed for our GHZ state.

We also note that all errant cases analyzed here are signified by the fact that not all intended detectors register a photon. From a practical point of view this is the same as non-firing due to the unavoidable detection inefficiency.

4. FINAL REMARKS

We might finally venture into discussing some possible avenues for future research, as far as they can be identified at the moment. Considering the status of technology available at present, a dedicated technological program for the development of novel detectors would be extremely useful. The detectors I envisage should be able to distinguish between one-photon events and two-photon events. These detectors should have little cross-talk, that is, they should confuse the two kinds of events with very small probability even though the detection efficiencies themselves need not be large. I submit that such detectors and their generalizations to $N-$photon detection will be very useful for many future quantum information protocols involving a higher number of photons.

Such a higher number of photons will be employed in many future experiments. A specifically interesting experiment would be to demonstrate coding schemes in multi-photon states, particularly states demonstrating non-trivial error correction schemes.

Another very interesting future avenue will be to realize generalizations[25] of quantum teleportation and of entanglement swapping to more complicated cases like quantum switchboards which again involve multi-photon states.

Presently the most successful line of research towards multiphoton entanglement is to exploit the easily realizable two-photon entanglements as resources for more complicated cases. This will generalize the experimental approaches of the type used in experiments discussed above in the near future.

ACKNOWLEDGMENTS

I would like to thank the theorists M.A. Horne, D.M. Greenberger and M. Żukowski and the experimentalists D. Bouwmeester, J.-W. Pan and H. Weinfurter for useful discussions. I am also grateful to the organizers of ISQM-Tokyo '98 for their kind invitation to present some of our results. This work was supported by the Austrian Science Foundation FWF, project S06502, and by the U.S. National Science Foundation, grant No. PHY 97-22614.

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Quantum Coherence and Decoherence

Proceedings of the 6th International Symposium on Foundations of Quantum Mechanics in the Light of New Technology (ISQM-Tokyo '98), Advanced Research Laboratory, Hitachi, Ltd., Hatoyama, Saitama, Japan, August 24-27, 1998

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1999

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First edition 1999

Library of Congress Cataloging in Publication Data
International Symposium Foundations of Quantum Mechanics in the Light of New Technology (6th : 1998 : Hatoyama-machi, Japan)
Quantum coherence and decoherence : proceedings of the 6th International Symposium of Quantum Mechanics in the Light of New Technology (ISQM-Tokyo'98), Advanced Research Laboratory, Hitachi Ltd., Hatoyatama, Saitama, Japan, August 24-27, 1998 / edited by Y.A. Ono, K. Fujikawa.-- 1st ed.
p. cm. -- (North-Holland delta series)
Includes bibliographical references and index.
ISBN 0-444-50091-X (alk. paper)
1. Coherence (Nuclear physics)--Congresses. 2. Quantum theory--Congresses. I. Ono, Yoshimasa A. II. Fujikawa, K. III. Title. IV. Series.

QC794.6.C58 I55 1998
539--dc21

99-056387

ISBN: 0 444 50091 X

⊜The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

Printed in The Netherlands.