# EXPERIMENTAL AND THEORETICAL ASPECTS OF QUANTUM TELEPORTATION

Lei Zhang, Jacob Barhen, and Hua-Kuang Liu

***Center for Engineering Science Advanced Research***
Computer Science and Mathematics Division
**Oak Ridge National Laboratory**
*Oak Ridge, TN 37831-6355, USA*
zhangl@ornl.gov, barhenj@ornl.gov, and 9hl@ornl.gov

ABSTRACT

We present a short summary of progress achieved at the Center for Engineering Science Advanced Research (CESAR) of the Oak Ridge National Laboratory (ORNL) in the recently initiated Quantum Teleportation project. The primary objective of this effort is to study the signaling potential of quantum information processing systems based on quantum entanglement. Our initial effort has focused on the development and demonstration of a novel, ultra-bright EPR source, based upon the innovative concept of cascaded type-II optical parametric downconversion. The main features of this source are analyzed, and results of a multi-photon entanglement experiment are presented. Theoretical challenges for superluminal communications are also highlighted.

## I. INTRODUCTION

In recent years, there has been increased interest in exploiting the unique capabilities that quantum mechanics offers for the processing of information. In that context, quantum teleportation (QT) is a particularly attractive paradigm. It involves the transfer of an unknown quantum state over an arbitrary spatial distance by exploiting the prearranged entanglement (correlation) of "carrier" quantum systems in conjunction with the transmission of a minimal amount of classical information. This concept was first discussed by Aharonov and Albert (AA) using the method of nonlocal measurements [1].

Over a decade later, Bennett, Brassard, Crepeau, Jozsa, Peres, and Wooters (BBCJPW) developed a detailed alternate protocol for teleportation [2]. It consists of three stages. First, an Einstein-Podolsky-Rosen (EPR) [3] source of entangled particles is prepared. Sender and receiver share each a particle from a pair emitted by that source. Second, a Bell-operator measurement is performed at the sender on his EPR particle and the teleportation-target particle, whose quantum state is unknown. Third, the outcome of the Bell measurement is transmitted to the receiver via a classical channel. This is followed by an appropriate unitary operation on the receiver's EPR particle. To justify the name "*teleportation*", BBCJPW note that the unknown state of the transfer-target particle is destroyed at the sender site and instantaneously appears at the receiver site. Actually, the state of the EPR particle at the receiver site becomes its exact replica. The teleported state is never located between the two sites during the transfer.

A number of exciting theoretical developments has appeared since the publication of the AA and BBCJPW protocols. For instance, Vaidman has shown [4] how nonlocal measurements can be used for the teleportation of the unknown quantum states of systems with continuous variables. In AA, nonlocal refers to measurements that cannot be reduced to a set of local measurements; for example, the measurement of a sum of two variables related to two separated spatial locations. He was also the first to suggest a method for two-way teleportation. Braunstein and Kimble extended Vaidman's analysis to incorporate finite degrees of correlation among the relevant particles and to include inefficiencies in the measurement process [5]. In their proposed implementation of QT of continuous quantum variables, the entangled state shared by sender and receiver is a highly squeezed two-mode state of the electromagnetic field, with the quadrature modes of the field playing the roles of position and momentum. Stenholm and Bardroff have generalized the BBCJPW protocol to systems of arbitrary dimensionality [6]. Zubairy has considered the teleportation of a field state (a coherent superposition of $2^n$ Fock states) from one high-Q cavity to another [7]. In the previously cited studies, QT dealt with "*intraspecies*" teleportation e.g., photon-to-photon. Maierle, Lidar, and Harris were recently the first to introduce an "*interspecies*" teleportation scheme [8]. Specifically, in their proposal, the information contained in a superposition of molecular chiral amplitudes is to be teleported to a photon. Finally, let us mention that Brassard, Braunstein, and Cleve have argued [9] that QT is an essential ingredient for quantum computing, and have presented a simple circuit that implements QT in terms of primitive operations in quantum computing.

Let us turn to experimental realizations of QT. The first laboratory implementation of QT was carried out in 1997 at the University of Innsbruck by a team led by Anton Zeilinger [10]. It involved the successful transfer of a polarization state from one photon to another. A type-II degenerate, pulsed parametric down-conversion process was used to generate the polarization-entangled EPR source. The experimental design is relatively easy to implement. The drawback is that only one of the four EPR-Bell states can be distinguished. In 1998, the Zeilinger team demonstrated that freely propagating particles that never physically interacted with one another could also readily be entangled [11]. In this experiment, one photon each from two pairs of polarization-entangled photons were subjected to Bell-state measurement. As a result, the other two photons were projected into an entangled state. This result is remarkable, since it shows that quantum entanglement does not require entangled particles to originate from a common source or to have interacted in the past. The second QT experiment reported in the open literature in February 1998 was carried out at the University of Rome by a team lead by Boschi and Popescu [12]. It involved a quantum optical implementation. The polarization degree of freedom of one of the photons in the EPR pair was employed for preparing the unknown state. The idea is to exploit the fact that the two degrees of freedom of a single photon can be ***k***-vector entangled. This method cannot, however, be used to teleport an external, unknown quantum state. The conservation of energy and time photon entanglement over distances exceeding 10 km has been demonstrated experimentally [13] using a telecommunications fiber network. In a similar vein, the distribution of cryptographic quantum keys over open space optical paths of approximately 1km was also reported [14].

The potentially enormous economic and national security implications of a successful realization of a loopholes-free QT system has led to an intense competition among the few laboratories that have the experimental capabilities to adequately address this challenge. A particularly "hot" topic is to demonstrate which scheme is more "*complete*" [15] or more "*unconditional*" [16]. However, Vaidman has proved that reliable QT can not be achieved using the methods implemented in the experiments reported to date [17]. Specifically, it is impossible to perform complete Bell operator measurements without using interaction between the quantum states of the particles.

Our purpose in this paper is to present a short summary of progress achieved at the Center for Engineering Science Advanced Research (CESAR) of the Oak Ridge National Laboratory (ORNL) in a recently initiated QT project. The primary objective of this effort is to study the signaling potential of quantum information processing systems based on quantum entanglement. Our initial effort has focused on the development of an ultra-bright EPR source. This has been accomplished successfully, and is discussed in Section II. The theoretical challenges are highlighted in Section III. Near-term objectives (e.g., multi-channel quantum teleportation employing multi-particle, or GHZ photons) and conclusions reached so far are included in Section IV

.

## II. EXPERIMENTS

The simplest quantum states for QT involve two-level systems, including spin states of a spin ½ particle, the polarization states of a photon, the ground and excited state of an atom or ion, or the Fock states of a microwave cavity. In the following discussion, without loss of generality, we will use polarization states. Before a polarization-entangled photon can be used for QT (including applications such as quantum cryptography or quantum remote sensing), it is essential to characterize the EPR source in detail.

### *Preparation of entangled photon pairs*

The preparation of polarization-entangled photons uses the process of optical parametric down-conversion (OPDC) [18] to produce correlated photon pairs. This process employs a nonlinear medium, which allows pump photons to decay into pairs of photons under the restrictions of energy and momentum conservation. Since the two "decay" photons are created at the same time, the detection of one photon indicates with almost certainty the existence of the other. The conservation of energy and momentum also allows the determination of one photon’s wavelength and direction provided the other one’s are known. Three phase-matching methods are available for generation of correlated photons. They are referred to as type-I, type-II and cascaded type-I.

In a type-I process, the generated photon pair shares the same polarization. With this method, a broad range of momentum and energy entangled photon pairs can be produced, either in a non-degenerate geometry, such that they have different wavelengths, or in a degenerate geometry, where the two photons share the same wavelength. The limitation of type-I OPDC is that the photons are actually created in polarization product-states, and may not violate a true test of Bell's inequalities. In a type-II process [19], the photon pair is created with orthogonal polarizations. Therefore, as opposed to the type-I source, the photons emitted into two distinct modes are usually not entangled, because they can be distinguished on the basis of their polarization. It was found that, when the cut angle of the crystal is larger than that of the degenerate OPDC (or when the crystal is tilted toward that direction), the two emission cones corresponding to different modes would overlap. In the two directions determined by the cones’ intersection the polarization distinguishability disappears. Therefore, such a source can produce polarization-entangled photon pairs. Typical emission patterns of type-I and type-II OPDC are shown in Figure 1. The type-I BBO crystal has a cut angle of 29.6º and was tilted 0.2º (internal) while the type-II BBO crystal has a cut angle of 42.9º and was tilted 2.5º (internal). Detailed explanations are provided in the caption.

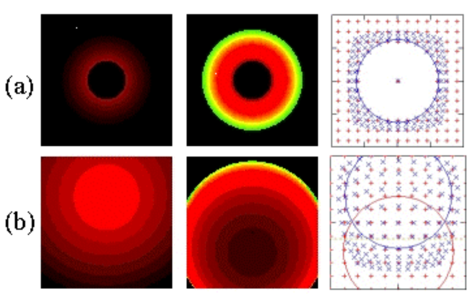


**Figure 1** Simulated emission patterns of extraordinary beams (left), ordinary beams (center) and separations between extraordinary beams (“×”) and ordinary beams (“+”) with (a) type-I and (b) type-II phase matched OPDC in a BBO crystal. The pump wavelength is 395 nm. The solid circles correspond to a degenerate case. All patterns are calculated over a 10º×10º solid angle except the top right one, which is calculated over a 4º×4º solid angle.

Figure 2 shows the geometry when the crystal cut angle is larger than that of the degenerate OPDC. Polarization-entangled photon pairs, labeled as *A* and *B*, propagate along the two directions where the cones intersect. The horizontal polarization (→, ordinary) and the vertical polarization (↑, extraordinary) are orthogonal, and the corresponding polarization-entangled two-photon state is given by

$$\left|\psi_{A,B}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\rightarrow_A, \uparrow_B\right\rangle + e^{i\alpha}\left|\uparrow_A, \rightarrow_B\right\rangle\right) \qquad (1)$$

The relative phase $a$ arises from the crystal birefringence, and an overall phase shift is omitted. With the help of additional half wave or quarter wave plates, one can easily produce any of the four EPR-Bell states,

$$\left|y^{\pm}_{A,B}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\rightarrow_A, \uparrow_B\right\rangle \pm \left|\uparrow_A, \rightarrow_B\right\rangle\right), \tag{2}$$

$$\left|f^{\pm}_{A,B}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\rightarrow_A, \rightarrow_B\right\rangle \pm \left|\uparrow_A, \uparrow_B\right\rangle\right). \tag{3}$$

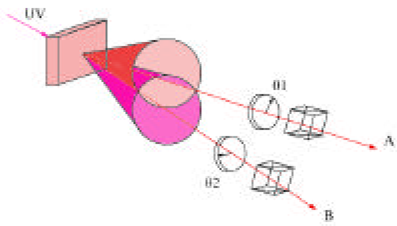


**Figure 2** Geometry of a type-II OPDC. Polarization entangled photons are found along the two intersection directions (*A* and *B*) of the two emission cones.

We have already demonstrated type-II OPDC with a femtosecond pump source. The pump laser system is a mode-locked Ti: Sapphire laser (Mira 900-F from Coherent) pumped by an Argon laser (INNOVA Sabre from Coherent). The output gives a 76 MHz pulse train at a wavelength of 790 nm, with 120 femtosecond pulse width and 1.2 watt CW power. The UV beam is generated with a 7-mm thick LBO crystal (from CASIX) cut for second harmonic generation (SHG) at 790 nm. The conversion efficiency from IR to UV is about 40%. After passing through a prism pair for dispersion compensation and fundamental removal, the final UV beam has a pulse width of less than 200 fs and 300 mW power. Figure 3 shows the overlapped photon cones, generated by type-II OPDC. An interference filter with a bandwidth of 2 nm (from Avdover) is placed before the single photon counting module (SPCM-AQR-14 from EG&G Canada). The maximum photon counting rate is 7000 ($sec^{-1}$) (counted by fiber with background subtracted).

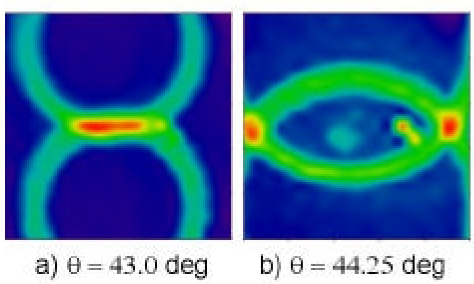


**Figure 3** Emitted photon cones scanned with a 100-μm diameter fiber over a 1 cm × 1 cm area, 6.5 cm behind the crystal's output surface. A 3-mm thick BBO with cut angle of 43° is used for type-II OPDC. An interference filter with bandwidth of 2 nm is placed before the SPCM. a) corresponds to a collinear and b) corresponds to a non-collinear case. $q$ corresponds to effective internal angle between the optical axis and the pump UV beam direction.

The polarization correlations were measured using the setup shown in Figure 2. With $q_1$ set at -45° and $q_2$ rotated from -45° to 315°, the coincidence rate from the two detectors was recorded. It corresponds to the $|y^+>$ state. Then a half-wave plate was inserted into one of the arms to rotate the polarization by 90° in that arm. The corresponding polarization entanglement was measured and gave the $|f^+>$ state. These measurement results can be seen in Figure 4.

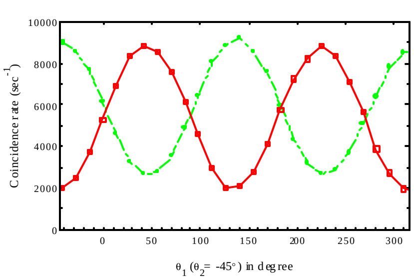


**Figure 4** Measurement of the polarization entanglement of an EPR source generated with a type-II phase matched BBO crystal. The solid square corresponds to the $|y^+>$ state and the circle corresponds to the $|f^+>$ state. The solid line is the fitting with $\sin^2(\theta_1 + \theta_2)$ and the dashed line is the fitting with $\cos^2(\theta_1 + \theta_2)$.

### *Cascaded Type-I Downconversion Source of Correlated Photons*

A new method, that uses the process of OPDC in an innovative geometry involving two type-I crystals, has recently been reported [20]. Two adjacent, relatively thin, nonlinear crystals are operated with type-I phase matching. The identically cut crystals are oriented so that their optic axes are aligned in perpendicular planes. Under such conditions, a 45° polarized pump photon will be equally likely to down convert in either crystal. Generally photons generated by different crystals can be distinguished by their polarizations. This problem was solved by inserting quarter-wave plates behind the crystal pairs. Furthermore, these two possible down-conversion processes are *coherent* with one another.

### *Cascaded Type-II Optical Parametric Down-conversion*

We now present some new experimental results that we have achieved in the short period since the inception of this project. First, we discuss our novel EPR source, which is based on optical parametric down-conversion, but with a cascaded type-II OPDC configuration. It combines the main advantages of, and outperforms previously reported entangled photon generators. Next, we analyze its main features and limitations. Our new source consists of two adjacent thin nonlinear crystals with identically cut angles, which correspond to degenerated type-II phase matching. The two crystals are oriented with their optic axes aligned in opposite direction. A pump photon may be equally down-converted in either crystal, and these two possible downconversion processes generate two pairs of correlated photons (see Figure 5). The advantage of our proposed configuration is obvious. First, the limitation in overlap of idler and signal photons has been greatly relaxed (see Figure 1) compared with the case in cascaded type-I OPDC. Our architecture can thus provide much brighter polarization-entangled photons in either degenerate or non-degenerate cases. Second, the outputs are naturally polarization-entangled. Third, in the directions corresponding to the intersections of the two cones, the two pairs of polarization-entangled photons coincide exactly. By selected alignment, such a source may work as a *four-photon entanglement* source.

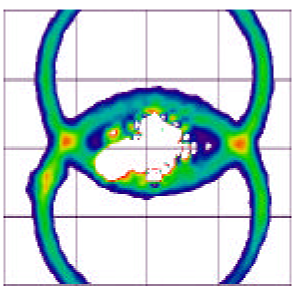

**Figure 5** Emitted photon cones generated by type-II OPDC, scanned with a 100-μm diameter fiber over a 1.6 cm × 1.6 cm area, 7.5 cm behind the crystal's output surface. The background has been subtracted. The residual of the UV pump photons at the center has been cropped. The thickness of both BBO crystals is 1-mm and cut at an angle of 43.9°.

The single photon counting modules (SPCM-AQR-14 from EG&G, Canada) that we used have internal amplifiers. For each photon detected, there is a 5 V output signal with 30 ns pulse width. Since the pump source is a mode locked Ti: Sapphire laser with 76 MHz modulation frequency, the separation between pulse trains is 13 ns. Hence, we have used a Quad Constant-Fraction Discriminator (935-CFD from EG&G ORTEC) to compress the output pulse width to 5 ns. The outputs from two CFD output connectors are then routed to a Quad 4-Input Logic Unit (CO4020 from EG&G ORTEC) for coincidence count. The output from CO4020 is sent to a Universal Time Interval Counter (SR620 from Stanford Research Systems). The outputs from the 935-CFD are also sent to a Quad Timer/Counter (974 from EG&G, ORTEC) to record the single counting rate.

### *Two-photon interferometry for analyzing the entanglement*

If one overlaps two photons at a beamsplitter, interference effects determine the probabilities to find the two photons incident one each from *A* and *B* either both in one of the two outputs or to find one in each output. Only if two photons are in the state

$$|\psi^-_{A,B}\rangle = \frac{1}{\sqrt{2}}\left(|\rightarrow_A, \uparrow_B\rangle - |\uparrow_A, \rightarrow_B\rangle\right), \quad (4)$$

will they leave the beam splitter in different output arms. If one puts detectors there, a click in each of them, i.e. a coincidence, means the projection of the two photons onto the state $|\psi^-\rangle$. For the other three Bell states both photons will exit together through one of the two output arms. To register two photons in one output arm additional detectors or a certain detuning of the setup is necessary since these detectors do not distinguish between one or more photons.

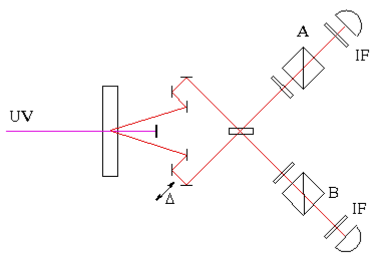


**Figure 6** Experimental setup for measurement of entanglement and interference

The experimental results for multi-photon entanglement, obtained using our cascaded type-II OPDC source in the setup shown in Figure 6 above, are illustrated in Figures 7 and 8.

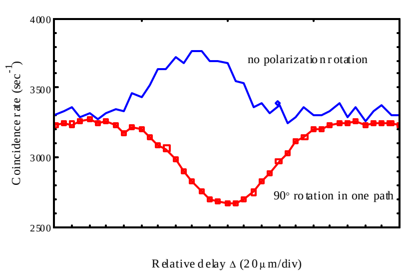


**Figure 7** Coincidence rate as a function of the delay between the arrival of photon A and photon B. The lower curve shows the measured destructive interference when the polarization in one path was rotated 90°. The upper curve shows the measured constructive interference with no polarization rotation. It includes a strong *biphoton effect* in our cascaded type-II OPDC.

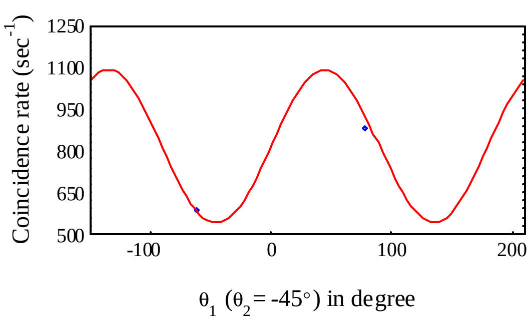


**Figure 8** Measurement of the polarization entanglement. The polarization analyzer of photon *B* was varied, while that of photon *A* was fixed at –45°. The solid line is the fitting with $\sin^2(\theta_1 + \theta_2)$.

## III. THEORETICAL CHALLENGES

The nonlocality of the correlations of two particles in quantum entanglement has no classical analog. It allows coherent effects to occur instantaneously in spatially separate locations. The question naturally arises as to whether a more general formulation of QT could provide a basis for superluminal communications. This issue has recently been the subject of considerable debate in the open literature.

There are basically two schools of thought: one, which precludes this possibility (based, for example, on conflicts with the theory of special relativity), and one which allows it under special provisions. We will discuss these issues in some detail in the sequel. First, however, we briefly highlight a few of the more significant new findings in the growing experimental and theoretical evidence of superluminal effects.

A conference on superluminal velocities took place in June 1998 in Cologne [21]. Theoretical and experimental contributions to this topic focused primarily on evanescent mode propagation and on superluminal quantum phenomena. The issues of causality, superluminality, and relativity were also examined. In the area of electromagnetic propagation, two exciting developments were addressed. Nimtz reported on experimental measurements of superluminal velocities achieved with frequency band-limited signals carried by evanescent modes [22]. Specifically, he timed a microwave pulse crossing an evanescent barrier (e.g., undersized waveguides, or periodic dielectric heterostructures) at 4.7*c*. He demonstrated that, as consequence of the frequency band limitation of information signals, and if all mode components are evanescent, an actual signal might travel faster than the speed of light. Capelas de Oliveira and Rodrigues introduced the intriguing theory of superluminal electromagnetic X-waves (SEXW) defined as undistorted progressive waves solutions of the relativistic Maxwell equations [23]. They present simulations of finite aperture approximations to SEXW, illustrate the signaling mechanism, and discuss supporting experimental evidence.

What are the key arguments put forward against the possibility of superluminal signaling? Chiao and Steinberg analyze quantum tunneling experiments and tachyon-like excitations in laser media [24]. Even though they find the evidence conclusive that the tunneling process is superluminal, and that tachyon-like excitations in a population-inverted medium at frequencies close to resonance give rise to superluminal wave packets, they argue that such phenomena can not be used for superluminal information transfer. In their view, the group velocity can not be identified as the signal velocity of special relativity, a role they attribute solely to Sommerfeld's front velocity. In that context, Aharonov, Reznik, and Stern have shown that the unstable modes, which play an essential role in the superluminal group velocity of analytical wave packets, are strongly suppressed in the quantum limit as they become incompatible with unitary time evolution [25].

Let us now examine EPR-based superluminal schemes. Furuya *et al* analyze a paradigm proposed by Garuccio, in which one of the photons of a polarization-entangled EPR pair is incident upon a Michelson interferometer in which a phase-conjugation mirror (PCM) replaces one of the mirrors [26]. The sender (located at the source site) can superluminally communicate with a receiver (located at the detector site), based on the presence or absence of interferences at the detector. The scheme uses the PCM property that a reflected photon has the same polarization as the incident photon (contrary to reflection by an ordinary mirror), allowing to distinguish between circular and linear polarization. In a related context, Blaauboer *et al* also proposed [27] a connection between optical phase conjugation and superluminal behavior. Furuya *et al* prove that Garuccio's scheme would fail if non coherent light is used, because then the interferometer could not distinguish between unpolarized photons prepared by mixing linear polarization states or by mixing circular polarization states. They admit, however, that their counterproof would not apply to a generalized Garuccio approach, which would use coherent light states. Finally, in terms of criticism, let us mention the recent article by Peres [28], where criteria that prevent superluminal signaling are established. These criteria must be obeyed by various operators involved in classical interventions on quantum systems localized in mutually spacelike regions.

What are the arguments in favor of superluminal information transfer? Gisin shows [29] that Weinberg's general framework [30] for introducing nonlinear corrections into quantum mechanics allows for arbitrary fast communications. It is interesting to note that, in a recent book [31], Weinberg himself states: "I could not find a way to extend the nonlinear version of quantum mechanics to theories based on Einstein's special theory of relativity (…) both N. Gisin in Geneva and my colleague Joseph Polchinsky at the University of Texas independently pointed out that (…) the nonlinearities of the generalized theory *could* be used to send signals instantaneously over large distances".

At the Cologne symposium [21] Mittelstaedt reviewed the arguments that had been put forward in recent years in order to show that non-local effects in quantum systems with EPR-like correlations can not be used for superluminal communications. He demonstrated that most of these arguments are based on circular proofs. For instance, a "locality principle" can not be used to exclude superluminal quantum signals and to justify quantum causality, since the locality principle itself is justified by either quantum causality or an equivalent "covariance postulate" [32]. In a similar vein, van Enk shows that the proof given by Westmoreland and Schumacher in [33] that superluminal signaling violates the quantum no-cloning theorem is in fact incorrect [34]. Hegerfeld uses the formalism of relativistic quantum mechanics to show that the wave function of a free particle initially in a finite volume instantaneously spreads to infinity and, more importantly, that transition probabilities in widely separated systems may also become nonzero instantaneously [35]. His results hold under amazingly few assumptions (Hilbert space framework and positivity of the energy). Hegerfeld observes that, in order to retain Einstein causality, a mechanism such as "clouds of virtual particles or vacuum fluctuations" would be needed. To conclude this review, we note a recent suggestion of Mittelstaedt [36]. If the existence of superluminal signals is assumed *ab initio* (viz. [22] and [35]), and consequently a new space-time metric (different from the Minkowskian metric) is adopted, all the paradoxes and difficulties discussed above would immediately disappear.

## IV. FUTURE ACTIVITIES

In this paper, we have presented recent progress achieved at CESAR/ORNL in the area of QT. We have also highlighted some of the formidable theoretical challenges that must be overcome if an application of this technology to communications is to become possible. The feasibility question is, in our minds, still open. To summarize, we now succinctly indicate our near-term proposed road map.

From a theory perspective, we will focus our attention on two recent proposals for superluminal communications. Greenberger has demonstrated [37] that if one can construct a macroscopic Schrodinger cat state (i.e., a state that maintains quantum coherence), then such a state can be used for sending superluminal signals. His scheme assumes that the following two requirements can be realized. First, it should be possible to entangle the signal-transmitting device with the signal itself, thereby constructing a GHZ state. Second, that non-unitary evolution can be established and controlled in a subset of the complete Hilbert space. This latter property has already been demonstrated successfully in several downconversion experiments. Greenberger uses an optical phase shifter as model for his signaling device. We believe that as of this date better alternatives are available. The second Gedankenexperiment we intend to examine was introduced by Srikanth [37]. His proposed method uses a momentum-entangled EPR source. Assuming a pure ensemble of entangled pairs, either position or momentum is measured at the sender. This leaves the counterpart in the EPR pair as either a localized particle or a plane wave. In Srikanth's scheme, the receiver distinguishes between these outcomes by means of interferometry. Since the collapse of the wavefunction is assumed to be instantaneous, superluminal signal transmission would be established.

We intend to explore possible experimental realizations of the above paradigms. We will also continue to focus on cascaded type-II OPDC, with emphasis on walk-off, optical collimation, optimal generation efficiency, and maximal entanglement. Special attention will also be given to multi-photon entanglement.

## ACKNOWLEDGMENT

This research was performed at the Oak Ridge National Laboratory (ORNL), managed by UT-Battelle, LLC for the United Stated Department of Energy (U. S. DOE) under Contract No. DE-AC05-00OR22725. Funding for the effort was provided the Basic Energy Sciences Engineering Research Program of the Office of Science, U.S. DOE.

# REFERENCES


1. Y. Aharonov and D. Albert, "Can we make sense of the measurement process in relativistic quantum mechanics?", *Phys. Rev.*, **D 24**(2), 359-370 (1981).
2. C. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres and W. Wootters, "Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels, " *Phys. Rev. Lett.*, **70**(13), 1895-1899 (1993).
3. A. Einstein, B. Podolsky and N. Rosen, "Can quantum mechanical description of physical reality be considered complete?, " *Phys. Rev.*, **47**, 777-780 (1935).
4. L. Vaidman, "Teleportation of quantum states", *Phys. Rev.*, **A 49**(2), 1473-1476 (1994).
5. S. Braunstein and J. Kimble, "Teleportation of continuous quantum variables", *Phys. Rev. Lett.*, **80**(4), 869-872 (1998).
6. S. Stenholm and P. Bardroff, "Teleportation of *N* – dimensional states", *Phys. Rev.*, **A 58**(6), 4373-4376 (1998).
7. S. Zubairy, "Quantum teleportation of a field state", *Phys. Rev.*, **A 58**(6), 4368-4372 (1998).
8. C. Maierle, D. Lidar, and R. Harris, "How to teleport superpositions of chiral amplitudes", *Phys. Rev. Lett.*, **81**(26), 869-872 (1998).
9. G. Brassard, S. Braunstein, and R. Cleve, "Teleportation as a quantum computation", *Physica D*, **120**, 43-47 (1998).
10. D. Bouwmeester, J. -W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, "Experimental quantum teleportation, " *Nature*, **390**, 575–579 (1997).
11. J.-W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, "Experimental entanglement swapping", *Phys. Rev. Lett.*, **80**(18), 3891-3894 (1998).
12. D. Boschi, S. Branca, F. De Martini, L. Hardy and S. Popescu, "Experimental realization of teleporting an unknown pure quantum state via dual classical and Einstein-Podolski-Rosen channels," *Phys. Rev. Lett.*, **80**(6), 1121-1125 (1998).
13. W. Tittel, J. Brendel, B. Gisin, T. Herzog, H. Zbinden, and N. Gisin, "Experimental demonstration of quantum correlations over more than 10 km", *Phys. Rev.*, **A 57**(5), 3229-3232 (1998).
14. W. Buttler, R. Hughes, P. Kwiat, S. Lamoreaux, G. Luther, G. Morgan, J. Nordholt, C. Peterson, and C. Simmons, "Practical free-space quantum key distribution over 1km", *Phys. Rev. Lett.*, **81**(15), 3283-3286 (1998).
15. M. Nielsen, E. Knill, and R. Laflamme, "Complete quantum teleportation using nuclear magnetic resonance", Nature, **396**, 52-55 (1998).
16. A. Furosawa, J. Sorensen, S. Braunstein, C. Fuchs, J. Kimble, and E. Polzik, "Unconditional quantum teleportation", *Science*, **282**, 706-710 (1998).
17. L. Vaidman and N. Yoran, "Methods for reliable teleportation", *Phys. Rev.*, **A 59**(1), 116-125 (1999).
18. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics*, Cambridge University Press (1995).
19. P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko and Y. Shih, "New high-intensity source of polarization-entangled photon pairs," *Phys. Rev. Lett.*, **75**(24), 4337-4341 (1995).
20. P. G. Kwiat, E. Waks, A. G. White, I. Appelbaum and P. H. Eberhard, "Ultrabright source of polarization-entangled photons", *Phys. Rev. A.*, **60**(2), R773 –R776 (1999).
21. P. Mittelstaedt and G. Nimtz eds., " Workshop on Superluminal Velocities", Annalen *der Physik*, **7**(7-8), 591-592 (1998).
22. G. Nimtz, "Superluminal signal velocities", *Annalen der Physik*, **7**(7-8), 618-624 (1998).
23. E. C. de Oliveira and W. Rodriguez, "Superluminal electromagnetic waves in free space", *Annalen der Physik*, **7**(7-8), 654-659 (1998).
24. R. Chiao and A. Steinberg, "Quantum optical studies of tunneling and other superluminal phenomena", *Physica Scripta*, **T76**, 61-66 (1998).
25. Y. Aharonov, B. Reznik, and A. Stern, "Quantum limitations of superluminal propagation", *Phys. Rev. Lett.*, **81**(11), 2190-2193 (1998).
26. K. Furuya, P. Milonni, A. Steinberg, and M. Wolinsky, "Failure of a proposed superluminal scheme", *Phys. Lett.*, **A 251**, 294-296 (1999).
27. M. Blaauboer, A. Kozekhin, A. Kofman, G. Kurizki, D. Lenstra, and A. Loder, "Superluminal pulse transmission through a phase conjugating mirror", *Optics Communications*, **148**, 295-299 (1998).
28. A. Peres, "Classical intervention in quantum systems. II. Relativistic invariance", *Phys. Rev.*, **A 61**, 022117(8) (2000).
29. N. Gisin, "Weinberg's non-linear quantum mechanics and superluminal communications", *Phys. Lett.*, **A 143**, 1-2 (1990).
30. S. Weinberg, "Testing Quantum Mechanics", *Ann. Phys.*, **194**, 336-386 (1989).
31. S. Weinberg, *Dreams of a Final Theory*, pp. 88-89, Vintage Books (1992).
32. P. Mittelstaedt, "Can EPR-correlations be used for the transmission of superluminal signals?", *Annalen der Physik*, **7**(7-8), 710-715 (1998).
33. M. Westmoreland and B. Schumacher, "Quantum entanglement and the non existence of superluminal signals", arXiv: quant-*phys*/9801014, Los Alamos National Laboratory (March 1998).
34. S. van Enk, "No-cloning and superluminal signaling", *arXiv*: *quant-phys*/9803030, Los Alamos National Laboratory (March 1998).
35. G. Hegerfeldt, "Instantaneous spreading and Einstein causality in quantum theory", *Annalen der Physik*, **7**(7-8), 716-725 (1998).
36. P. Mittelstaedt, "What if there are superluminal signals?", *Eur. Phys. Jour.*, **B 13,** 353-355 (2000).
37. D. Greenberger, "If one could build a macroscopical Schrodinger cat state, one could communicate superluminally", *Physica Scripta*, **T76**, 57-60 (1998).
38. R. Srikanth, "Noncausal superluminal nonlocal signaling", *arXiv*: *quant-phys*/9904075, Los Alamos National Laboratory (July 1999).