QUANTUM ENTANGLEMENT, PURIFICATION, AND LINEAR-OPTICS QUANTUM GATES WITH PHOTONIC QUBITS

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1. Entanglement

Strikingly, quantum information processing has its origins in the purely philosophically motivated questions concerning the nonlocality and completeness of quantum mechanics sparked by the work of Einstein, Podolsky and Rosen in 1935 [1]. In experiments using entanglement, the system of spin-$\frac{1}{2}$ particles is realized by the usage of single photons, whose properties are defined by their polarization. Considering the H/V bases, a logical $|0\rangle$ corresponds to a horizontally polarized photon $|H\rangle$, respectively a logical $|1\rangle$ corresponds to a vertically polarized photon $|V\rangle$. A single qubit can be written as a coherent superposition of the form $|\psi\rangle = \alpha|H\rangle + \beta|V\rangle$, where the the probabilities α^2 and β^2 sum up to $\alpha^2 + \beta^2 = 1$. For the two qubit case the four different maximally entangled Bell-states are defined as:

$$|\Phi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2)$$
$$|\Psi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2)$$

The Bell states have the unique feature that all information on polarization properties is completely contained in the (polarization-)correlations between the separate photons, while the individual particle does not have any polarization prior to measurement. In other words, all of the information is distributed among two particles, and none of the individual systems carries any information. This is the essence of entanglement. At the same time, these (polarization-)correlations are stronger than classically allowed since they violate bounds imposed by local realistic theories via the Bell-inequality [2] or they lead to a maximal contradiction between such theories and quantum mechanics as signified by the Greenberger-Horne-Zeilinger theorem [3,4]. Distributed entanglement thus allows to establish non-classical correlations between distant parties and can therefore be considered the quantum analogue to a classical communication channel, a quantum communication channel.

The most widely used source for polarization-entangled photons today utilizes the process of spontaneous parametric down-conversion in nonlinear optical crystals [5]. Occasionally the nonlinear interaction inside the crystal leads to the annihilation of a high frequency pump photon and the simultaneous creation of two lower frequency photons, signal and idler, which satisfy the phase matching condition:

$$\omega_p = \omega_s + \omega_i \qquad \text{and} \qquad \vec{k}_p = \vec{k}_s + \vec{k}_i$$

where ω is the frequency and $\vec{k}$ the wavevector of the pump p, signal s and idler i photon. A typical picture of the emerging radiation is shown in Figure 1.

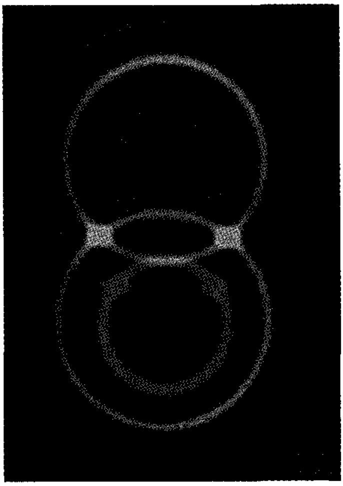

Figure 1. Photograph of the light emitted in type-II parametric down-conversion (false colours). The polarization-entangled photons emerge along the directions of the intersection between the white rings and are selected by placing small holes there

The possibility to establish such quantum communication channels over large distances offers the fascinating perspective to eventually take advantage of these novel communication capabilities in networks of increasing size. Naturally, non-trivial problems emerge in scenarios involving long distances or multiple parties. Experiments based on present fiber technology have demonstrated that entangled photon pairs can be separated by distances ranging from several hundreds of meters up to about 10 km [6,7,8], but no improvements by orders of magnitude are to be expected. Optical free-space links could provide a solution to this problem since they allow in principle for much larger propagation distances of photons because of the low absorption of the atmosphere in certain wavelength ranges. Single optical free-space links have been studied and successfully implemented already for several years for their application in quantum cryptography based on faint classical laser pulses [9,7]. We have recently demonstrated a next crucial step, namely the distribution of quantum entanglement via two simultaneous optical free-space links in an outdoor environment [11]. Polarization-entangled photon pairs have been transmitted across the Danube River in the city of Vienna via optical free-space links to independent receivers separated by 600m and without a line of sight between them (see Figure 2). A Bell inequality between those receivers was violated by more than 4 standard deviations confirming the quality of the entanglement:

$$S = |E(\phi_A, \phi_B) - E(\phi_A, \hat{\phi}_B) + E(\hat{\phi}_A, \phi_B) + E(\hat{\phi}_A, \hat{\phi}_B) \leq 2$$

where S is the "Bell parameter" and E the two photon visibility when polarizers are set to ϕ or $\hat{\phi}$ at receiver A or B. In this experiment, the setup for the source generating the entangled photon pairs has been miniaturized to fit on a small optical breadboard and it could easily be operated completely independent from an ideal laboratory environment.

Obviously, terrestrial free-space links are limited to rather short distances because they suffer from possible obstruction of objects in the line of sight, from atmospheric attenuation and, eventually, from the Earth's curvature. To fully exploit the advantages of free-space links, it will eventually be necessary to use space and satellite technology. By transmitting and/or receiving either photons or entangled photon pairs to and/or from a satellite, entanglement can be distributed over truly large distances. This would allow quantum communication applications on a global scale. From a fundamental point of view, satellite-based distribution of quantum entanglement is also the first step towards exploiting quantum correlations on a scale larger by orders of magnitude than achievable in laboratory and even