4. N.H. Bonadeo *et al.*, "Coherent optical control of the quantum state of a single quantum dot," Science (in press).
5. A. Barenco *et al.*, "Conditional quantum dynamics logic gates," Phys. Rev. Lett. **74**, 4083 (1995).

Quantum Correlation Over More Than 10 km

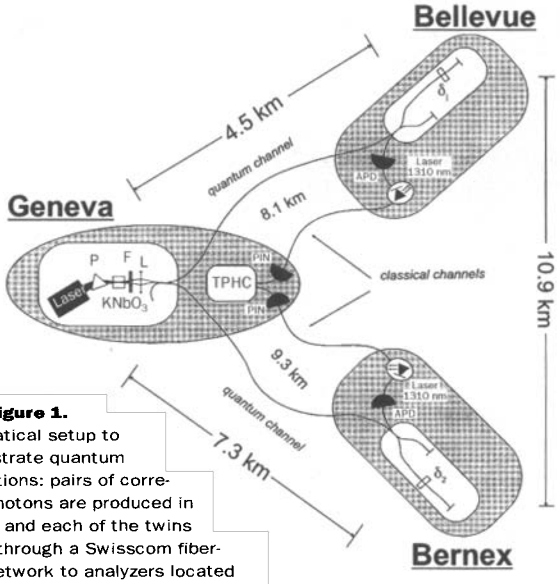
N. Gisin, J. Brendel, W. Tittel, and H. Zbinden, Group of Applied Physics, Univ. of Geneva, Geneva, Switzerland.

We live in a quantum world—something physicists have considered with amazement for more than 70 years. But we now realize that quantum physics is more than a radical departure from classical physics. It also offers many new possibilities for information processing.

In particular, quantum theory is nonlocal: it predicts entanglement between distant systems leading to correlations that cannot be explained by any theory based only on local variables,[1] as demonstrated by Bell inequality. All experiments are in remarkable agreement with quantum theory. Hence, the physics community faces a very strange worldview: in theory, everything is entangled, but, in practice, decoherence makes it impossible to reveal this entanglement. In addition to its "experimental metaphysics" aspects,[2] quantum entanglement has recently gained much interest and respect because it is at the heart of quantum information processing. The general idea is that entanglement provides means to carry out tasks that are either impossible classically (quantum cryptography) or that would require significantly more steps to perform on a classical computer (searching a database, factorization).[3]

But, how robust is quantum entanglement? How long can one maintain it under control? Over what distances? Can one really exploit it? A step toward answering these questions is provided by an experiment carried out in Geneva,[4] using the fiber optics network of Swisscom. Two IR photons (1310 nm) entangled in energy and time are produced by spontaneous parametric downconversion in a nonlinear crystal ($KNbO_3$) pumped by a 10-mW single-mode laser diode. Energy-time entanglement can be understood as follows.[5] First, thanks to the long coherence time of the pump laser, the time at which the two photons are created is affected by quantum uncertainty, but the two photons are created at exactly the same time. Next, the energy (wavelength) of each photon is uncertain by 45 nm, but the sum of the two energies is well defined and equals that of the pump.

The two photons are sent through optical fibers to two nearby villages separated by more than 10 km (see Fig. 1). There, energy and time measurements are performed. First, the photons pass two identically imbalanced Michelson interferometers (sensitive to wavelength: energy measurement). The arm length difference of both interferometers is much larger than the coherence length of the individual photons, hence, no single photon interferences occur. Next, the photons are detected in coincidence (time measurement) by germanium avalanche photodiodes in Geiger mode. A coincidence may be obtained through two alternative paths: both photons could pass through the short arm of their interferometers, or both through the long arms. These two alternatives being indistinguishable, one should add the probability amplitudes. The coincidence rate thus depends on the phases of both interferometers: it is affected by changing the phase in either interferometer. Scanning these phases produces 2-photon fringe visibilities of up to 95.5%, yielding clear violations of Bell inequalities. Accordingly, we conclude that entanglement is robust enough to manifest itself in the violation of Bell inequality by 2 photons separated by more than 10 km.



Gisin Figure 1. Schematical setup to demonstrate quantum correlations: pairs of correlated photons are produced in Geneva and each of the twins routed through a Swisscom fiber-optic network to analyzers located in the villages of Bernex and Bellevue, respectively. The results of the measurements are retransmitted to Geneva, revealing the nonlocal quantum correlations.

References

1. J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge Univ., Cambridge, U.K., 1997).
2. *Experimental Metaphysics*, R.S. Cohen *et al.*, eds. (Kluwer Acad. Pub., Dordrecht, The Netherlands, 1997).
3. See *e.g.*, the March issue of Phys. World (1998).
4. W. Tittel *et al.*, "Experimental demonstration of quantum correlations over more than 10 km," Phys. Rev. A **57**, 3229 (1998); W. Tittel *et al.*, "Violation of Bell inequalities by photons more than 10 km apart," Phys. Rev. A **81**, 3563 (1998).
5. J.D. Franson, "Bell inequality for position and time," Phys. Rev. Lett. **62**, 2205 (1989).

RF Coupled Optical Gain in a Solid Owing to Quantum Interference

Byoung S. Ham and Selim M. Shahriar, Research Lab. of, Electronics, MIT, Cambridge, MA; Philip R. Hemmer, Air Force Research Laboratory, Hanscom AFB, MA.

The interaction of a strong resonant laser field with two levels in a three-level system can modify the absorption and refractive index of a probe field whose transition involves the third level. Particularly, the probe field is not absorbed at line center due to two-photon coherence and destructive quantum interference, so that an optically thick medium can become transparent. This is called electromagnetically induced transparency (EIT).[1]

EIT has been studied extensively using atomic vapors