ing that (for a given distance) the set of periodic PI WFs is associated with rational numbers, while the set of aperiodic PI WFs is associated with irrational numbers.

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QUANTUM OPTICS

Coherent Optical Control of the Quantum State of a Single Quantum Dot

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Semiconductor quantum dots are nano-scale 3-D semiconductor heterostructures characterized by dimensions that are comparable to electronic scale lengths. In the case of excitons in GaAs this corresponds to tens of nanometers. The recent developments in nano-optical probing have resulted in the observation of many electronic and optical properties of these structures, which show great similarity to simple atomic systems including sharp line spectra and relatively simple nonlinear optical signatures.[1] Using these "solid-state atoms," we have shown that we can extend the concepts of coherent control and wave function engineering developed in atomic/molecular systems[2] and higher dimensional semiconductor structures[3] to the limit of a single quantum system in a zero-dimensional quantum dot.[4] Such proposals have been envisioned for implementation of various schemes for quantum computation and coherent information processing and transfer, in which it is important to address and coherently control individual quantum units.[5]

The excitonic wave function is manipulated and monitored on a time scale short compared to the loss of quantum coherence by controlling the optical phase of two picosecond pulses through timing and polarization. An exciton in an isolated QD is probed by exciting through a 500-nm diameter Al aperture. The photoluminescence (PL) and photoluminescence excitation (PLE) spectra exhibit atomic-like spectra (see Fig. 1a).

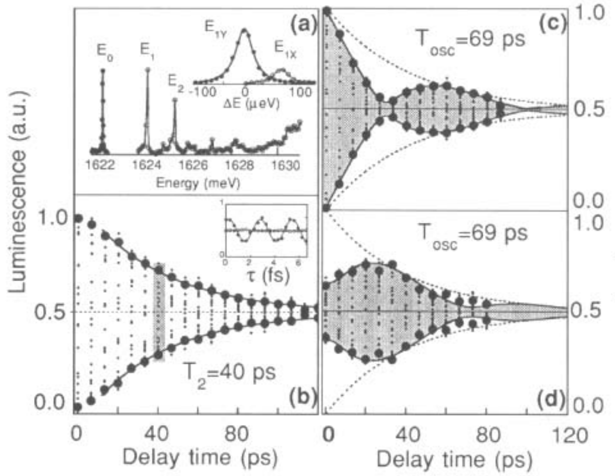
The experiments concentrated on the $|E_1\rangle$ state that shows a linewidth of 17 μeV and a fine structure splitting of 60 μeV (see Fig. 1a, inset). We probed the state of the system by monitoring the luminescence from $|E_0\rangle$. Figure 1b shows the luminescence intensity as a function of the delay time between the phase-locked pulses (Y-polarized) and represents the autocorrelation function of the excitonic wavefunction corresponding to state $|E_{1Y}\rangle$. The exponential decay arises from the loss of coherence. Even more interesting is the behavior shown in Figure 1c when a non-stationary wavefunction composed of a coherent superposition of $|E_{1X}\rangle$ and $|E_{1Y}\rangle$ states was created and measured by a pulse sequence polarized at 45°. The autocorrelation shows the wavefunction oscillating between two orthogonal states, $|E_{1X}\rangle + |E_{1Y}\rangle$ and $|E_{1X}\rangle - |E_{1Y}\rangle$. The oscillation period corresponds to the inverse of the difference frequency between the two optical transitions.

In the third experiment we created a superposition of the states that had a π shift in the quantum phase with respect to the reference wavefunction (see Fig. 1d). This is accomplished by polarizing the first beam –45° and the second beam at +45°.

The measurements show coherent optical control of the quantum state of a single dot and the feasibility of generating a simple target wave function. This work establishes the basic tools for developing more sophisticated control and creating a more complex wave function as achieved in atomic systems.

Acknowledgments

This work was supported by ARO, AFOSR, ONR, and NSF (Center for Ultrafast Optical Science).



Bonadeo Figure 1. (a) PL (filled circles) and PLE (open circles) spectra of the $|E_0\rangle$ state. Inset: $|E_1\rangle$ fine structure shows the splitting of the $|E_{1X}\rangle$ and $|E_{1Y}\rangle$ states. (b) The amplitude of the oscillation in PL as a function of delay (large filled circles), for Y-polarized pulses. The quantum interferogram measures the autocorrelation function of the excited state wavefunction. The inset shows an expanded view around τ = 40 ps (corresponding to the shadowed region) showing the oscillations in PL on a femtosecond timescale. The large filled circles in the main figure are determined from a fit of the amplitude of the oscillations. (c) The auto-correlation function of the excited state wave function for both pulses co-polarized and rotated to equally excite both the $|E_{1X}\rangle$ and $|E_{1y}\rangle$ states. (d) The cross-correlation function between two excited state wave functions generated by orthogonally polarized optical pulses. The relative phase of the two superposition of states produced by each pulse differs by π.

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Quantum Correlation Over More Than 10 km

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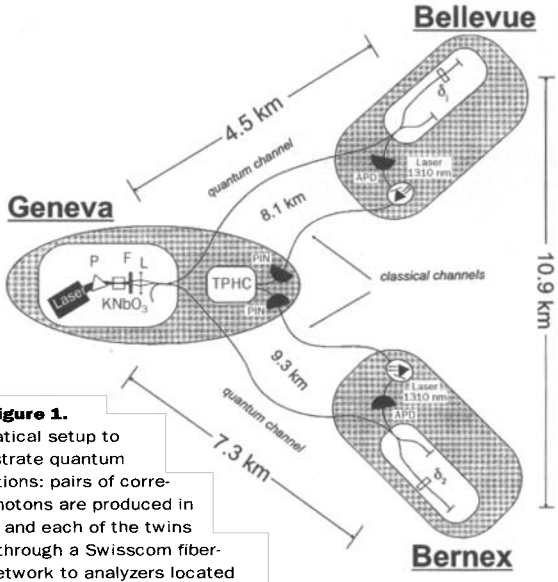
We live in a quantum world—something physicists have considered with amazement for more than 70 years. But we now realize that quantum physics is more than a radical departure from classical physics. It also offers many new possibilities for information processing.

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.

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RF Coupled Optical Gain in a Solid Owing to Quantum Interference

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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