and 1. When extended to many quantum bits, the parallelism of quantum superpositions allows speed to increase exponentially over classical computers in certain algorithms.[1] Cirac and Zoller[2] showed that a collection of trapped ions is well-suited for quantum computation. In their scheme, the quantum bits are represented by internal electronic levels that are "wired" together by virtue of their collective motion in the trap, and externally applied laser light entangles quantum bits and allows the construction of quantum logic gates.

We demonstrate a two-bit quantum controlled-NOT gate with a single $^9Be^+$ ion confined in a rf (Paul) trap.[3] The two quantum bits are represented by a vibration bit $|n\rangle$, spanned by the lowest two quantum harmonic oscillator states $|0\rangle$ and $|1\rangle$, and a spin bit $|S\rangle$, spanned by the F=2, $m_F=2(|\downarrow\rangle)$ and F=1, $m_F=1$ ($|\uparrow\rangle$) electronic hyperfine ground states. Following laser cooling to the $|S\rangle|n\rangle = |\downarrow\rangle|0\rangle$ vibrational ground state, pairs of laser beams are applied to the ion which drive two-photon stimulated Raman transitions between spin states and can entangle the spin and vibration bits. The controlled-NOT gate is realized by applying three appropriately tuned pulses of the Raman beams. These pulses flip the spin state ($|\downarrow\rangle \leftrightarrow |\uparrow\rangle$) if and only if the vibration bit is high ($|n\rangle = |1\rangle$), as depicted in the figure. We verify the controlled-NOT truth table by studying the evolution of several coherently prepared states as they propagate through the gate. The gate speed of 20 kHz is several times the observed decoherence rate, implying a loss of coherence after approximately 10 gates. Extended computations will require suppression of this decoherence, which will likely be dominated by relaxation of the motional degree of freedom.

To further our understanding of decoherence of motional superpositions, we have created an atomic "Schrödinger cat" state by preparing the $^9Be^+$ ion in a superposition of two widely separated locations.[4] Following cooling to the n=0 ground state, we create a superposition of spin states $|\uparrow\rangle$ and $|\downarrow\rangle$. The internal superposition is then transformed into a larger superposition of motional states by applying a resonant driving force with laser beams which effectively displaces the $|\uparrow\rangle$ component one direction and the $|\downarrow\rangle$ component in another direction. By interfering these two coherent state wavepackets, we are able to ascertain the maximum spatial separation ($\approx$ 84 nm, as opposed to the $\approx$ 7 nm rms size of each wavepacket) and the degree of coherence of the motional superposition.

Acknowledgments

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References

1. S. Lloyd, "Quantum-mechanical computers," Sci. Amer. **273**, 140 (1995); D. DiVincenzo, "Quantum computation," Science **270**, 255 (1995); A. Ekert and R. Jozsa, "Quantum computation and Shor's factoring algorithm," Rev. Mod. Phys. **68**, 733 (1996).
2. J. I. Cirac and P. Zoller, "Quantum computations with cold trapped ions," Phys. Rev. Lett. **74**, 4091 (1995).
3. C. Monroe *et al.*, "Demonstration of a fundamental quantum logic gate," Phys. Rev. Lett. **75**, 4714 (1995).
4. C. Monroe *et al.*, "A Schrödinger cat superposition state of an atom," Science **272**, 1131 (1996).

Polarization-entangled Photons and Quantum Dense Coding

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Entangled states of particles form the cornerstone of the newly emerging field of quantum information: they are central to tests of nonlocality, have been proposed for use in quantum cryptography schemes, and would arise automatically in the operation of quantum computers. Polarization-entangled photons are preferable because they are easier to handle. Unfortunately, until recently, no adequate source of polarization-entangled photons has been available. In Innsbruck, we have developed a down-conversion source of truly

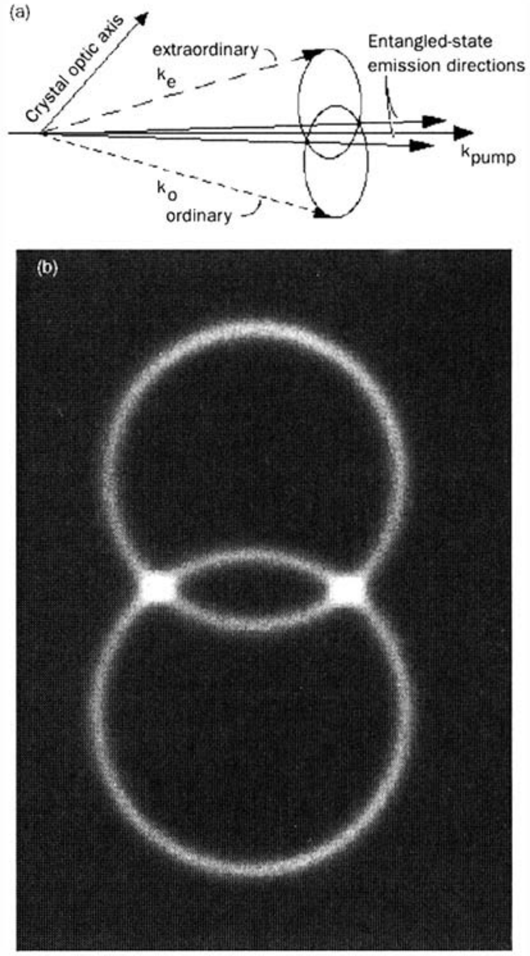

Figure 1. (a) Spontaneous down-conversion cones present with type-II phase-matching. Correlated photons lie on opposite sides of the pump beam. (b) Down-converted photons (from a BBO source), showing the overlap directions in which the polarization-entangled photons are emitted.

polarization-entangled photons, which is much brighter and more stable than all previous ones.[1] In type-II phase-matching, the correlated photons are emitted with orthogonal polarizations. In contrast to the more familiar case of type-I phase matching, the cones of the emitted light are not concentric with the pump beam direction. Instead, the cone of photons that are extraordinary-polarized inside the birefringent nonlinear crystal (BBO, in our experiments) lies predominately between the pump and the crystal optic axis, while the cone of the ordinary-polarized photons lies opposite (Fig. 1a). As a result, if the crystal is tilted slightly away from the collinear condition (where the two cones are tangent exactly along the pump beam direction), there arise two directions in which the photons belong to both the ordinary and the extraordinary cones (Fig. 1b).

The resulting quantum mechanical state is polarization-entangled. By adjusting appropriate waveplates in just one of the paths, we can prepare any of the four Bell states:

$$\left|\psi^{\pm}\right\rangle=\frac{1}{\sqrt{2}}\left\{\left|e_1,o_2\right\rangle\pm\left|o_1,e_2\right\rangle\right\};\left|\varphi^{\pm}\right\rangle=\frac{1}{\sqrt{2}}\left\{\left|o_1,o_2\right\rangle\pm\left|e_1,e_2\right\rangle\right\}$$

To characterize the source, polarization analyzers in each of the beams were used to measure the polarization correlations of the photons, allowing us to test Bell's inequalities. Assuming, as is customary, that the measured pairs were a fair sample of all pairs emitted, all of the states violated the Bell inequalities, in some cases by more than 100 standard deviations, and with the necessary statistics acquired in less than five minutes!

Remarkably, manipulation of only one photon is sufficient to change any of the four Bell states into any other one. The quantum dense coding scheme proposed by Bennett and Wiesner[2] is based on this quantum phenomenon. Thus, we could transmit more than 1 bit of information in a single two-state particle. A "sender" (Bob), with access to only one photon, transforms the two-photon state into one of the four Bell-states, then sends his photon to the "receiver" (Alice), who also has access to the correlated twin photon. By making a suitable joint measurement on the pair, Alice can determine which of the states Bob prepared.

To be able to discriminate all four of the Bell states, one needs a nonlinear interaction which is strong at the single-photon level. However, we have demonstrated that one can distinguish fairly easily three of the Bell states using an interferometric analyzer setup consisting solely of beam splitters and polarizers.[3] The increased channel capacity (ln23 = 1.58 bits per photon) was demonstrated by sending ASCII characters in 5 trits, instead of the usual 8 bits.

References

1. P. G. Kwiat *et al.*, "New high-intensity source of polarization-entangled photon pairs," Phys. Rev. Lett. **75**, 4337 (1995).
2. C. H. Bennett and S. J. Wiesner, "Communication via one-particle and two-particle operators on Einstein-Podolsky-Rosen States," Phys. Rev. Lett. **69**, 2881 (1992).
3. K. Mattle *et al.*, "Dense coding in experimental quantum communication," Phys. Rev. Lett. **76**, 4656 (1996).

Excitation of a Schrödinger Cat State Within an Atom

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Experiments in a number of laboratories over the past few years have explored the classical limit of a single atom.[1] In this limit, the electron wave function takes on the form of a spatially localized wave packet moving with the classical orbital period around a classical Keplerian orbit of near macroscopic dimensions. In various experiments the diameter of this orbit ranges from approximately 100 to 100,000 nm. The behavior of the atom, even in this limit, is quite rich, displaying a range of classical as well as distinctly quantum features.

A particularly intriguing area to be investigated concerning the classical limit of a quantum system is the behavior of Schrödinger cat states, *i.e.*, states in which the quantum system is in a coherent superposition of two macroscopically distinct quantum states. In a recent paper[2] we described an experiment in which the atomic electron is placed in a state that is a coherent superposition of being located on opposite sides of an elliptical orbit, a distance of separation of approximately 500 nm.

While this distance is more accurately described as mesoscopic rather than macroscopic, it is well outside the usual quantum mechanical domain, and the loca-

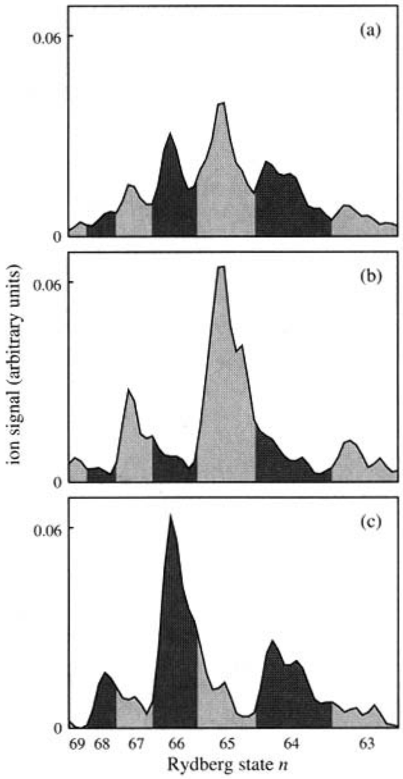

Figure 1. Energy level population distribution measured by state-selective ionization. The measured distributions are shown for cases in which: (a) only one wave packet is excited, (b) two wave packets have a π relative phase shift, (c) two wave packets have zero relative phase.