Entanglement of Four Atoms

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We have produced an entangled state of four atoms, in the form of a superposition of all four atoms in their ground state and all four atoms in their excited state [1]. The entanglement was engineered with a single pulse of laser light using a scheme proposed by Mlmer and Srensen [2]. Unlike previous sources of entanglement such as nonlinear photon down-conversion and thermal atomic beam cavity-QED, the technique is scalable in that it does not rely on random processes or selection procedures. Such deterministic entanglement is necessary for applications in large-scale quantum computing and quantum error-correction, and may also prove useful for precision spectroscopy and more stringent tests of quantum nonlocality.

Four beryllium ions are held in a linear rf-trap, laser-cooled to near their ground state of collective motion, and each optically-pumped to the —g¿ (F = 2, mF = -2) hyperfine ground state. By uniformly illuminating the ions with laser beams tuned red of the first lower motional sideband and blue of the first upper motional sideband, transitions are driven in from —g¿ to a second hyperfine ground state —e¿ (F = 1, mF = -1) on all pairs of ions. After these laser beams are applied for a certain time, the resulting state is —gggg¿ + —eeee¿. The coherence of the entangled superposition is measured by subsequently applying a p/2-pulse to each of the ions and measuring the populations as the phase of this second pulse is varied. The measured fidelity of the entangled state is 0.57, sufficient to show four-particle entanglement. Sources of decoherence which limit the fidelity will be discussed.

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[1] C.A. Sackett, D. Kielpinski, B.E. King, C. Langer, V. Meyer, C.J. Myatt, M. Rowe, Q.A. Turchette, W.M. Itano, D.J. Wineland, and C. Monroe, *Nature* **404** 256 (2000).

[2] K. Mølmer and A. Sørensen, *Phys. Rev. Lett.* **82** 1835 (1999).