

to the cavity, which greatly enhanced the coupling of the laser light to the cesium atoms by concentrating their radiative interactions along the cavity axis. "The cavity gave us, in effect, one-dimensional atoms," Kimble told us.

Serge Haroche, Jean-Michel Raimond and colleagues at the Ecole Normale Supérieure, in Paris, are doing related work in the microwave regime. They're experimenting with single Rydberg atoms interacting with very weak microwave fields in superconducting cavities. In 1994 they reported the observation of atomic wavefunction phase shifts due to microwave fields with, on average, much less than one photon in the cavity.⁴ "That dispersive-cavity QED experiment was already a demonstration of conditional dynamics at the single quantum level," Haroche contends, "at a time when logic gates were not yet fashionable in quantum optics. Whether such experiments should be heralded as first steps toward a large-scale quantum computer, which I consider an impossibility, is a matter of taste."

Caveat emptor

Rolf Landauer at IBM has long been the field's leading voice of caution.⁵ In addition to the much-discussed problem of decoherence, he stresses problems that arise from the fact that quantum computing is, in a sense, a return to old-fashioned analog computing. The coherent superposition states of a binary qubit form a continuum.

Whereas in digital computing you can always restore a slightly degraded bit to a pristine 0 or 1, the degradation of analog information is dangerously cumulative. It can quickly run an extended calculation off the rails. In quantum computing, Landauer points out, small but insidious errors arise particularly from the stringent requirements on the timing, amplitudes and classical phases of the perturbing radiative pulses that are supposed to flip the qubits.

Various error-correcting schemes have recently been put forward. But even if error accumulation proves to be a crippling limit on the number of sequential steps, the investigation of quantum computing still promises numerous rewards short of a general-purpose computer. Very few sequential steps are required, for example, in quantum communication schemes for cryptography or for EPR-type tests of the quantum theory itself. The Boulder group's work began with the idea of creating entangled quantum states to circumvent the shot-noise limit in spectroscopy.

The very notion of quantum computing makes a liberating contribution

to computer science. All attempts to state or prove theorems on the intrinsic computational complexity of a class of problems must now take into account what an idealized quantum computer could do.

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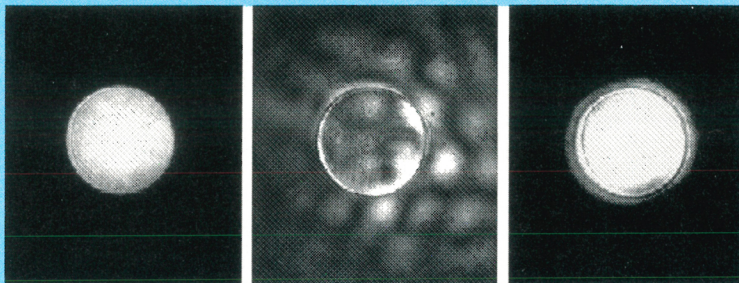
References

1. C. Monroe, D. Meekhof, B. King, W. Itano, D. Wineland, *Phys. Rev. Lett.* **75**,

4714 (1995).

2. Q. Turchette, C. Hood, W. Lange, H. Mabushi, H. J. Kimble, *Phys. Rev. Lett.* **75**, 4710 (1995).
3. J. I. Cirac, P. Zoller, *Phys. Rev. Lett.* **72**, 4091 (1994).
4. M. Brune, P. Nussenzveig, F. Schmidt-Kaler, F. Bernadot, A. Maali, J. Raimond, S. Haroche, *Phys. Rev. Lett.* **72**, 3339 (1994).
5. R. Landauer, *Philos. Trans. R. Soc. London, Ser. A* **353**, 367 (1995).

Quantum Interference Used to Eliminate Optical Problem



The series of images shown above depicts the onset of a problem in optical imaging (first two panels) and a solution to it (third panel). The panel on the left displays the undistorted image of a low-intensity laser beam that has passed through a circular aperture followed by a refracting medium.

In the middle panel the beam intensity is increased and the image breaks into many random spots. The culprit is the self-focusing that occurs within the refractive medium: As the laser intensity grows, the index of refraction increases quadratically, causing any regions of the beam that are more intense than others to develop refractive index gradients. Thus the local intensity maxima grow, and the beam becomes focused into narrow pencils, or filaments, within the original beam envelope. (A comparable phenomenon involving the defocusing of the beam can occur if the index of refraction decreases rather than increases with growing intensity.)

In the panel on the right, the problem has been corrected, even though the beam is just as intense as in the middle panel. The idea, reported recently by Maneesh Jain, Andrew Merriam, Athos Kasapi, Guang-Yu Yin and Stephen Harris at Stanford University, is to couple a second laser beam to the first within the refractive medium.¹ The coupling laser is then separated out and the probe beam is imaged.

The technique is simple enough, but its explanation is more complex, tied as it is to the quantum interaction among laser beams and atoms. Essentially, the combination of the two laser beams prevents the formation of an atomic dipole moment, which otherwise would contribute to the index of refraction of the material. The two laser beams trap a fixed portion of the atoms in a particular energy state and thereby freeze the dipole moment.

In the Stanford demonstration the refractive medium was a gas of three-level atoms (²⁰⁸Pb). A key requirement was that the frequency difference between the probe laser (at 283 nm) and the coupling laser (at 406 nm) must equal a Raman resonance of the atoms.

Previous work by Harris and his colleagues² has shown that quantum interference can make an optically thick medium become transparent to a certain wavelength of light (See *PHYSICS TODAY*, May 1992, page 17). Now, notes Jain, the Stanford group has shown that one can also use such interference effects to render a *refractively* thick medium transparent.

Harris warns that this technique is strictly for laboratory-scale applications, because the energy needed is proportional to the number of atoms along the beam path. Except in special cases, the linewidths in solids or liquids are too broad for this technique to work. But within these constraints, Harris sees many potential applications to devices such as nonlinear converters.

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References

1. M. Jain, A. J. Merriam, A. Kasapi, G. Y. Yin, S. E. Harris, *Phys. Rev. Lett.* **75**, 4385 (1995).
2. K. J. Boller, A. Imamoglu, S. E. Harris, *Phys. Rev. Lett.* **66**, 2593 (1991). A. Kasapi, M. Jain, G. Y. Yin, S. E. Harris, *Phys. Rev. Lett.* **74**, 2447 (1995).