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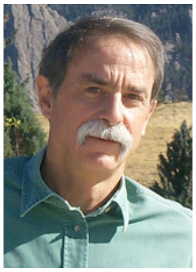
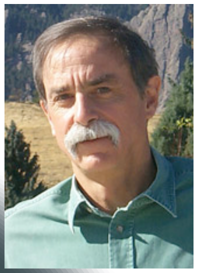
The Nobel Prize in Physics 2012
Serge Haroche, David J. Wineland

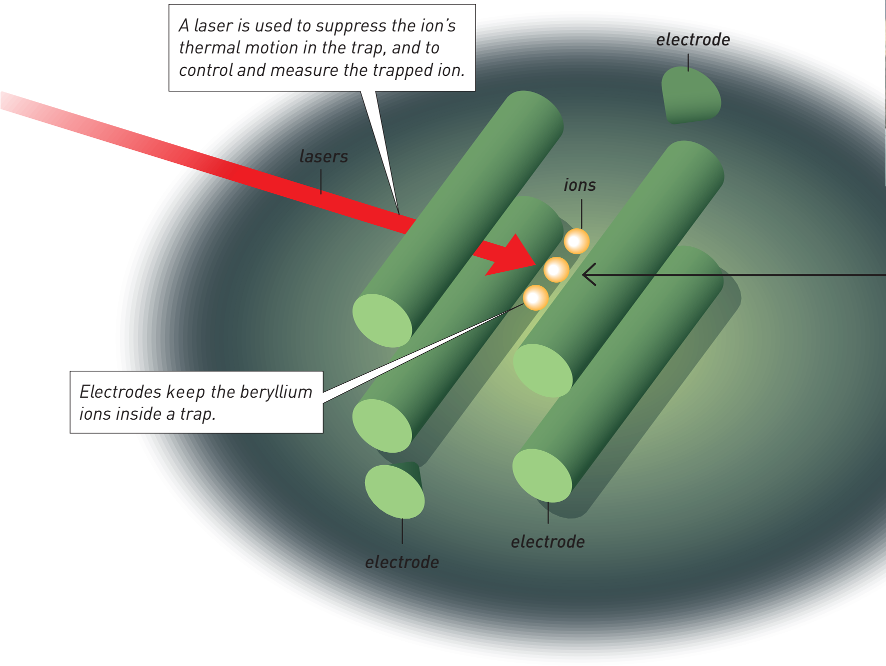
The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland *"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"*



David J. Wineland, U.S. citizen. Born 1944 in Milwaukee, WI, USA. Ph.D. 1970 from Harvard University, Cambridge, MA, USA. Group Leader and NIST Fellow at National Institute of Standards and Technology (NIST) and University of Colorado Boulder, CO, USA
www.nist.gov/pml/div688/grp10/index.cfm

Serge Haroche, French citizen. Born 1944 in Casablanca, Morocco. Ph.D. 1971 from Université Pierre et Marie Curie, Paris, France. Professor at Collège de France and Ecole Normale Supérieure, Paris, France.
www.college-de-france.fr/site/en-serge-haroche/biography.htm

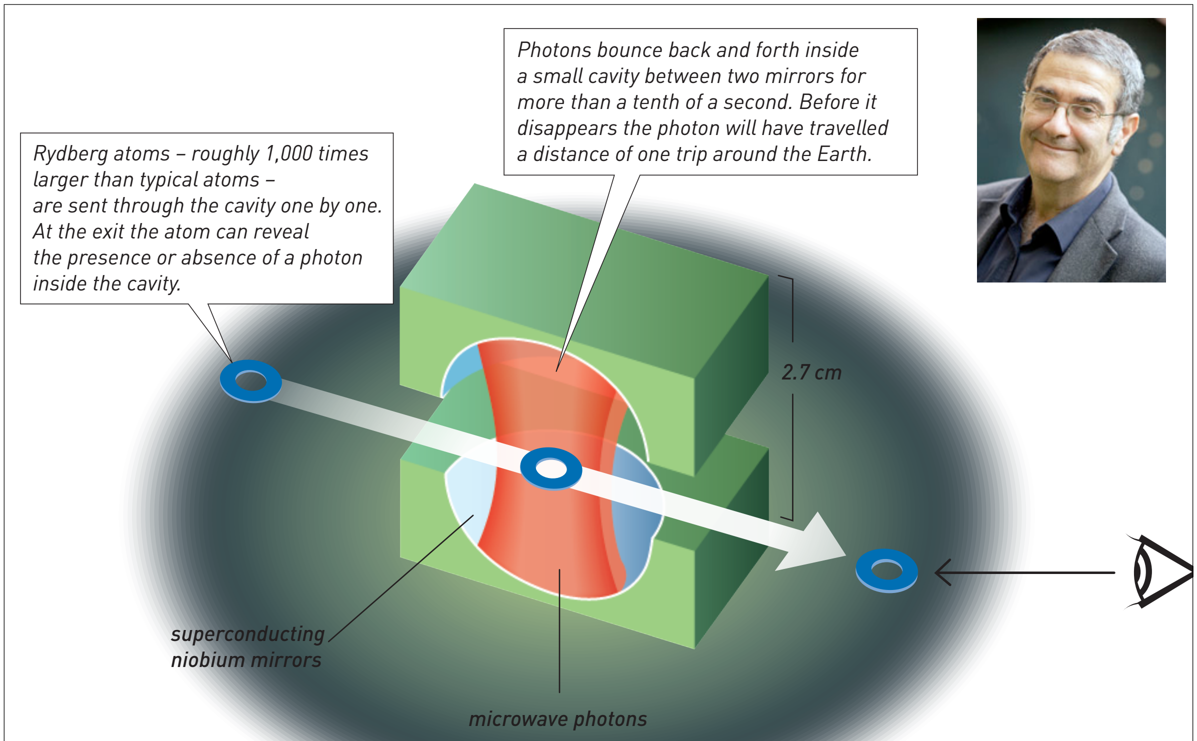




A laser is used to suppress the ion's thermal motion in the trap, and to control and measure the trapped ion.

Electrodes keep the beryllium ions inside a trap.

Figure 2. In David Wineland's laboratory in Boulder, Colorado, electrically charged atoms or ions are kept inside a trap by surrounding electric fields. One of the secrets behind Wineland's breakthrough is mastery of the art of using laser beams and creating laser pulses. A laser is used to put the ion in its lowest energy state and thus enabling the study of quantum phenomena with the trapped ion.



Rydberg atoms – roughly 1,000 times larger than typical atoms – are sent through the cavity one by one. At the exit the atom can reveal the presence or absence of a photon inside the cavity.

Photons bounce back and forth inside a small cavity between two mirrors for more than a tenth of a second. Before it disappears the photon will have travelled a distance of one trip around the Earth.

Figure 3. In the Serge Haroche laboratory in Paris, in vacuum and at a temperature of almost absolute zero, the microwave photons bounce back and forth inside a small cavity between two mirrors. The mirrors are so reflective that a single photon stays for more than a tenth of a second before it is lost. During its long life time, many quantum manipulations can be performed with the trapped photon without destroying it.

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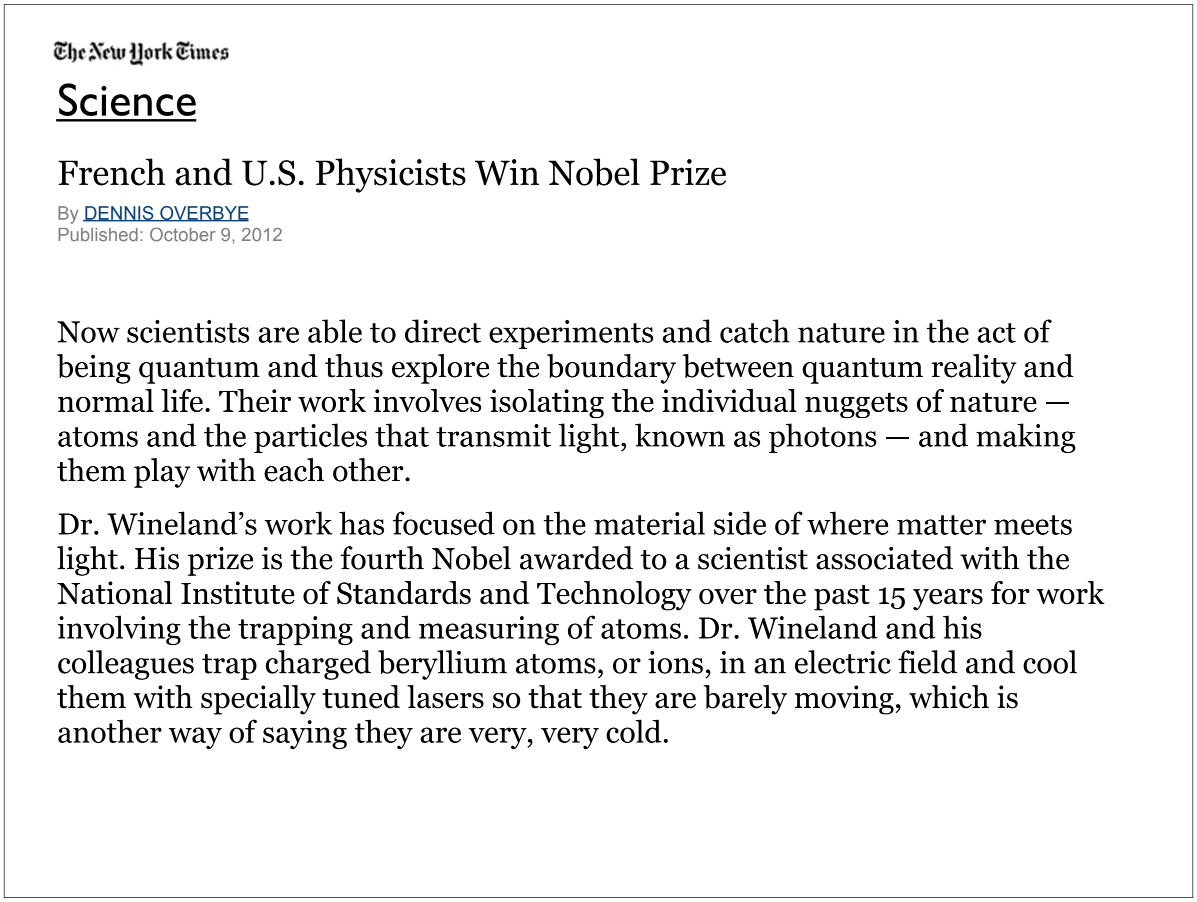

The New York Times

Science

French and U.S. Physicists Win Nobel Prize

By DENNIS OVERBYE
Published: October 9, 2012

Now scientists are able to direct experiments and catch nature in the act of being quantum and thus explore the boundary between quantum reality and normal life. Their work involves isolating the individual nuggets of nature — atoms and the particles that transmit light, known as photons — and making them play with each other.

Dr. Wineland's work has focused on the material side of where matter meets light. His prize is the fourth Nobel awarded to a scientist associated with the National Institute of Standards and Technology over the past 15 years for work involving the trapping and measuring of atoms. Dr. Wineland and his colleagues trap charged beryllium atoms, or ions, in an electric field and cool them with specially tuned lasers so that they are barely moving, which is another way of saying they are very, very cold.

PHYSICAL REVIEW A VOLUME 20, NUMBER 4 OCTOBER 1979

Laser cooling of atoms

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(Received 16 May 1979)

Various aspects of the laser cooling of atoms are investigated theoretically. More generally, the authors investigate a process through which the kinetic energy of a collection of resonant absorbers can be reduced by irradiating these absorbers with near-resonant electromagnetic radiation. The process is described here as anti-Stokes spontaneous Raman scattering. Cooling mechanisms, rates, and limits are discussed for both free and bound atoms.

B. Laser cooling of free atoms

Assume that we have an unbound gas of atoms (or resonant absorbers in general) which possess a resonant electric dipole transition (frequency, ν_0) in some convenient spectral region with radiative linewidth $\gamma/2\pi$ (full width at half-intensity points). Now suppose that we irradiate these atoms with monochromatic, directed, low intensity radiation tuned near, but slightly lower than, the resonance frequency. We assume that the in-

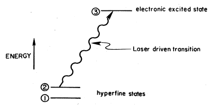


FIG. 1. Levels of interest in a hypothetical alkali-like atom. Optical pumping into state 1 occurs while driving the $2 \longleftrightarrow 3$ transition with a laser.

Those atoms of a particular velocity class moving against the radiation are Doppler shifted toward the resonant frequency ν_0 and scatter the incoming light at a higher rate than those atoms moving with the radiation which are Doppler shifted away from resonance. For each scattering event, the atom receives a momentum impulse $\hbar\vec{k}$ ($\vec{k}$ is the photon wave vector) in the absorption process. For an atom which is moving against the radiation, this impulse retards its motion. This retardation can also be described in terms of radiation pressure.[1,10] The average momentum per scattering event transferred to the atom by the reemitted photons is zero, because of the randomness of the photons' directions (if we neglect terms of second order in $|\vec{v}|/c$, where $\vec{v}$ is the atom velocity and c is the speed of light). The average net effect then is that the atomic velocity is changed by an amount $\Delta\vec{v} \cong \hbar\vec{k}/M$ per scattering event, where M is the atomic mass. When $\vec{v}$ and $\vec{k}$ are antiparallel, this leads to a net cooling, provided $|\vec{v}+\Delta\vec{v}| < |\vec{v}|$.[1] (See Fig. 2.) In a practical cooling experiment it would be desirable to irradiate the atoms from all sides with radiation that covered the entire lower half of the Doppler profile.[1] Alternatively, nar-

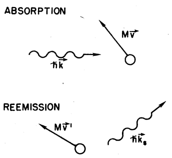
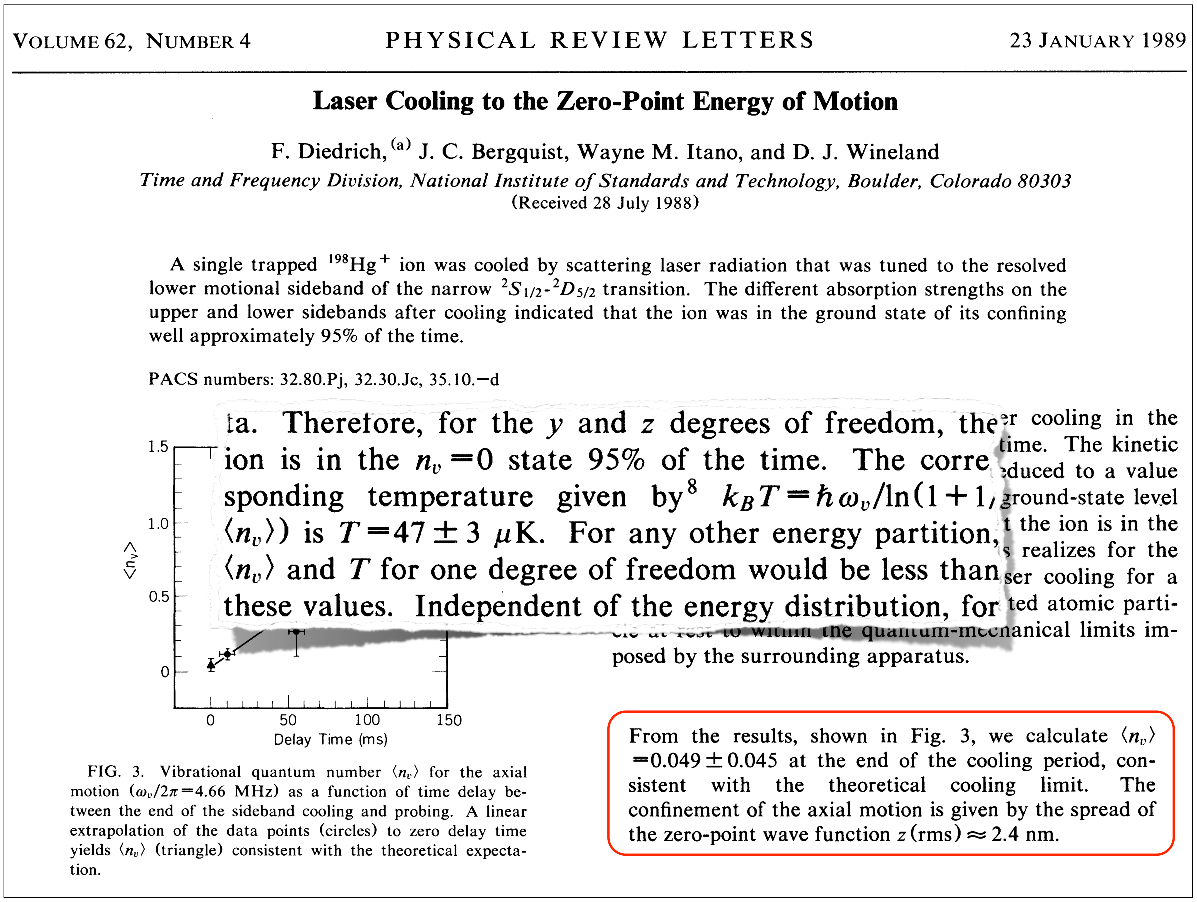


FIG. 2. Qualitative description of radiation-pressure cooling. In the absorption process, the atomic velocity is changed (reduced for $\vec{k}\cdot\vec{v} < 0$) by an amount $\Delta\vec{v} = \hbar\vec{k}/M$. In the reemission process, the average change in velocity is zero. Therefore in the overall scattering process, the kinetic energy can be reduced.



VOLUME 62, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1989

Laser Cooling to the Zero-Point Energy of Motion

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(Received 28 July 1988)

A single trapped $^{198}\mathrm{Hg}^+$ ion was cooled by scattering laser radiation that was tuned to the resolved lower motional sideband of the narrow $^2S_{1/2}$-$^2D_{5/2}$ transition. The different absorption strengths on the upper and lower sidebands after cooling indicated that the ion was in the ground state of its confining well approximately 95% of the time.

PACS numbers: 32.80.Pj, 32.30.Jc, 35.10.−d

ta. Therefore, for the y and z degrees of freedom, the ion is in the $n_v=0$ state 95% of the time. The corre sponding temperature given by[8] $k_BT=\hbar\omega_v/\ln(1+1$ $\langle n_v\rangle))$ is $T=47\pm3$ μK. For any other energy partition, $\langle n_v\rangle$ and T for one degree of freedom would be less than these values. Independent of the energy distribution, for

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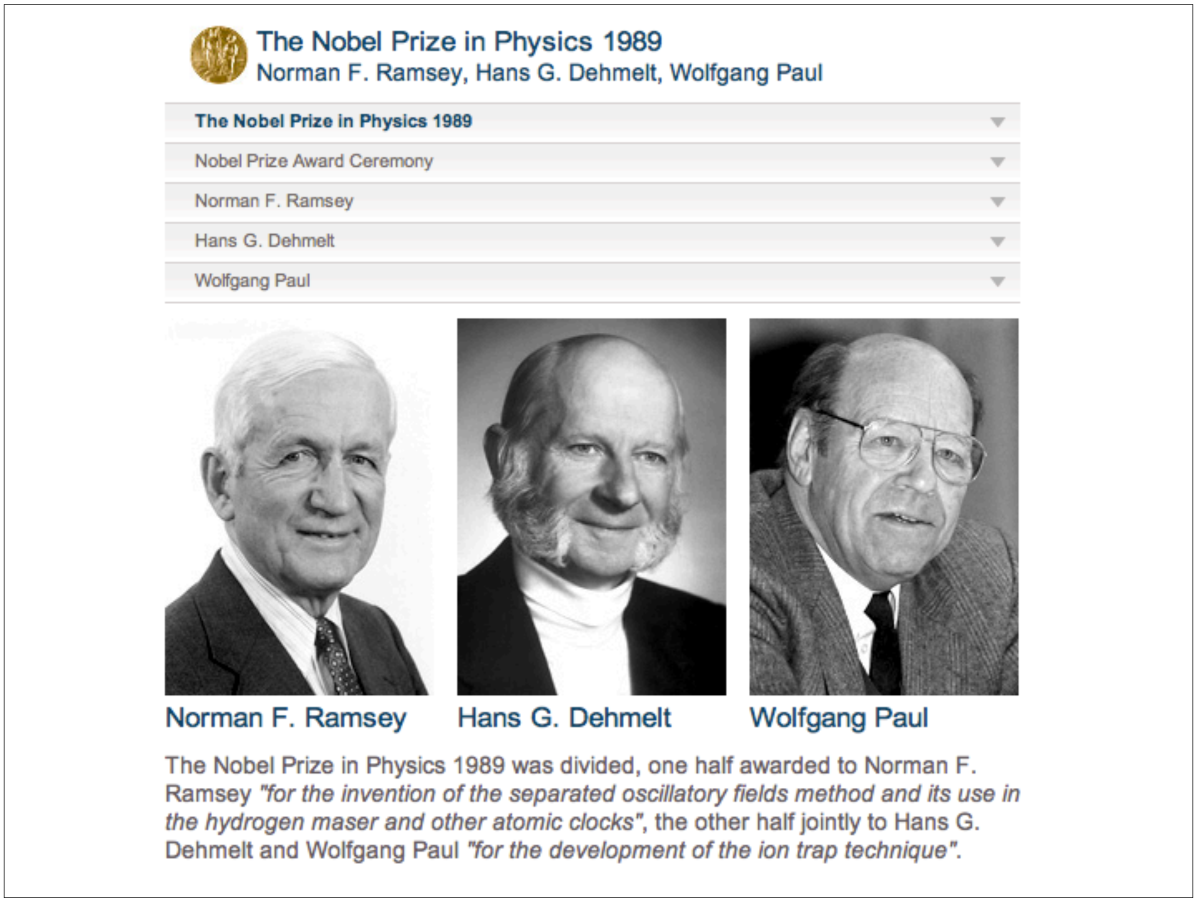
the quantum-mechanical limits imposed by the surrounding apparatus.

FIG. 3. Vibrational quantum number $\langle n_v\rangle$ for the axial motion ($\omega_v/2\pi=4.66$ MHz) as a function of time delay between the end of the sideband cooling and probing. A linear extrapolation of the data points (circles) to zero delay time yields $\langle n_v\rangle$ (triangle) consistent with the theoretical expectation.

From the results, shown in Fig. 3, we calculate $\langle n_v\rangle=0.049\pm0.045$ at the end of the cooling period, consistent with the theoretical cooling limit. The confinement of the axial motion is given by the spread of the zero-point wave function $z(\mathrm{rms})\approx2.4$ nm.



The Nobel Prize in Physics 1989

Norman F. Ramsey, Hans G. Dehmelt, Wolfgang Paul

Norman F. Ramsey Hans G. Dehmelt Wolfgang Paul

The Nobel Prize in Physics 1989 was divided, one half awarded to Norman F. Ramsey *"for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"*, the other half jointly to Hans G. Dehmelt and Wolfgang Paul *"for the development of the ion trap technique"*.

Electromagnetic traps for charged and neutral particles

Wolfgang Paul

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Experimental physics is the art of observing the structure of matter and of detecting the dynamic processes within it. But in order to understand the extremely complicated behavior of natural processes as an interplay of a few constituents governed by as few as possible fundamental forces and laws, one has to measure the properties of the relevant constituents and their interaction as precisely as possible. And as all processes in nature are interwoven, one must separate and study them individually. It is the skill of the experimentalist to carry out clear experiments in order to get answers to his questions undisturbed by undesired effects, and it is his ingenuity to improve the art of measuring to ever higher precision.

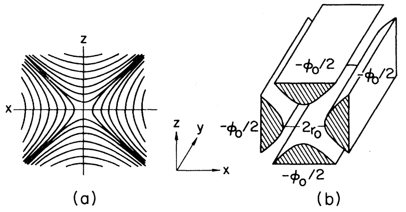


FIG. 1. (a) Equipotential lines for a plane quadrupole field. (b) The electrode structure for the mass filter.

Reviews of Modern Physics, Vol. 62, No. 3, July 1990

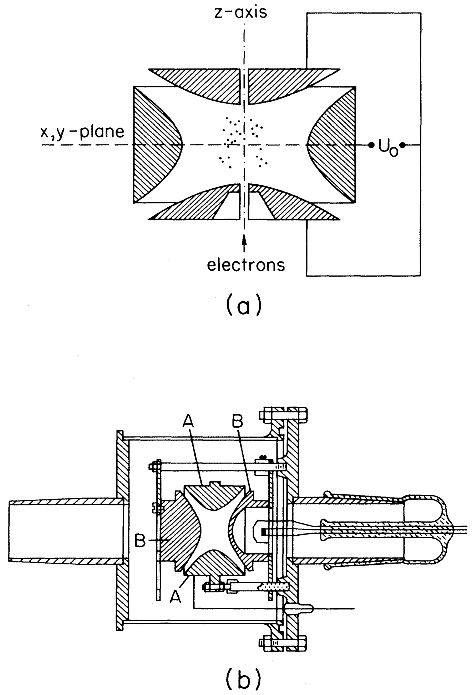
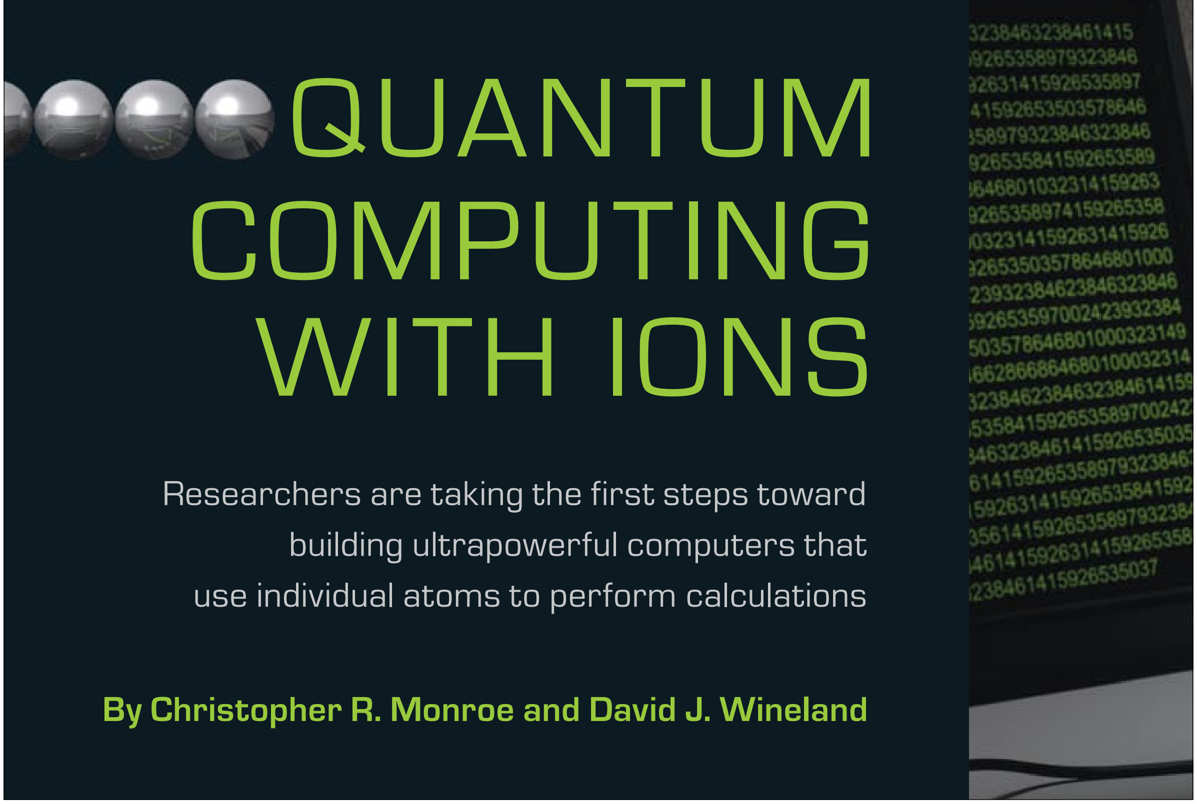


FIG. 6. (a) Schematic view of the ion trap. (b) Cross section of the first trap (1955).

Scientific American (August, 2008)



QUANTUM COMPUTING WITH IONS

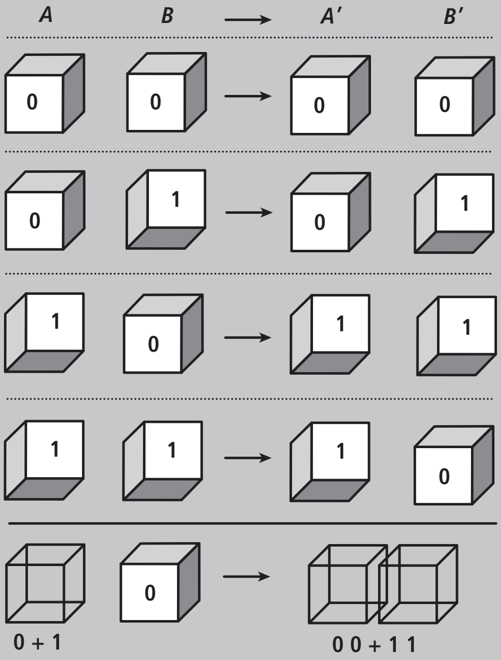
Researchers are taking the first steps toward
building ultrapowerful computers that
use individual atoms to perform calculations

By Christopher R. Monroe and David J. Wineland

[BASICS]

TRUTH TABLE

A trapped-ion computer would rely on logic gates such as the controlled not (CNOT) gate, which consists of two ions, *A* and *B*. This truth table shows that if *A* (the control bit) has a value of 0, the gate leaves *B* unchanged. But if *A* is 1, the gate flips *B*, changing its value from 0 to 1, and vice versa. And if *A* is in a superposition state (0 and 1 at the same time), the gate puts the two ions in an entangled superposition. (Their state is now identical to the one shown in the box on the bottom of the opposite page.)



POWERS OF TWO

The enormous potential of trapped-ion computers lies in the fact that a system with *N* ions can hold 2^N numbers simultaneously. And as *N* increases, the value of 2^N rises exponentially.

$2^5 = 32$

$2^{10} = 1{,}024$

$2^{50} = 1{,}125{,}899{,}906{,}842{,}624$

$2^{100} = 1{,}267{,}650{,}600{,}228{,}229{,}401{,}496{,}703{,}205{,}376$

Demonstration of a Fundamental Quantum Logic Gate

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(Received 14 July 1995)

We demonstrate the operation of a two-bit "controlled-NOT" quantum logic gate, which, in conjunction with simple single-bit operations, forms a universal quantum logic gate for quantum computation. The two quantum bits are stored in the internal and external degrees of freedom of a single trapped atom, which is first laser cooled to the zero-point energy. Decoherence effects are identified for the operation, and the possibility of extending the system to more qubits appears promising.

We report the first demonstration of a fundamental quantum logic gate that operates on prepared quantum states. Following the scheme proposed by Cirac and Zoller [1], we demonstrate a controlled-NOT gate on a pair of quantum bits (qubits). The two qubits comprise two internal (hyperfine) states and two external (quantized motional harmonic oscillator) states of a single trapped atom. Although this minimal system consists of only two qubits, it illustrates the basic operations necessary for, and the problems associated with, constructing a large scale quantum computer.

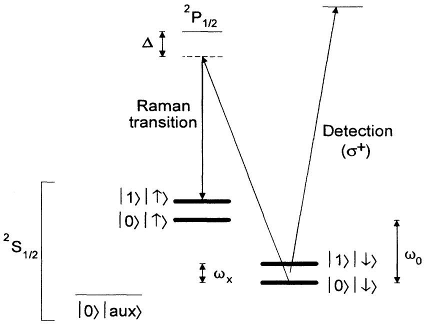
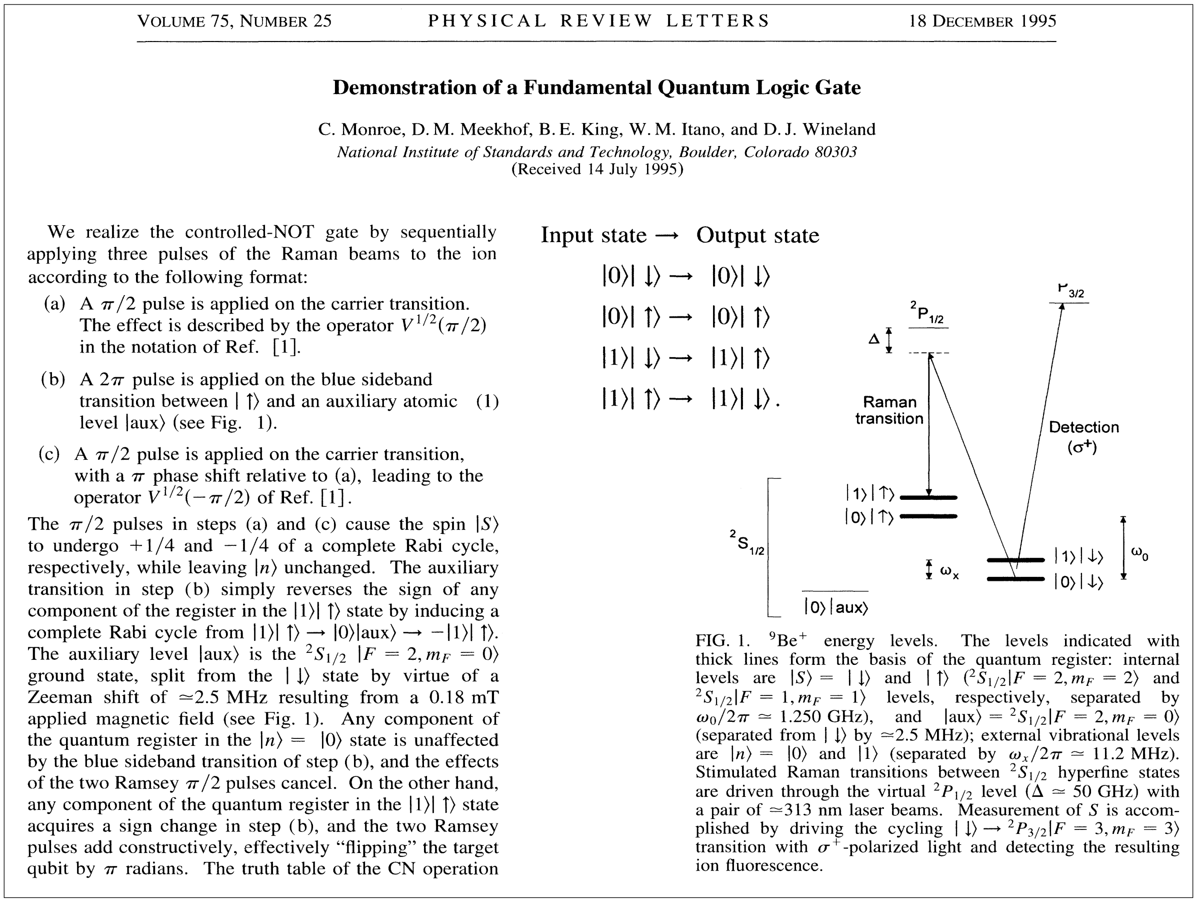


FIG. 1. ^{9}Be$^+$ energy levels. The levels indicated with thick lines form the basis of the quantum register: internal levels are $|S\rangle = |\downarrow\rangle$ and $|\uparrow\rangle$ ($^2S_{1/2}|F = 2, m_F = 2\rangle$ and $^2S_{1/2}|F = 1, m_F = 1\rangle$ levels, respectively, separated by $\omega_0/2\pi \simeq 1.250$ GHz), and $|\mathrm{aux}\rangle = {}^2S_{1/2}|F = 2, m_F = 0\rangle$ (separated from $|\downarrow\rangle$ by $\simeq$2.5 MHz); external vibrational levels are $|n\rangle = |0\rangle$ and $|1\rangle$ (separated by $\omega_x/2\pi \simeq 11.2$ MHz). Stimulated Raman transitions between $^2S_{1/2}$ hyperfine states are driven through the virtual $^2P_{1/2}$ level ($\Delta \simeq 50$ GHz) with a pair of $\simeq$313 nm laser beams. Measurement of S is accomplished by driving the cycling $|\downarrow\rangle \rightarrow {}^2P_{3/2}|F = 3, m_F = 3\rangle$ transition with σ^+-polarized light and detecting the resulting ion fluorescence.



VOLUME 75, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1995

Demonstration of a Fundamental Quantum Logic Gate

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(Received 14 July 1995)

We realize the controlled-NOT gate by sequentially applying three pulses of the Raman beams to the ion according to the following format:

(a) A $\pi/2$ pulse is applied on the carrier transition. The effect is described by the operator $V^{1/2}(\pi/2)$ in the notation of Ref. [1].

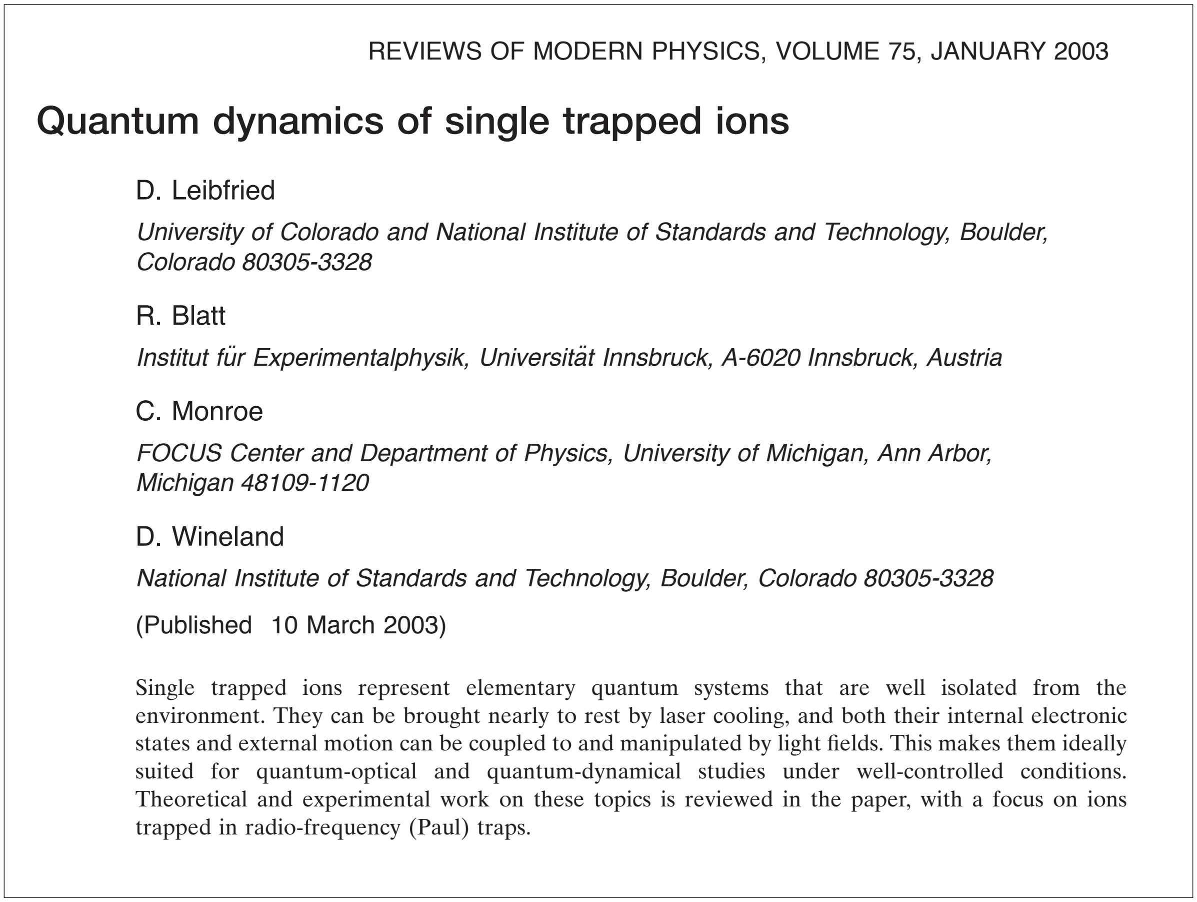
(b) A 2π pulse is applied on the blue sideband transition between $|\uparrow\rangle$ and an auxiliary atomic level $|\text{aux}\rangle$ (see Fig. 1).

(c) A $\pi/2$ pulse is applied on the carrier transition, with a π phase shift relative to (a), leading to the operator $V^{1/2}(-\pi/2)$ of Ref. [1].

The $\pi/2$ pulses in steps (a) and (c) cause the spin $|S\rangle$ to undergo $+1/4$ and $-1/4$ of a complete Rabi cycle, respectively, while leaving $|n\rangle$ unchanged. The auxiliary transition in step (b) simply reverses the sign of any component of the register in the $|1\rangle|\uparrow\rangle$ state by inducing a complete Rabi cycle from $|1\rangle|\uparrow\rangle \rightarrow |0\rangle|\text{aux}\rangle \rightarrow -|1\rangle|\uparrow\rangle$. The auxiliary level $|\text{aux}\rangle$ is the ${}^2S_{1/2}$ $|F=2, m_F=0\rangle$ ground state, split from the $|\downarrow\rangle$ state by virtue of a Zeeman shift of ≃2.5 MHz resulting from a 0.18 mT applied magnetic field (see Fig. 1). Any component of the quantum register in the $|n\rangle = |0\rangle$ state is unaffected by the blue sideband transition of step (b), and the effects of the two Ramsey $\pi/2$ pulses cancel. On the other hand, any component of the quantum register in the $|1\rangle|\uparrow\rangle$ state acquires a sign change in step (b), and the two Ramsey pulses add constructively, effectively "flipping" the target qubit by π radians. The truth table of the CN operation

$$\begin{array}{l}
\text{Input state} \rightarrow \text{Output state} \\
|0\rangle|\downarrow\rangle \rightarrow |0\rangle|\downarrow\rangle \\
|0\rangle|\uparrow\rangle \rightarrow |0\rangle|\uparrow\rangle \\
|1\rangle|\downarrow\rangle \rightarrow |1\rangle|\uparrow\rangle \\
|1\rangle|\uparrow\rangle \rightarrow |1\rangle|\downarrow\rangle .
\end{array} \tag{1}$$

FIG. 1. ${}^9\text{Be}^+$ energy levels. The levels indicated with thick lines form the basis of the quantum register: internal levels are $|S\rangle = |\downarrow\rangle$ and $|\uparrow\rangle$ (${}^2S_{1/2}|F=2, m_F=2\rangle$ and ${}^2S_{1/2}|F=1, m_F=1\rangle$ levels, respectively, separated by $\omega_0/2\pi \simeq 1.250$ GHz), and $|\text{aux}\rangle = {}^2S_{1/2}|F=2, m_F=0\rangle$ (separated from $|\downarrow\rangle$ by ≃2.5 MHz); external vibrational levels are $|n\rangle = |0\rangle$ and $|1\rangle$ (separated by $\omega_x/2\pi \simeq 11.2$ MHz). Stimulated Raman transitions between ${}^2S_{1/2}$ hyperfine states are driven through the virtual ${}^2P_{1/2}$ level ($\Delta \simeq 50$ GHz) with a pair of ≃313 nm laser beams. Measurement of S is accomplished by driving the cycling $|\downarrow\rangle \rightarrow {}^2P_{3/2}|F=3, m_F=3\rangle$ transition with σ^+-polarized light and detecting the resulting ion fluorescence.



REVIEWS OF MODERN PHYSICS, VOLUME 75, JANUARY 2003

Quantum dynamics of single trapped ions

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Single trapped ions represent elementary quantum systems that are well isolated from the environment. They can be brought nearly to rest by laser cooling, and both their internal electronic states and external motion can be coupled to and manipulated by light fields. This makes them ideally suited for quantum-optical and quantum-dynamical studies under well-controlled conditions. Theoretical and experimental work on these topics is reviewed in the paper, with a focus on ions trapped in radio-frequency (Paul) traps.

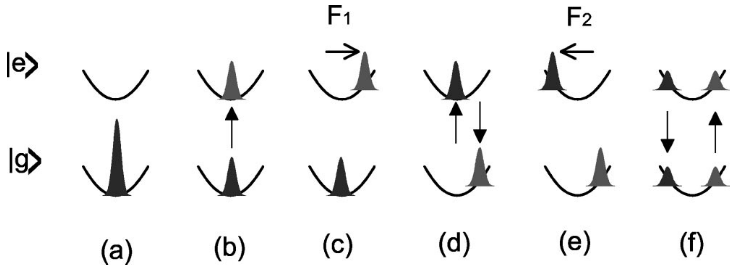

FIG. 15. Steps for creation of a Schrödinger-cat state (Monroe *et al.*, 1996). For detailed explanation, see text.

The evolving state of the system during the sequence is summarized in Fig. 15. Following (a) laser cooling to the $|g\rangle|n=0\rangle$ state, the Schrödinger-cat state was created by applying several sequential pulses of the Raman beams: (b) A $\pi/2$ pulse on the carrier transition split the wave function into an equal superposition of states $|g\rangle|0\rangle$ and $|e\rangle|0\rangle$. (c) The selective dipole force of the coherent displacement beams excited the motion correlated with the $|e\rangle$ component to a state $|\alpha\rangle$. (d) A π pulse on the carrier transition then swapped the internal states of the superposition. (e) Next, the displacement beams excited the motion correlated with the new $|e\rangle$ component to a second coherent state $|\alpha e^{i\phi}\rangle$. (f) A final $\pi/2$ pulse on the carrier combined the two coherent states. The relative phases [ϕ and the phases of steps (b), (d), and (f)] of the steps above were controlled by phase locking the rf sources that created the frequency splitting of the Raman or displacement beams, respectively.

The state created after step (e) is a superposition of two independent coherent states, each correlated with an internal state of the ion (for $\phi=\pi$),

$$|\Psi\rangle=\frac{|\alpha\rangle|e\rangle+|-\alpha\rangle|g\rangle}{\sqrt{2}}. \qquad (145)$$

In this state, the widely separated coherent states replace the classical notions of "dead" and "alive" in Schrödinger's original thought experiment. The coherence of this mesoscopic superposition was verified by recombining the coherent wave-packet components in the final step (f). This resulted in different degrees of

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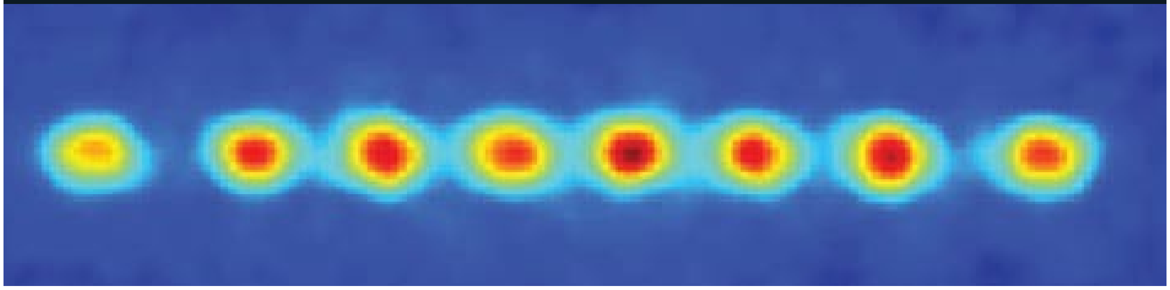
LEVITATED STRING **of eight calcium ions are confined in a vacuum chamber and laser-cooled to be nearly at rest. Such a string can perform quantum calculations.**



Ion Highways

But can researchers really make a full-fledged quantum computer out of trapped ions? Unfortunately, it appears that longer strings of ions—those containing more than about 20 qubits—would be nearly impossible to control because their many collective modes of common motion would interfere with one another. So scientists have begun to explore the idea of dividing the quantum hardware into manageable chunks, performing calculations with short chains of ions that could be shuttled from place to place on the quantum computer chip. Electric forces can move the ion strings without disturbing their internal states, hence preserving the data they carry. And researchers could entangle one string with another to transfer data and perform processing tasks that require the action of many logic gates. The resulting architecture would somewhat resemble the familiar charge-coupled device (CCD) used in digital cameras; just as a CCD can move electric charge across an array of capacitors, a quantum chip could propel strings of individual ions through a grid of linear traps.

Architecture for a large-scale ion-trap quantum computer

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Among the numerous types of architecture being explored for quantum computers are systems utilizing ion traps, in which quantum bits (qubits) are formed from the electronic states of trapped ions and coupled through the Coulomb interaction. Although the elementary requirements for quantum computation have been demonstrated in this system, there exist theoretical and technical obstacles to scaling up the approach to large numbers of qubits. Therefore, recent efforts have been concentrated on using quantum communication to link a number of small ion-trap quantum systems. Developing the array-based approach, we show how to achieve massively parallel gate operation in a large-scale quantum computer, based on techniques already demonstrated for manipulating small quantum registers. The use of decoherence-free subspaces significantly reduces decoherence during ion transport, and removes the requirement of clock synchronization between the interaction regions.

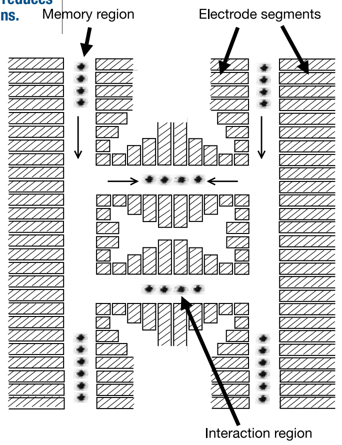

Figure 1 Diagram of the quantum charge-coupled device (QCCD). Ions are stored in the memory region and moved to the interaction region for logic operations. Thin arrows show transport and confinement along the local trap axis.