Cold atoms and quantum control

Steven Chu

Physics Department, Stanford University, Stanford, California 94305-4060, USA

This overview prefaces a collection of Insight review articles on the physics and applications of laser-cooled atoms. I will cast this work into a historical perspective in which laser cooling and trapping is seen as one of several research directions aimed at controlling the internal and external degrees of freedom of atoms and molecules.

On 10 December 2001, the most spectacular application of laser cooling and atom trapping was recognized on the 100th anniversary of the Nobel prize. The physics prize was awarded to Eric Cornell, Carl Wieman and Wolfgang Ketterle for the "achievement of Bose–Einstein condensation of alkali atoms and for the early fundamental studies of the properties of the condensates". The demonstration of Bose–Einstein condensation marked the fulfilment of a 70-year-old dream that began with a remarkable prediction of Albert Einstein, building on the calculations of Satyendra Nath Bose. They showed that a gas of atoms, when cooled to sufficiently low temperatures and high densities, would collapse into a single quantum state in which all of the physical properties used to describe each atom, such as its position and velocity, would be the same.

The achievement of Bose–Einstein condensation is one of the highlights of our ability to manipulate the position and velocity of atoms. This technology has led to a flurry of research activity where the pace of fundamental discoveries shows no signs of diminishing. A sample of recent scientific progress is reviewed in this collection of Insight articles, beginning with a review of Bose–Einstein condensation by Anglin and Ketterle on pages 211–218. The work discussed in the following pages can be viewed as an extension of our ability to control the quantum degrees of freedom of atoms. The control of these variables is linked to our ability to place atoms and photons into a well-defined set of quantum states and to manipulate these states coherently.

Control of the internal degrees of freedom of atoms

Radio-frequency techniques

The first step in the coherent control the quantum states of atoms and molecules began with I. I. Rabi, who introduced radio-frequency resonance techniques to molecular beams in 1938 (ref. 1). These methods formed the basis of precision molecular, atomic and nuclear spectroscopy and have served as a standard in the coherent control of atoms.

The outline of a typical apparatus used in the 1940s for atomic-beam resonance is shown in Fig. 1. It consists of a state-selection region, a radio-frequency resonance region and an analyser region. Radio-frequency radiation in the C region is used to excite an atom in an initial state $|a\rangle$ to a final state $|b\rangle$ by tuning the frequency to the atomic resonance, $\omega_{ab} = (E_a - E_b)/\hbar$, where E_a and E_b are the energies of the quantum states $|a\rangle$ and $|b\rangle$. In modern optical experiments, a laser replaces the radio-frequency source, optical pumping methods[2] are now the preferred method of preparing the initial internal state of the atoms, and fluorescence detection is used instead of the analysing B magnet.

It required four decades before laser methods could match the coherent phase control of the early radio-frequency measurements. There were three primary reasons why the optical control of atomic states lagged behind the radio-frequency and microwave work. First, radio- and microwave-frequency sources were far superior to visible-light sources. Second, the coherent interaction of radio and electric dipole microwave radiation with atoms is not plagued by the dephasing effects of spontaneous emission present in optical transitions. Third, radio-frequency transitions do not have complications arising from Doppler effects.

Radio-frequency radiation was relatively easy to generate because the essential components used to produce an oscillating circuit were made out of parts that were macroscopic in size. After Maxwell's prediction that visible light and heat were oscillating electric and magnetic fields that obeyed a wave equation, Heinrich Hertz turned to radio waves. It was the ability to generate and detect low-frequency radio waves with wave properties such as interference and refraction that made the dramatic connection between visible light and the time-varying fields studied by Michael Faraday.

Atomic clocks and the extension to the optical domain

In 1949, Norman Ramsey extended Rabi's atomic-beam resonance method by dividing the resonance region into two separated, oscillatory-field regions (ref. 3; and see Fig 2). In the first microwave cavity, atoms are excited into an equal superposition of ground and excited states. The atoms then travel through a radiation-free region with their magnetic moments rotating at the precession frequency $\omega_{ab} = (E_a - E_b)/\hbar$, and enter into a second excitation region. If the radiation in the second cavity is tuned to the atomic resonance and is exactly in phase with the radiation in the first cavity, the excitation is completed. After many ($\sim 10^6$) cycles of oscillation between the two zones of interaction, if the radiation is half a cycle out of phase with the precessing atom, the atom is returned to the ground state. This measurement, based on the quantum interference between two internal atomic states, was the first atom interferometer.

The frequency linewidth $\Delta\omega = \Delta E/\hbar$ of the atomic resonance in this type of microwave experiment is limited by the Heisenberg uncertainty principle, $\Delta E \Delta t \geq \hbar$, where Δt is the measurement time. Ramsey's invention allowed the measurement time to be increased by two-to-three orders of magnitude. This measurement technique produces an atomic clock of extraordinary precision and accuracy when the microwave oscillator is locked to the well-defined and reproducible atomic resonance frequency. With the advent of laser cooling, Ramsey's method could be used on an atomic fountain of atoms[4,5] that increased the measurement time by another two orders of magnitude. Atomic clocks

(Fig. 3) remain one of the most important applications of the coherent interaction of atoms with electromagnetic radiation.

Improvements in our ability to parse time into increasingly self-consistent and reproducible intervals (that is, the 'measurement of time') have been associated with our ability to count the passage of ever-shorter time intervals. In essence, faster oscillators make better clocks. The caesium atomic clock standard, oscillating 9,192,631,770 times a second, has an absolute uncertainty $\Delta\nu/\nu \sim 10^{-15}$. To improve this accuracy by several orders of magnitude, the Ramsey method must be extended to the optical domain.

In the microwave domain, it is straightforward to ensure that all the atoms in an experiment experience the same electromagnetic phase, as the dimensions $\lambda/2$ of the standing wave in the cavities are larger than the transverse spread of the atomic beam. However, if two optical standing waves are used, atoms with different transverse velocities can easily experience trajectories through the apparatus where the overall phase difference between the two Ramsey zones differs by half a cycle, as shown in Fig. 4. Solutions to this problem were found by moving to a geometry with three, separated standing-wave regions[6,7], the use of two-photon Doppler-free transitions[8], or the interaction with four successive running waves of light[9].

Initially, the atomic recoil due to the light was not considered, but in 1989, Christian Bordé[10] realized that the four-zone geometry[11,12] created an atom interferometer with spatially separated atomic paths. Thus, the direct extension of Ramsey's separated oscillatory-field method in the microwave regime to the optical domain led to spatially separated atom interferometers. Atom interferometers based on optical transitions (and also methods adapted from work using nuclear magnetic resonance) have led to precise and accurate measurements of gravity[13], gravity gradients[14], rotations[15] and the photon recoil of an atom[16].

There is one very important distinction between atom interferometers designed for atomic clocks and the atom interferometers developed to measure inertial effects or fundamental constants. Chebotayev, Bordé and their co-workers were motivated to look for a method that would allow them to stabilize a laser to a high-Q optical resonance, whereas the atom interferometers developed by Kasevich and Chu bypassed the requirement of an ultra-stable laser by using Raman transitions between two ground states of the atom[17]. The achieved resolution of these atom interferometers ($\sim 10^{-3}$ Hz out of a frequency shift of $\sim 10^{7}$ Hz) is determined by the frequency difference of the two laser beams used to excite the Raman transition. Because the two laser frequencies can be phase-locked to each other with radio-frequency methods, this configuration allowed complete phase control of the two-photon optical transitions.

Control of the external degrees of freedom of atoms

The development of atomic clocks is one example of the considerable work done in the past 50 years to extend the molecular-beam resonance methods and the closely related nuclear magnetic resonance methods into the optical domain. But physical processes exist that do not have counterparts in the radio or microwave region of the electromagnetic spectra, one example being the laser cooling of atoms.

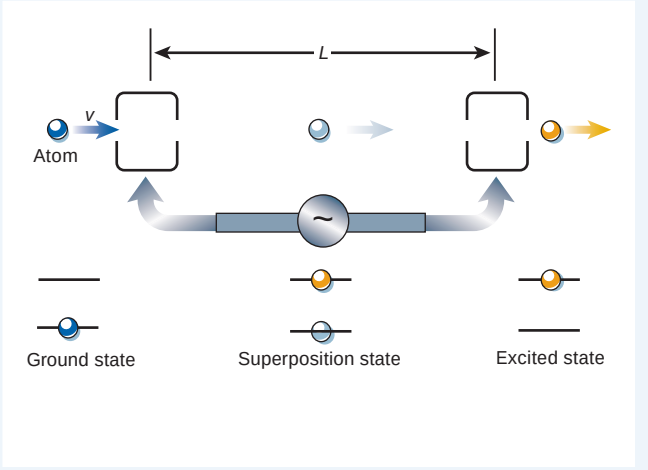

Figure 2 Ramsey's separated oscillatory-field method. The quantum measurement time $\Delta t = L/v$, where v is the velocity of the atom. If the microwave oscillator is tuned to the precise frequency of the atomic resonance, the excitation is completed. As the frequency of the microwave oscillator is varied slightly, the atomic population will oscillate between the ground and excited states, depending on the phase of the microwave radiation relative to the phase difference of the two atomic states.

Laser cooling was first demonstrated with ions confined in traps in 1978 (ref. 18). Subsequently, ion-cooling methods were improved to the point where a single ion could be cooled to the lowest vibrational energy level of the trap[19]. This capability then led to the creation of quantum states where the electronic and motional degrees of freedom of the ion became intimately connected and could no longer be factored into separate Hilbert spaces[20]. Much of the early progress in quantum computing (see review in this issue by Monroe, pages 238–246) came from the ability to coherently link and entangle these degrees of freedom. In contrast to ions, the laser cooling of neutral atoms[21–25] required two more decades to reach the zero-point limit.

Laser cooling requires the transfer of the entropy from the ensemble of atoms being cooled to the radiation field. All the demonstrated cooling methods use spontaneous scattering of radiation as the means of transferring this entropy; unfortunately, however, spontaneous emission also is a heating mechanism. At sufficiently high densities, cooling efficiency degrades owing to inelastic collisions that allow the transfer of energy from the internal to the external degrees of freedom. For that reason, the final stages of cooling used in Bose–Einstein condensation use evaporative cooling[26,27].

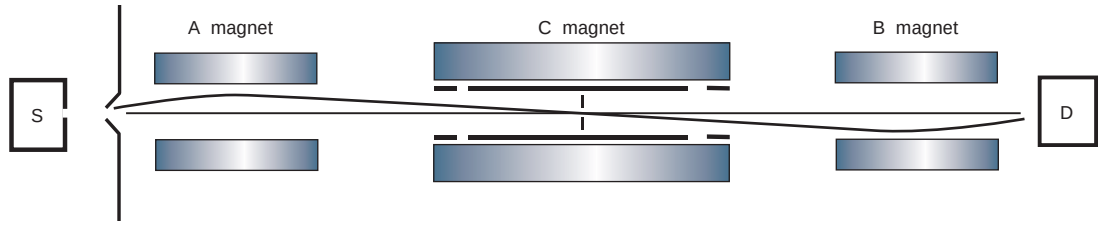

Figure 1 Traditional atomic-beam resonance apparatus. Atoms emerge from a source chamber S into a vacuum chamber and are sent through three regions of magnetic field. The first region consists of an inhomogeneous magnetic field that is used to deflect the atoms with a particular magnetic moment through a slit in the C region. The atoms drift through a C region consisting of a uniform-bias magnetic field and radio frequency coils, and then through a B region. In the absence of the B magnet, the atoms that pass through the slit will not reach the detector. However, with the proper choice of field gradient, the B magnet will focus atoms in a particular atomic state onto the detector, D.

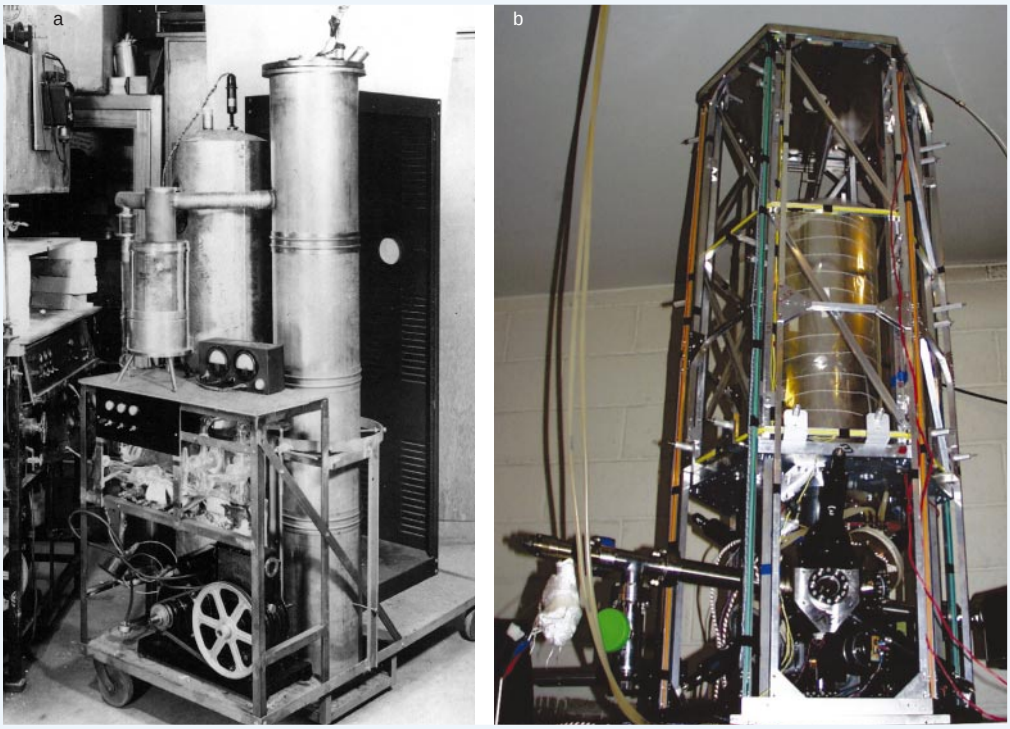

Figure 3 Atomic clocks. **a**, The first caesium atomic clock, built by Jerrold Zacharias in 1953. Zacharias also proposed a caesium clock using a fountain of atoms to test Einstein's prediction that a clock would slow down in raised in a gravitational potential. He failed to construct an atomic fountain, and although he never published his proposal, his attempt was passed down to two generations of physicists by word of mouth. (Photo: MIT Museum.) **b**, A rubidium atomic fountain clock built by the BNM-LPTF (Bureau National de Métrologie — Laboratoire Primaire du Temps et des Fréquences) and the Ecole Nomale Supérieure, Paris. The atoms are trapped and cooled in the lower part of the apparatus before being launched upwards to a height of ~ 1 metre. The estimated accuracy of this clock is 1 part in 10^{15}, or 7 minutes over a period of time equal to the age of the Universe (~14 billion years). (Photo: C. Solomon, ENS.)

Improved laser-cooling methods use spontaneous scattering in the initial stages of cooling, but once a particular atom is cooled, the interaction of that atom with light is suppressed. This elegant trick was introduced in the first laser sideband cooling scheme by Wineland and Dehmelt[28], and then repeated in many subsequent cooling schemes, such as velocity-selective coherent population trapping of neutral atoms[29], the Raman cooling of free atoms[30], Raman sideband cooling of atom in optical lattices[31], as well as in improved optical traps such as the 'dark' magneto-optic trap[32].

Control of spontaneous emission

Remarkably, the spontaneous emission properties of atoms can be altered significantly by placing them in an electromagnetic cavity[33]. The electromagnetic fluctuations of the quantum vacuum still have to obey Maxwell's equations, and if a high-Q microwave cavity is made to be out of resonance with radiation at an atomic transition, the quantum fluctuations that drive spontaneous emission are greatly reduced[34]. The suppression of spontaneous emission, first demonstrated with Rydberg atoms in 1983 (refs 35,36), was later extended to the optical regime with an ultra-high-finesse Fabry–Perot cavity that enhanced the probability of spontaneous emission into one mode of the cavity above the probability of spontaneous emission into all other competing vacuum modes[37].

The use of electromagnetic cavities is increasingly important in the coherent manipulation of both the internal and external states of atoms and their coupling to the radiation field. For example, a non-resonant cavity (but still one strongly coupled to the atomic transition) was used to mediate a resonant exchange collision. Here, an atom in state $|e_1\rangle$ and another atom in state $|g_2\rangle$ exchange two virtual photons to create an entangled state $|\Psi\rangle = \alpha|e_1,g_2\rangle + \beta|g_1,e_2\rangle$ (ref. 38). There are also several quantum computing proposals based on atomic and photonic quantum states entangled with an optical cavity, discussed by Monroe on pages 238–246.

A number of authors have discussed how an optical cavity can be used to laser cool atoms[39,40]. For example, Vuletić[41,42] has proposed cooling atoms with a non-resonant, two-photon scattering process by embedding atoms in three sets of counter-propagating laser beams tuned to the red wavelength side of a Fabry–Perot cavity fringe. Cooling is accomplished by causing the atoms to preferentially scatter blue-shifted light into a resonant cavity mode. Because this cooling process is determined by the cavity resonance, it applies to atoms or molecules with an arbitrary internal level structure.

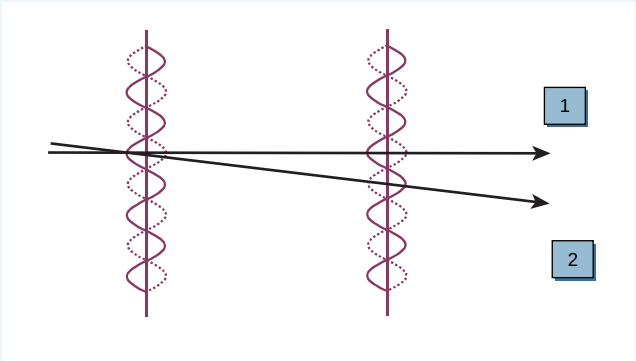

Figure 4 Two atomic trajectories are shown interacting with optical beams of light. In the transit time between the two Ramsey zones, atoms accumulate many cycles of optical phase. Atoms that move along trajectory 1 see a half-cycle phase difference in the number of accumulated cycles of phase relative to the atoms that move along trajectory 2. An average over the spread of transverse velocities in an atomic beam washes out the oscillations in atomic population that would have occurred if all the atoms had the same transverse velocity.

Control of optical frequencies

The control and measurement of optical sources of light are finally beginning to match and even exceed radio and microwave devices. The stability of laser sources is now starting to surpass the best microwave sources, and broadly tunable, optical-frequency synthesizers with a frequency resolution of one part in 10^{14} will soon be available commercially (T. W. Hänsch, personal communication; and see http://www.menlosystems.com for more information on this development). Given the remarkable developments that have occurred within the past few years, the frequency accuracy of an optical clock may reach an uncertainty of one part in 10^{18} within the next decade.

It is worth noting that this revolution in metrology benefited from a number of technological advances. First, the short-term stability of lasers is vastly improved by locking them to an ultra-stable Fabry–Perot cavity with electro- and/or acousto-optic devices[43]. Second, the high-Q reference cavities are fashioned out of mirrors with scattering and absorption losses of a few parts per million. Third, the long-term stability is supplied by ions confined in traps or neutral atoms in an atomic fountain. Fourth, we now have an elegant method to count directly the optical cycles of phase. This achievement, described in the review in this issue by Udem, Holzwarth and Hänsch on pages 233–237, launches us onto a new epoch in optical metrology by supplying the last critical component needed to make an absolute frequency measurement of light.

Control of collisions

Atomic collisions are generally thought to be messy, incoherent interactions, but the apparent incoherence is the result of our inability to keep track of the large number of degrees of freedom accessible in a typical study of collision. As pointed out Julienne and colleagues (see review in this issue on pages 225–232), all collisions are inherently coherent, as the scattering matrix is unitary.

When atoms are cooled to very low temperatures and large de Broglie wavelengths, atomic scattering is dominated by the lowest allowed angular momentum partial wave: s waves for bosons and p waves for spin-polarized fermions. With the number of collisional degrees of freedom severely reduced, it has become possible to understand the quantum mechanical collision effects with unmatched precision. For example, photo-association spectroscopy[44] and threshold resonance spectroscopy based on magnetically tunable (Feshbach) resonances[45–47] allow the measurement of collision parameters with an accuracy of up to five significant digits. In the case of caesium atoms, the agreement between theory and experiment is remarkable[48,49].

Because single ions and atoms can now be confined to the lowest lying quantum state of micro-traps, the spatial extent of the atoms becomes well defined and the duration and strength of collision interactions become controllable. A number of authors have pointed out the power of controlled cold collisions for creating entangled states for use in quantum information processing and spectroscopy[50–52]. In the near future, the creation of single-mode atom waveguides and the control of the number of interacting atoms through collision blockade effects or Fermi statistics may also be demonstrated. We are entering an era where (sometimes maligned) collisions will enable us to manipulate the internal and external degrees of freedom of atoms. Indeed, coherent, nonlinear collision interactions may become one of the most powerful tools for the creation of deeply entangled quantum states.

Control of atomic de Broglie waves

Atoms in a Bose–Einstein condensate can be described by the same wavefunction and the same phase, and when released out of the trap, they retain memory of their initial phase. With the proper coherent manipulation of the atoms, nonlinear interference experiments such as four-wave mixing and the creation of solitons have now been extended to atomic de Broglie waves[53–55]. These experiments are examples of the new field of nonlinear and quantum atom optics, which is covered in the review by Rolston and Phillips on pages 219–224 of this issue.

Atoms, however, are not like photons: they have mass and many more internal degrees of freedom. Consequently, nonlinear atom optics will not merely mirror phenomena already seen in the optical domain. Additionally, unlike photons that must interact with each other through a polarizable medium, atoms have strong, direct nonlinear interactions with each other. These interactions have already been used to create non-classical quantum states with number fluctuations well below the shot noise 'limit'[56].

One lure of nonlinear atom interactions is the possibility of creating massively entangled states of particles (or to establish non-local quantum correlations between particles) in two arms of an interferometer. Virtually all photon or atom interferometer experiments carried out so far are based on single-particle interference profoundly enunciated by Dirac 70 years ago: "Each photon interferes only with itself. Interference between two different photons never occurs."[57] As a result, the phase uncertainty of interferometers scales as $1/\sqrt{n}$, where n is the number of particles contributing to the interference. There are currently a number of proposals to generate deeply entangled, non-classical states[50] that may allow one to operate an interferometer in the Heisenberg limit where the phase noise scales as $1/n$ (refs 58,59).

Control of many-body and macroscopic wavefunctions

The attractiveness of a Bose–Einstein condensate of a dilute gas is that we have unparalleled control of its properties, together with powerful methods to measure those properties. Long-standing predictions in the weakly interacting domain can be tested for the first time, but that is not where the real excitement lies. Because of the great variation in atom–atom interaction strengths of alkali atoms, and because the s-wave scattering lengths can be tuned with a magnetic field from large positive to large negative values, experiments have been done[60] that previously could not have been contemplated. With suitable choice of scattering length, we can bridge the gap between a nearly non-interacting dilute gas and a strongly interacting quantum fluid.

More generally, these systems may allow us to study the transition between quantum properties of isolated atoms and the rich set of phenomena seen in many-body quantum systems. As a excellent example, a Bose–Einstein condensate embedded in an optical lattice has allowed us to observe a Mott insulator-to-superfluid quantum phase transition[61] in a clean system[62]. In a many-body system at zero temperature, this is characterized by a transition from an ordered solid with integer lattice occupancy to a superfluid, as the quantum coupling between lattice sites is increased relative to the potential well depth (for further details, see review in this issue by Anglin and Ketterle, pages 211–218). Future work may include the study of the effects of static disorder imposed by a stable speckle pattern (Anderson localization) and time varying disorder on this phase transition.

From the perspective of control, the phase transitions provided to us by nature are wonderfully opportune. Bose–Einstein condensation allows us to create large samples of well-ordered atoms long before the atoms are forced into a ground quantum state (where k_BT is much less than the energy-level separation between the ground and first excited states of the trapped atoms) by brute-force cooling. Similarly, the phase transition of the Mott insulator presents us with an entire lattice of (maximally squeezed) atom number states.

With Bose–Einstein condensates, degenerate Fermi gases[63] or an array of atom number states as a starting point, exciting applications are inevitable. Not surprisingly, these new research opportunities have stimulated many researchers to think about how to exercise further quantum control over still larger ensembles of atoms and photons, and how to exploit these systems in new ways. To quote Yogi Berra, the noted American philosopher and former catcher for the New York Yankees, "it is difficult to make predictions, especially about the future". Nevertheless, I predict that the most exciting developments are yet to come. □

1. Rabi, I. I., Zacharias, J. R., Millman, S. & Kusch, P. A new method of measuring nuclear magnetic moments. *Phys. Rev.* **53,** 318 (1938).
2. Kastler, A. in *Nobel Lectures in Physics, 1963-1970* 180–208 (World Scientific, Singapore, 1991).
3. Ramsey, N. F. A new molecular beam resonance method. *Phys. Rev.* **76,** 996 (1949).
4. Kasevich, M. A., Riis, E., Chu, S. & DeVoe, R. G. Rf spectroscopy in an atomic fountain. *Phys. Rev. Lett.* **63,** 612–615 (1989).
5. Laurent, P. *et al.* in *Laser Spectroscopy XIV* (eds Blatt, R., Escher J., Liebfried, D. & Schmidt-Kaler, F.) 41–50 (World Scientific, Singapore, 1999).
6. Baklanov, Ye. V., Dubetsky, B. Ya. & Chebotayev, V. P. Non-linear Ramsey resonance in the optical region. *Appl. Phys.* **9,** 171–173 (1976).
7. Chebotayev, V. P., Dubetsky, B. Ya., Kasantsev, A. P. & Yakolev, V. P. Interference of atoms in separated optical fields. *Opt. Soc. Am. B* **2,** 1791–1798 (1985).
8. Beausoleil, R. G. & Hänsch, T. W. Ultra-high resolution two-photon optical Ramsey spectroscopy of

an atomic fountain. *Phys. Rev. A* **33,** 1661–1670 (1986).
9. Bordé, C. R. On Ramsey fringes in spectroscopy without Doppler broadening. *C.J. Acad. Sci. Ser. B* **284,** 101–104 (1977).
10. Bordé, Ch. Atomic interferometry with internal state labeling. *Phys. Lett. A* **140,** 10–12 (1989).
11. Helmcke, J., Zevgolis, D. & Yen. B. Ü. Observation of high contrast ultra narrow optical Ramsey fringes in saturated absorption utilizing four interaction zones of traveling waves. *Appl. Phys. B* **28,** 83–84 (1988).
12. Salomon, Ch., Avillier, S., van Lerberghe, A. & Bordé, Ch. in *Laser Spectroscopy VI* (eds Weber, H. P., Lüthy, W.) 159–160 (Springer, Berlin, 1983).
13. Peters, A., Chung, K. Y. & Chu, S. High precision gravity measurements using atom interferometry. *Metrology* **38,** 25–61 (2001).
14. Sadden, M. J., McGrirk, J. M., Boiyer, P., Hariots, K. G. & Kasevich, M. A. Measurement of the Earth's gravity gradient with an atom interferometer-based gravity gradiometer. *Phys. Rev. Lett.* **81,** 971–974 (1998).
15. Gustavson, T. L., Boyer, P. & Kasevich, M. A. Precision rotation measurements with an atom interferometer gyroscope. *Phys. Rev. Lett.* **78,** 2046–2049 (1997).
16. Hensley, J., Wicht, A., Young, B. & Chu, S. in *Proc. 17th Int. Conf. Atomic Physics* (eds Arimondo, E., De Natale, P. & Inguscio, M.) 43–57 (Am. Inst. Phys., New York, 2000).
17. Kasevich, M. & Chu, S. Atomic interferometry using stimulated Raman transitions. *Phys. Rev. Lett.* **67,** 181 (1991).
18. Wineland, D. J., Drullinger, R. E. & Walls, F. L. Radiation-pressure cooling of bound resonant absorbers. *Phys. Rev. Lett.* **40,** 1639–1642 (1978).
19. Diedrich, F., Bergquist, J. C., Itano, W. M. & Wineland, D. J. Laser cooling to the zero-point energy of motion. *Phys. Rev. Lett.* **62,** 403–407 (1989).
20. Monroe, C., Meekhof, D. M., King, B. E., Itano, W. M. & Wineland, D. J. Demonstration of a universal quantum logic gate. *Phys. Rev. Lett.* **75,** 4714–4717 (1995).
21. Hänsch, T. W. & Schawlow, A. L. Cooling of gases by laser radiation. *Opt. Commun.* **13,** 68–70 (1975).
22. Wineland, D. J. & Itano, I. Laser cooling of atoms. *Phys. Rev. A* **20,** 1521–1540 (1979).
23. Gordon, J. P. & Ashkin, A. Motion of atoms in a radiation trap. *Phys. Rev. A* **21,** 1606–1617 (1980).
24. Letokov, V. S. & Minogin, V. G. Laser radiation pressure on free atoms. *Phys. Rep.* **73,** 1 (1981).
25. Chu, S., Cohen-Tannoudji, C. & Phillips, W. D. 1997 Nobel Lectures in physics. *Rev. Mod. Phys.* **70,** 685–706, 707–720,721–741 (1998).
26. Hess, H. F. Evaporative cooling of magnetically trapped and compressed spin-polarized hydrogen. *Phys. Rev. B* **34,** 3476–3479 (1986).
27. Mashara, N. *et al.* Evaporative cooling of spin-polarized hydrogen. *Phys. Rev. Lett.* **61,** 935–938 (1988).
28. Wineland, D. & Dehmelt, H. Proposed $10^{14}\,\Delta\nu < \nu$ laser fluorescence spectroscopy on Tl^+ mono-ion oscillator. *Bull. Am. Phys. Soc.* **20,** 637 (1975).
29. Aspect, A., Arimondo, E., Kaiser, R., Vansteenkiste, N. & Cohen-Tannoudji, C. Laser cooling below the one photon recoil by velocity selective coherent population trapping. *Phys. Rev. Lett.* **61,** 826–829 (1988).
30. Kasevich, M. & Chu, S. Laser cooling below a photon recoil with stimulated Raman transitions. *Phys. Rev. Lett.* **69,** 1741–1743 (1992).
31. Kerman, A. J., Vuletić, V., Chin, C. & Chu, S. Beyond optical molasses: 3D Raman sideband cooling of atomic cesium to high phase space density. *Phys. Rev. Lett.* **84,** 439–442 (2000).
32. Ketterle, W., Davis, K. B., Joffe, M. A., Martin, A.& Pritchard, D. E. High densities of cold atoms in a *dark* spontaneous force optical trap. *Phys. Rev. Lett.* **70,** 2253–2257 (1993).
33. Purcell, E. M. Spontaneous emission probabilities at radio frequencies. *Phys. Rev.* **69,** 681 (1946).
34. Kleppner, D. Inhibited spontaneous emission. *Phys. Rev. Lett.* **47,** 233–237 (1981).
35. Goy, P., Raimond, J. M., Gross, M. & Haroche, S. Observation of cavity enhanced single atom spontaneous emission. *Phys. Rev. Lett.* **50,** 1903–1907 (1983).
36. Hulet, R. G., Hilfer, E. S. & Kleppner, D. Inhibited spontaneous emission by a Rydberg atom. *Phys. Rev. Lett.* **55,** 2137–2140 (1985).
37. Berman, P. R. (ed.) *Cavity Quantum Electrodynamics* (Academic, San Diego, 1994).
38. Osnaghi, S. *et al.* Coherent control of an atomic collision in a cavity. *Phys. Rev. Lett.* **87,** 037902-1–037902-4 (2001).
39. Mossberg, T. W., Lewenstein, A. & Gauthier, D. J. Trapping and cooling of atoms in a vacuum perturbed in a frequency dependent manner. *Phys. Rev. Lett.* **67,** 1723–1726 (1991).
40. Gangl, M. & Ritsch, H. Cooling neutral particles in multimode cavities without spontaneous emission. *J. Mod. Opt.* **47,** 2741–2753 (2000).
41. Vuletić, V. & Chu, S. Laser cooling of atoms, ions, or molecules by coherent scattering. *Phys. Rev. Lett.* **84,** 3787–3790 (2000).
42. Vuletić, V., Chan, H. W. & Black, A. T. Three dimension cavity Doppler cooling and cavity sideband cooling by coherent scattering. *Phys. Rev. A* **64,** 033405-1–033405-7 (2001).
43. Young, B. C. *et al.* in *Laser Spectroscopy XIV* (eds Blatt, R., Eschner, J., Leibfried, D. & Schmidt-Kaler, F.) 61–70 (World Scientific, Singapore, 1999).
44. Stwalley, W. C. & Wang. H. Photoassociation of ultra-cold atoms: a new spectroscopic technique. *J. Mol. Spect.* **195,** 194–228 (1999).
45. Feshbach, H. A unified theory of nuclear reactions II. *Ann. Phys.* **19,** 287–313 (1962).
46. Tiesinga, E., Verhaar, B. J. & Stoof, H. T. C. Threshold and resonance phenomena in ultracold ground-state collisions. *Phys. Rev. A* **47,** 4144–4122 (1993).
47. Inouye, S. *et al.* Observation of Feshbach resonances in a Bose–Einstein condensate. *Nature* **392,** 151–154 (1998).
48. Chin, C., Vuletić, V., Kerman, A. J. & Chu, S. High resolution Feshbach spectroscopy of cesium. *Phys. Rev. Lett.* **85,** 2717–2720 (2000).
49. Leo, P. J., Williams, C. J. & Julienne, P. S. The collision properties of ultracold ^{133}Cs atoms. *Phys. Rev. Lett.* **85,** 2721–2724 (2000).
50. Jaksch, D., Briegel, H.-J., Cirac, J. I., Gardiner, C. W. & Zoller, P. Entanglement of atoms via cold controlled collisions. *Phys. Rev. Lett.* **82,** 1975–1978 (1999).
51. Sørenson, A. & Mølmer, K. Spin-spin interaction and spin squeezing in an optical lattice. *Phys. Rev. Lett.* **83,** 2274–2277 (1999).
52. Helmerson, K. & Li, Y. Creating massive entanglement of Bose-Einstein condensed atoms. *Phys. Rev. Lett.* **87,** 170402-1–170402-4 (2001).
53. Deng, L. *et al.* Four-wave mixing with matter waves. *Nature* **398,** 218–220 (1999).
54. Denschlag, J. *et al.* Generating solitons by phase engineering of a Bose-Einstein condensate. *Science* **287,** 97–100 (2000).
55. Burger, S. *et al.* Dark solitons in Bose-Einstein condensates. *Phys. Rev. Lett.* **83,** 5198–5201 (1999).
56. Orzel, C., Tuchman, A. K., Teseslau, M. L., Yasuda, M. & Kasevich, M. A. Squeezed states in a Bose-Einstein condensate. *Science* **291,** 2386–2389 (2001).
57. Dirac, P. A. M. *The Principles of Quantum Mechanics* 3rd edn, p. 9 (Oxford Univ. Press, Oxford, 1947).
58. Heitler, W. *The Quantum Theory of Radiation* 3rd edn (Oxford Univ. Press, Oxford, 1954).
59. Holland, M. J. & Burnett, K. Interferometric detection of optical phase shifts at the Heisenberg limit. *Phys. Rev. Lett.* **71,** 1355–1358 (1993).
60. Donley, E., Anderson, B. P. & Wieman, C. E. New twists in Bose-Einstein condensation. *Opt. Photon. News* Oct. issue, 34–37 (2001).
61. Fisher, M. P. A., Weichman, P. B., Grinstein, G. & Fisher, D. S. Boson localization and the superfluid-insulator transition. *Phys. Rev. B* **40,** 546–570 (1989).
62. Greiner, M., Mandel, O., Esslinger, T., Hänsch, T. W. & Bloch, I. Quantum phase transition form a superfluid to a Mott insulator in a gas of ultracold atoms. *Nature* **415,** 39–44 (2002).
63. DeMarco, B. & Jin, D. S. Onset of Fermi degeneracy in a trapped atomic gas. *Science* **285,** 1703–1706 (1999).

Acknowledgements
This work was supported in part by grants from the National Science Foundation, the Air Force Office of Scientific Research, the Department of the Navy and the National Reconnaissance Office.