received a further 0.1 to 0.4 ms pulse of cooling laser radiation. The method produces position-dependent cooling. With a strongly saturated transition, the atoms will spend about a half of their time in the upper energy state, radiating at a rate governed by their natural lifetime of about 16 ns. Thus their maximum deceleration would be about 10^6 m s^{-2}, which means that a sodium beam could be stopped in about 1 ms, after travelling a distance of about 0.5 m. The deceleration achieved by Prodan *et al.* was about half maximum.

The temperatures of the cooled atoms were monitored by the fluorescence produced by a weak laser beam crossing the atomic beam at a convenient angle. Ertmer *et al.* estimate that some 10^6 atoms per ml could be cooled to a velocity distribution whose width corresponds to a temperature of 50 mK (25 MHz half-width). The corresponding velocity spread obtained by Prodan *et al.* was equivalent to about 100 mK with a density of about 10^5 atoms per ml. For their subsequent successful trapping of some of their cooled atoms, Prodan and his colleagues used a trap comprised of two opposed coils (reminiscent of an opposed Helmholtz pair); the downstream coil is energized, once the atoms have drifted into the trap. The coils produce a field gradient of about 1 T m^{-1}, which reflects and traps atoms with an axial temperature of below 17 mK. The upstream coil provides a gradient field which is used in the final stage of laser coding once the atoms have entered the trapping region. The atoms then spread out to fill the 20 ml volume of the trap and some 10^4 atoms are trapped for about 0.83 s (the decay time). The next stage will be to attempt to use optical trappings to cool the atoms even further so that they are sufficiently at rest to dispense with the trap. Meantime many exciting experiments are in prospect.

Atomic frequency standards

To appreciate the possibilities of the new technique one has only to consider a paper of J. J. Bollinger *et al.* (*Phys. Rev. Lett.* **54**, 1000; 1985) in which the successful operation of an atomic frequency standard based on laser cooled ions is reported. Bollinger *et al.* trapped $^9Be^+$ ions in a Penning trap, whereby the ions were confined axially by a hyperbolic electrostatic potential distribution, and radially by the combined action of the electrostatic and magnetic fields. The ion motion comprised the cyclotron motion about the magnetic flux axis and the circular ($E \times B$) drift (or magnetron motion) each in the radial plane, together with the axial motion. Each may have a temperature associated with it. In the experiment described, the cyclotron and axial temperatures were less than 100 mK and the magnetron temperature less than 2 K (with the cooling laser on continuously). Some 2,000 ions were confined for many hours in the trap, with ion cloud diameters of 0.3 to 0.5 mm. The laser radiation was directed along the axis of the field and tuned to be slightly on the low frequency side of the absorption. The radiation not only cooled the axial motion but also coupled with the magnetron motion, and so could be used to compress (cool) the ion orbit.

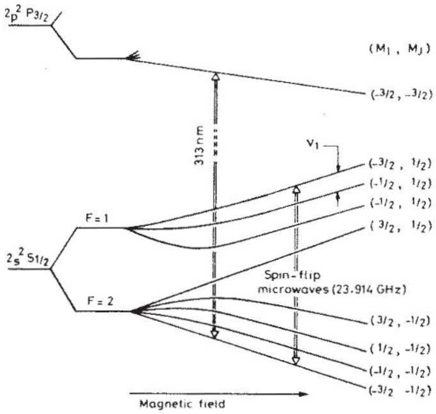

Fig. 2 The Zeeman splitting in a magnetic field, and the hyperfine structure of $^9Be^+$ showing the transition used for laser cooling by Bollinger *et al.* (not to scale).

Bollinger *et al.* report a measurement of the hyperfine ground-state transition frequency ν_1, at its magnetic-field independent point (0.8149 T), of 303 MHz with an estimated standard deviation uncertainty of only 57 μHz (see Fig. 2). The experiment involved triple resonance, requiring first, 20 μW of 313 nm radiation to excite the 2S-2P optical transition; next 23.9 GHz microwaves to excite the indicated electron spin-flip transition; and finally, radio-frequency radiation to excite the transition ν_1. The last was provided by a frequency synthesizer which was referenced to a hydrogen maser. The microwave radiation served to make the rate of excitation of the optical transition (and hence the observed fluorescence) sensitive to the upper level of the state pumped by the ν_1 line.

To excite and interrogate the ν_1 transition, a 0.5–2 s pulse of 303 MHz radiation was followed by a second 303 MHz pulse, 10 or 19 s later. This leads to a resonance some 25 mHz wide. It was only necessary to change the radiofrequency by millihertz steps over a 0.1 Hz range in order to scan the resonance. The optical and microwave signals were applied for 3 s before the first

Optically trapped oil droplets

In a recent article in *Physical Review Letters*[1], A. Ashkin and J. Dziedzic of AT&T Bell Laboratories report the first stable trapping and manipulation of single miniscule oil droplets using only the forces derived from the pressure of laser light. Although the force exerted by light on any object is normally so tiny that it is not of importance, the special circumstances contrived by the experimenters make it the dominant force. The techniques have a wide range of potential applications.

The new aspect of the work derives from the fact that the light beams are alternating rather than constant. Recent interest in optical trapping of free neutral atoms has produced an optical Earnshaw theorem[2] showing that steady radiation pressure traps cannot produce stable confinement, just as in the case of steady electrical fields and charged particles. However, just as ion traps can work very well with alternating fields, optical traps can work very well with alternating beams. Using an arrangement of mirrors and shutters to produce the appropriate beams, Ashkin and Dziedzic have confined and manipulated oil droplets of only 0.001 cm diameter for up to five hours. This was accomplished in the air, at atmospheric pressure, with no physical contact with the drop and no observable deterioration by heating.

Arthur Ashkin has been thinking about particle and atom trapping for a long time. In 1970, in his first paper on the subject[3], he laid out the fundamental principles and suggested a number of applications. The attractive features of his technique for manipulating micron sized particles are the lack of physical contact, complete control over motion and the lack of heating or disturbance by radiometric forces. The earliest experiments suggested the possibility of separation of particles by size or composition, as well as showing how to transport, levitate and handle them. Later in that same year, Ashkin described the possible application of these ideas to free neutral atoms[4], a subject of much interest in recent years (reviewed in ref. 5).

Ashkin and colleagues have also succeeded in detaining free sodium atoms in a configuration of laser beams that produces viscous optical forces (S. Chu, personal communication). Our own group has recently accomplished the first real trapping of neutral atoms by confining laser-cooled sodium in a magnetic trap for more than 1 s (see accompanying article[6]).

Whereas it is clear that a new field of applied physics, involving the optical manipulation of free neutral atoms, micron size particles and other tiny objects, is being born, we cannot yet foresee the complete range of its applications. They will include materials processing, information storage, precision atomic spectroscopy, studies in classical mechanics and chaos, isotope separation, control of chemical reactions and manipulation of single cells or even macromolecules. Surely there will be many others. Harold Metcalf

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