# Catching atoms in beams of light

*The past few weeks' excitement about the trapping of atoms in laser beams is well justified; the applications of the technique could be exciting.*

THE notion that it might be possible to trap an atom in a single beam of light is, of course, nonsensical. Atoms capable of interacting with light of specified frequency will sense what is called radiation pressure, and be propelled along in the direction of the beam. This is how newly formed stars clear a nearly empty space in their immediate vicinity and, for that matter, how the outer regions of all stars are prevented from gravitational collapse upon themselves. It is only natural that people should not hitherto have sought to trap single atoms in a single laser beam.

That diffidence will now have to be dispensed with. A group from AT&T Bell Laboratories, in a continuation of work by A. Ashkin going back to the early 1970s, has indeed been able to trap a large collection of sodium atoms in a single laser beam. The group now reports (*Phys. Rev. Lett.* **57**, 317; 1986) that it has been possible to gather as many as 500 atoms into a volume no more than 10 micro-metres in dimension, which corresponds to the respectable density of $10^{11}$ atoms per $cm^3$.

But how can such a feat be accomplished? Steven Chu, J.E. Bjorkholm, A. Ashkin and A. Cable have been able to start from a great deal of expertise accumulated over the years at their own establishment as well as from the many successes in recent years with different kinds of traps for atoms, usually built around combinations of electrostatic and magnetic forces. Devices of that kind, mostly elaborations of the Penning trap, have been widely used in recent years for the spectroscopy of isolated, or nearly-isolated, atoms.

The essential requirement for success appears, however, to have been the suspension of conventional belief. In a companion paper (*ibid.* **57**, 310; 1986), J.E. Pritchard *et al.* rehearse the case for believing that optical trapping is impossible — before showing that not to be the case. The principle is simple enough. In a coherent beam of light, the flux of momentum is represented by the Poynting vector, which is proportional to the vector product of the electric and magnetic field intensities (and thus directed in the direction of an ordinary light beam). By an extension of the nineteenth-century Earnshaw's theorem in electrostatics, it then turns out to be the case that the Poynting vector must be divergenceless across any closed surface that does not contain a source or sink for radiation, just as the divergence of the electrostatic force must be divergenceless over a surface containing no electrostatic charges.

In the optical case, what this seems to imply is that the force on irradiated atoms, which must be in the same direction as the Poynting vector, will also be divergenceless and thus could not be formed in such a way as to be directed inwards everywhere on some closed surface. Ironically, say Pritchard *et al.*, Ashkin is one of those to have argued that Earnshaw's theorem is a bar to laser trapping for atoms, thereby "discrediting these proposals and discouraging any others". One way round the difficulty would be to use light intensities varying with time, a technique that works with radio-frequencies; a temporarily inward array of forces can, for example, be switched off when a sufficient number of atoms have been corralled into some other kind of trap. Doing this at the frequency of optical radiation would be a different matter.

The essence of what Ashkin's group has now done is to use a strongly focused laser beam whose intensity profile is far from uniform but, rather, gaussian, with the peak intensity along the centre. Moreover, the laser generating the beam is tuned to a frequency some way below the natural resonance frequency of the sodium line, with the result that the force on sodium atoms can be controlled at an arbitrarily low level. In these circumstances, the only forces on sodium atoms that matter are those between the electric field of the laser beam and the electric dipole moments which they induce in atoms exposed to them. The forces depend on the detuning of the laser beam, but not as critically as the scattering.

The result is that sodium atoms can be made to move towards the most intense part of a non-uniform laser beam. To be sure, the magnitude of this effect is greater as the frequency of the laser approaches the resonance frequency (which is the condition when scattering could be a nuisance), which implies that a trade-off must be struck between the closeness of the approach to resonance and the steepness of the gaussian profile. That, says Ashkin's group, accounts for trapping on the axis of the laser beam. Trapping in the axial direction depends on the rapidity with which the beam is focused in space.

The actual success reported by Ashkin's group hangs crucially, as is acknowledged, on the way in which it has been possible to start with sodium atoms "cooled", again by the use of laser beams, to an effective temperature of a quarter of a millikelvin. The idea there, implemented in the past few years, is that it is possible to rob an atom of its translation velocity in the direction of a beam of light whose frequency is well-defined by means of the transfer of momentum that occurs on scattering. The trick is to arrange the difference of the laser and the resonance absorption frequency of the atom so that the Doppler shift works in the direction of cooling, but does not as easily allow the transfer of momentum to atoms which are already nearly at rest. But if this works in one dimension, why not arrange that three lasers at right angles should bring a whole package of atoms to near-rest? This arrangement, called "optical molasses" for obvious reasons, was demonstrated only last year. In the new experiments, a package of atoms trapped in such molasses is used as the sources of material to be trapped by the single convergent laser beam, suitably detuned.

For the time being, everybody seems too breathless to wish to speculate where the new development will lead. It is nevertheless remarkable that the lifetime of a package of some hundreds of sodium atoms in such a trap can be as much as several seconds — virtually aeons by the frequency of the resonance absorption line. The lifetime of the trap is limited, for practical purposes, by the residual scattering of light by the atoms in the trap, from which they gain energy and an increased capacity to escape. One little refinement is that, according to Ashkin's group, it is possible to move the package of trapped atoms bodily from place to place, which is why AT&T Bell Laboratories, public relations people have coined the term "optical tweezers".

So what happens next? The insatiable curiosity of spectroscopists is only the most obvious suitor of the new device. The substantial density of atoms that seems to have been achieved suggests that it should be possible almost directly to simulate astrophysical processes in, for example, molecular clouds, especially if there is a chance of using the tweezers effect to mix together different materials. But, inevitably, there will soon also be better traps. Pritchard *et al.* have thoughtfully given no fewer than three recipes that will no doubt be quickly followed.

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