physics in action

Cooled atoms in concert

From **Jean Dalibard** at the Ecole Normale Superieure, Paris, France

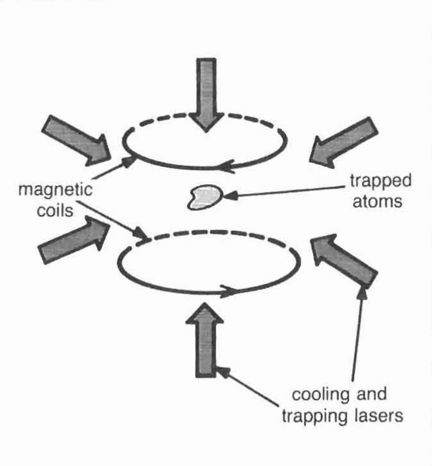
IN CONTRAST with charged particle systems, dilute gases of neutral atoms are very unlikely to undergo collective motions. Indeed, the interaction between neutral atoms is relatively weak and is mainly only effective when atoms are separated by a few ångströms as they are typically in liquids or solids.

Recently, however, Thad Walker and colleagues in Boulder, USA, have observed a strong collective behaviour for neutral caesium atoms – trapped using laser light – at densities as low as 10^{10} atoms cm^{-3}, 10^{12} times lower than the density of solid caesium (1990 *Phys. Rev. Lett.* **64** 408). Such an observation has only been made possible by the very low temperature of the laser-trapped atoms, typically in the millikelvin range. The authors propose that this unusual collective behaviour originates from a long-range atomic interaction induced by the laser irradiation: the laser photons scattered by a given trapped atom can be reabsorbed by another atom, and the repulsive radiation pressure force or RPF which results from this multiple scattering causes the observed collective motion.

The trapping and cooling processes themselves are also based on the RPF. Using several laser beams, one can create both a restoring force towards a central point – trapping – and a damping force opposed to the atomic velocity – cooling. This takes advantage of the strong dependence of the RPF on the detuning of the laser frequency with respect to the atomic resonance frequency: the closer the laser frequency is to an atomic resonance frequency, the stronger the force.

The laser trap is formed by the superposition of six identical running waves propagating in three orthogonal directions (see figure 1). First, the trapping force is created using the gradient of a magnetic field generated by opposing currents in the two coils above and below the centre of the trap. Due to the inhomogeneous Zeeman shifts of the atomic energy levels that ensue, one achieves a situation where the sum of the six forces created by the six laser beams is always directed towards the centre. For instance, an atom above the centre interacts more with the wave coming down than with the wave going up, and therefore feels an RPF directed downwards.

In the same manner, the atoms are 'Doppler cooled': the laser frequency is chosen to be below the atomic resonance frequency so that a moving atom is 'Doppler shifted' closer to resonance with the counterpropagating waves rather than with the co-propagating ones. The net RPF therefore has a velocity-dependent component whose direction always opposes the atomic velocity. This force produces strong cooling, which allows one to reach kinetic temperatures as low as 0.3 mK for the trapped atoms. This temperature is only limited by the unavoidable heating that occurs because of the random character of spontaneous emission processes. On the other hand, the depth of the trap is in the Kelvin range which allows strong confinement of the atoms in the trap.



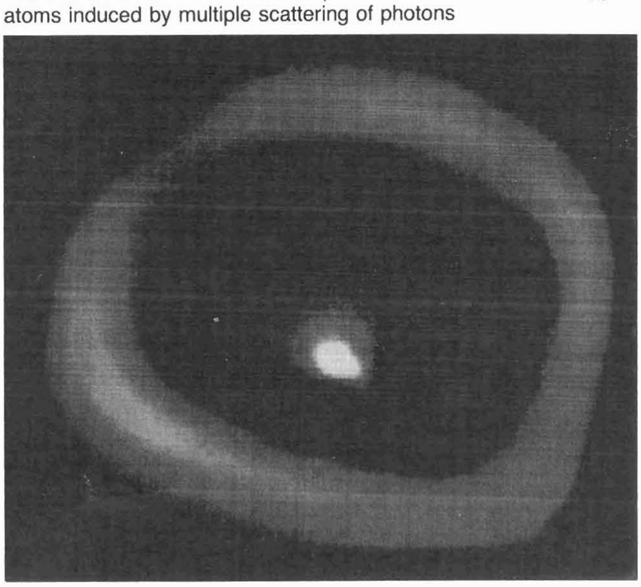
1 Six identical laser beams propagating along three orthogonal directions, superimposed on a magnetic field gradient, create a radiation pressure force which can trap and cool caesium atoms below one millikelvin

What happens when one allows more and more atoms to be in the trap? First, one finds ideal gas behaviour, provided that the number of atoms is less than 40000. The atomic cloud is spherical with a Gaussian distribution. Its diameter of 0.2 mm does not depend on the number of atoms and is determined solely by the ratio between the temperature and the well spring constant.

If the number of atoms exceeds 40000, the size of the cloud increases. Walker and colleagues checked that this increase could not be accounted for only by an increase in the temperature. It is therefore an indication that a strong repulsive interaction between the trapped atoms is taking place. The authors identify this repulsive force as being due to the RPF created by the scattered photons. Laser photons scattered by an atom A can be rescattered by an atom B. This creates on B a RPF, directed along the direction AB and pushing B away from A. This repulsive force is known to play a role in the stability of stars, but up to now it had not been found to be important in laboratory experiments. From a simple model that includes this long-range repulsive force, the authors have been able to reproduce in a satisfactory way the variations of the size of the atomic cloud with up to 5×10^7 atoms.

A new and spectacular feature occurred when a slight misalignment was imposed on the trapping laser beams in the horizontal plane. For $N \sim 10^8$ atoms, the atoms then jumped collectively into an orbital mode (figure 2). This mode consists of a ring of atoms (diameter 2.5 mm) rotating around a small central cloud with a frequency between 80 and 130 Hz (measured by strobing). Here also a simple model, taking into account both the long-range repulsive RPF and the vortex force produced by the laser-beam misalignment, allowed Walker and colleagues to derive the main characteristics of this spatial distribution.

2 Top view of the trapped atomic cloud containing 10^8 atoms. The structure of the cloud is due to a repulsive force between the trapped atoms induced by multiple scattering of photons



This experiment thus shows a fascinating array of collective behaviours at densities orders of magnitude below where such behaviour is usually expected. Many aspects of these collective motions remain to be studied and explained, for instance the transition dynamics and the detailed shapes of these spatial distributions. There is no doubt that this system will soon constitute an excellent sample for studying properties of systems with long-range interactions. □