The ultimate in atom manipulation

A remarkable experiment carried out in Paris has shown that it is possible to change the phase of quantum matter waves by modulating a virtual mirror reflecting atoms with a radio-frequency signal.

MANIPULATING atoms and molecules individually is more than a mere sport, of course, but it is increasingly full of fun. In the past year or so, we have had so many demonstrations of interference between atomic beams behaving for all the world as if they were photons that it can be only a matter of time before somebody uses such beams to take a photograph of some previously inaccessible object, probably one with dimensions of a few micrometres. But the important benefits will come in other ways, notably in spectroscopy and further improvement of atomic clocks.

Now a group at the Laboratoire Kastler Brossel (a joint operation of the Ecole Normale and the Pierre and Marie Curie University in Paris, supported by the CNRS) has gone one step further, managing to modulate the phase of the de Broglie waves that represent the physical motion of atoms in circumstances where quantum rules apply. This, in simple language, is what the group has done.

Caesium atoms are dropped from a height of 3.3 mm onto what can only be described as a virtual mirror — the pattern of oscillating electrical fields external to a polished quartz prism within which a laser beam is totally internally reflected. The mirror is made to alternate between reflection and transparency with a frequency in the MHz region. The result is that the kinetic energy of the reflected atoms is increased or decreased by the equivalent in energy of an integral multiple of the modulation frequency. So much is demonstrated by letting the reflected atoms bounce up to the top of a ballistic trajectory before measuring the positions at which they come down again with a laser probe.

That account is deliberately and misleadingly artless. In reality, what A. Steane, P. Szriftgiser, P. Desbiolles and J. Dalibard describe is technical wizardry of the highest order (*Phys. Rev. Lett.* **74**, 4972–4975; 1995). Among other things, they laconically describe how they are able to transfer cold caesium atoms from one cold trap to another simple by letting them fall there under gravity.

Cold trapping is so much the essence of the game that one would be well advised to learn the acronym MOT (for 'magneto-optical trap'). There is an excellently clear description of how such a trap functions, together with a diagram, in a News and Views article by Christopher Foot a few weeks ago (*Nature* **375**, 447–448; 8 June 1995). Briefly, a pair of coils set symmetrically facing each other and carrying equal currents in opposite directions make a quadrupole magnetic field with a trapping point at the centre of symmetry.

That will trap paramagnetic atoms from the surroundings when the current is switched on. Cooling requires the optical part of the MOT, which is an array of six identical lasers pointing at the symmetrical centre and operating at a frequency near some optically resonant frequency of the atom, the 862 nm line of caesium, for example.

Steane and colleagues operate the uppermost of their two MOTs on a brisk duty cycle of 1.4 seconds. They collect 300 million caesium atoms in a second, cool them to 5 K by detuning the lasers by up to 9 half-widths of the atomic resonance (which creates the sea of "optical molasses" in which atoms appear to be moving through an exceedingly viscous liquid). Then the lasers are detuned still further, allowing the atoms to fall 70 cm under gravity to a second MOT, operating on a different cycle. A second MOT is necessary because it must operate in a better vacuum than the first, whose surroundings must contain enough caesium for a trapful to be collected in a reasonable time.

That is where the fun begins. The essence of the experiment is the virtual mirror, which is a prism containing an internally reflected and linearly polarized beam (at the same resonant caesium frequency). The polarization of the beam is in the plane of the horizontal surface of the prism onto which the caesium atoms fall perpendicularly. The result is an intense electric field (oscillating at the frequency of the caesium line) above the reflecting surface and decaying with a scale height estimated at 0.19 μm. The result of that is to bounce the caesium atoms vertically backwards.

Apparently the virtual reflector works best when the operative surface is concave, making the effective reflector of caesium atoms a spot with diameter 0.4 mm. The laser beam that creates this field is the beam that must eventually be modulated at a MHz frequency.

With that arrangement, the function of the second MOT is first to compress and then to cool the 20 per cent of each load of atoms from the first trap that find their way into the second, and then to drip them onto the reflector. The next step is to select atoms with a particular velocity, which is done by the simple device of choosing the interval of time between a first unmodulated and a second modulated laser pulse in the reflecting prism.

The time required for a caesium atom to move vertically upwards and then down again is evidently a measure of its initial velocity, which must be $2gt$, where g is the acceleration due to gravity (at Paris) and t the time. This first report of the experiment describes the results of measurements when the first unmodulated laser pulse (0.4 ms long) is followed after an interval of 52 ms by a second modulated pulse of the same duration; that corresponds to a velocity of 25 cm s^{-1} at the reflecting spot.

So what happens when, for the second pulse, the laser beam in the prism is modulated? At this point, there is a bunch of atoms falling downwards onto the reflecting spot at 25 cm s^{-1} (with a spread of less than 1 per cent), but they are bounced back with the same velocity. But on this occasion, on what is their third descent, the atoms are detected individually by their absorbtion of a probe beam 1.7 mm above the virtual mirror. This is a time-of-flight measurement, but the probe laser must be switched on at just the time that the infall of caesium atoms is expected.

The results are remarkable. If the second "modulated" pulse is, in reality, unmodulated, the outcome is a simple gaussian distribution (which among other things makes it possible to tell exactly where the probe laser beam is located). But if the second pulse is modulated at 950 kHz, there is a central peak in the same location and two sidebands symmetrically placed on either side. What this implies is that the frequency of the modulation has been transferred to the kinetic energy of at least some of the caesium atoms, or that the phase of the matter (de Broglie) waves has been shifted by external intervention.

The question naturally arises, as always on occasions like this, of what devices will eventually be spawned by this experiment. The authors themselves are largely silent on the subject, although it is natural that they should offer their arrangement as a model for a natural beam-splitter of coherent atomic beams. But they also suggest that it may be a way of measuring g more accurately than is possible with macroscopic measurements, arranging for several unmodulated bounces before a final measurement. That would be worthwhile for its own sake, but somebody will think of something better. **John Maddox**