# Peeking and poking at atoms with laser light*

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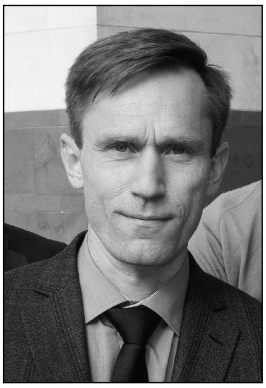
Richard Feynman, in his famous Lectures on Physics, toyed with the idea of all scientific knowledge being wiped out and facing the choice of passing one single idea down to future generations (Feynman *et al*. 1989). He believed it should be the hypothesis that all things are made of atoms. The idea that matter is built up from discrete fundamental units can be traced back to several ancient cultures (the word atom deriving from the Greek word *atomos* 'cannot be divided'). It is only within the last century or so, however, that theories for atomic structure were developed to explain a series of phenomena observed throughout the 18th–19th Centuries. Many of these phenomena were optical, such as Melvill's observation in 1752 that a mixture of sea salt and alcohol would burn with a yellow flame (see Figure 1) or Wollaston's observation in 1802 that sunlight contains black lines in its spectrum (Cajori 1962). Further refinement and characterisation from people like Fraunhofer, Kirchoff, Bunsen, Balmer, and Zeeman followed, but it was not until 1913, with the introduction of the Rutherford-Bohr atomic model, that a cornerstone was laid for what would become a quantum mechanical description of the atom.

## Emission of light by an atom

With quantum mechanics in hand, experimental findings in optical experiments relating to atoms can be explained. The reason why burning sea salt gives rise to a yellow flame is that the 11 electrons surrounding the nucleus of a sodium atom can reside in different quantum mechanical configurations, two of which correspond to energy levels separated by $\Delta E$ in the order of half an atto-joule. In quantum mechanics, an atom can decay from a higher to a lower energy level by emitting a burst of light with a wavelength $\lambda$ which is inversely proportional to the level separation $\lambda = hc/\Delta E$ (where $h$ is Planck's constant and $c$ is the speed of light). For the case of sodium, this wavelength turns out to be $\lambda \sim 600$ nm, corresponding to a yellow colour. If we imagined surrounding a single atom in its upper energy state with photographic plates, eventually the atom would decay, and a small localised dot resulting from the light burst would appear on one of the plates. We say that the atom has emitted a photon – a particle of light. There are two things we should keep note of at this point: (1) the dot on the plate reveals the direction the photon was emitted in, and because light carries momentum, the atom will recoil in the opposite direction; (2) the photon was emitted in a random direction. This traces back to the symmetry properties of the quantum mechanical states of the atom.

**Figure 1. Postgraduate student Lewis Williamson demonstrates that sodium chloride in alcohol burns with a yellow flame at the 2015 Year of Light – Luminescence event in Dunedin.**

**(Photo: Pat Wongpan)**



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## Absorption and scattering of light by an atom

Next we consider a sodium atom in its lower energy level and shine a beam of light of wavelength 600 nm onto it. This may stimulate the atom to jump to its higher energy level by absorbing a photon. Since light carries momentum, the absorption process gives the atom a kick in the propagation direction of the light beam. With the atom in the excited state, a photon can now be emitted in a random direction. Whatever that direction turns out to be, the atom recoils in the opposite direction to conserve momentum for the process. The net effect of several such absorption-emission cycles is a force on the atom in the direction of the light beam (see Figure 2). This means that atoms travelling towards a light source will be slowed down if the wavelength of light is selected to resonantly excite the moving atoms. Moreover, this force is velocity dependent because of the Doppler effect. As the atoms slow down, the light force will gradually wear off because a slow atom perceives the wavelength of light to be shifted away from the resonance condition. The laser is the device which, from a technical perspective, makes this an immediate possibility by providing light of a specific wavelength in a collimated beam.

## Cooling of atoms with light

By setting up a configuration with three pairs of counter-propagating laser beams (left/right, up/down, back/forward), a moving atom can be slowed down irrespective of its direction of motion. This means that a gas of atoms experiencing the velocity-dependent forces from light will be cooled, since temperature is just a measure of the average kinetic energy. The cooling of atoms by laser light can be surprisingly efficient. Laser cooling experiments routinely obtain gases with temperatures on a microkelvin scale – that is, some millionth of a degree above the absolute zero.

## Trapping and imaging atoms

If each in a pair of counter-propagating light beams used for cooling have left- and right-hand circular polarisations, respectively, an external radial magnetic field with a magnitude rising away from a field zero can then establish a situation in which an atom to the left of this origin will predominantly scatter light from the right-moving beam. Likewise an atom to the right will scatter light from the left-moving beam with obvious extensions to up and down and so on. Altogether, atoms are pushed towards the magnetic field zero. This can happen because, generally, an atomic energy level will have substates which will shift up or down according to the local magnetic field (the Zeeman effect) (Foot 2007). These substates refer to atomic angular momentum states. The handedness of circular polarisation states designates the angular momentum carried by the light beams, and restricts the range of allowed transitions amongst the atomic sublevels as these transitions must obey certain rules to conserve total angular momemtum.

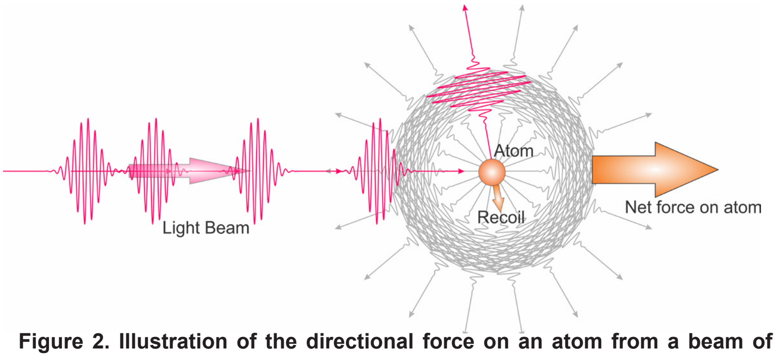

**Figure 2. Illustration of the directional force on an atom from a beam of light with a wavelength corresponding to the transition energy between two atomic levels. The light scattered away from the beam is in a random direction so that the average effect of many scattering events yields a net force along the propagating beam. The force becomes velocity dependent through the Doppler effect.**

Because the magnetic field can shift allowed transitions in or out of resonance, a situation may arise where a class of transitions driven by right-hand polarised light is favoured to the right of the origin and vice versa. A spatially dependent scattering force now pushes atoms towards the origin from all directions. Figure 3 shows a photo of such a magneto-optical trap (MOT) for rubidium atoms at work at the University of Otago.

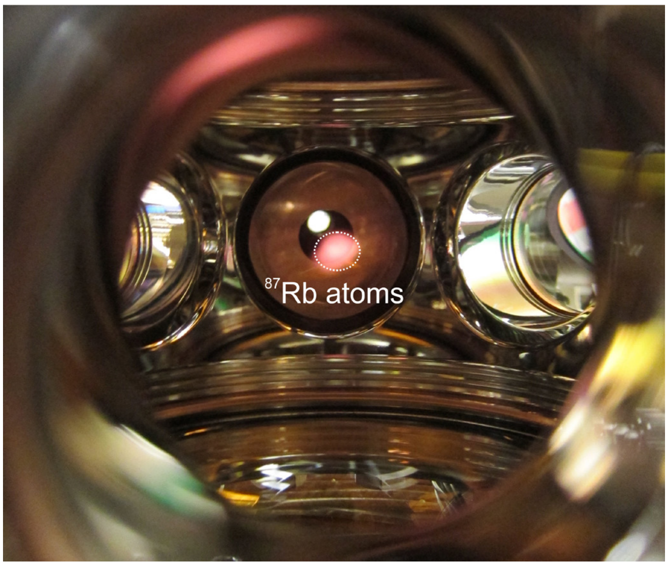

**Figure 3. Photo through a window in a vacuum chamber hosting a magneto-optical trap. Laser cooled $^{87}$Rb atoms are levitated by a combination of optical and magnetic fields and become visible as they scatter light away from three pairs of counter-propagating laser beams (not visible) towards the camera.**

While the characteristic colour for sodium is bright yellow, the corresponding transition for rubidium falls in the infrared at a wavelength of 780 nm, just at the verge of what the human eye can detect. We can see the atoms through a window in the vacuum chamber because they scatter reddish light away from the light beams setting up the MOT. If light is scattered out of a light beam passing through the atoms, it must imply that the beam is attenuated. This can be exploited to acquire shadow images of atomic clouds as illustrated in Figure 4. Such absorption imaging is a standard tool of the cold atoms trade, used to infer the properties of extremely cold clouds.

## Dipole force from a laser beam

An atom is an electrically neutral entity, where the negative charge of an electron cloud exactly matches the positive charge of the nucleus it surrounds. When placed in an electric field the electron cloud displaces with respect to the nucleus and the atom acquires a dipole moment. For a uniform field, equal and opposite forces act at either 'end' of the dipole – an atom at rest will remain so. In contrast, for an inhomogeneous field the polarised atom will be pulled towards the highest field intensity. Moreover, this remains true irrespective of the direction of the electric field.

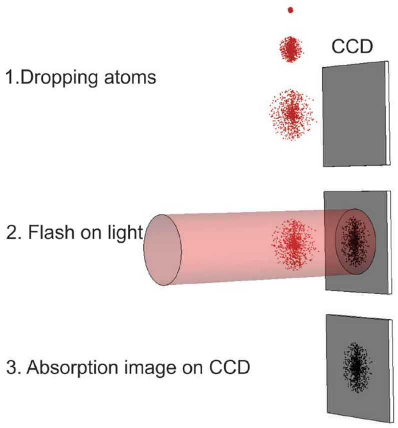

**Figure 4. Peeking at atoms with laser light. When dropped, an atomic cloud will expand according to its temperature. Atomic density distributions can be imaged by flashing on a beam of light resonant with an atomic transition. The scattering of light away from the beam gives rise to a shadow which can be captured on a charge-coupled device (CCD) as an absorption image of atoms.**

Let us consider the effect of placing a rubidium atom in a laser beam of wavelength 1064 nm, much larger than the 780 nm we played around with above to cool, trap and image the atoms. Because this light is so far from fulfilling any atomic transition resonance condition, it is very unlikely that the atom–light interaction will lead to observation of photons outside the laser beam – the scattering we previously discussed is suppressed. The atoms do, however, respond to the oscillating electromagnetic field which the laser field represents: they acquire an oscillating electric dipole moment and in turn experience a force if the beam intensity varies. In particular, rubidium atoms will seek the highest intensity of a 1064 nm light beam. This so-called dipole force provides a very convenient way of handling ultracold samples of atoms.

## Dipole traps for atoms

Figure 5a shows an absorption image of an ultracold rubidium cloud with a couple of million atoms, located at the crossing point of two laser beams characterised by a wavelength of 1064 nm. The crossed beams act as a trap for atoms, which seek the highest intensity at the intersection. The characteristic width of the laser beam, and hence the size of the atom trap formed, is about the breadth of a human hair. The atomic absorption image in Figure 5b shows the effect of lowering the beam power. Evidently, atoms escape the trap along the laser beams. Escaping the trap, however, requires kinetic energy, which means that it is selectively the most energetic ('hottest') atoms leaving the atomic ensemble. The ensemble may now rethermalise at a lower temperature. We say that the atoms have been evaporatively cooled.

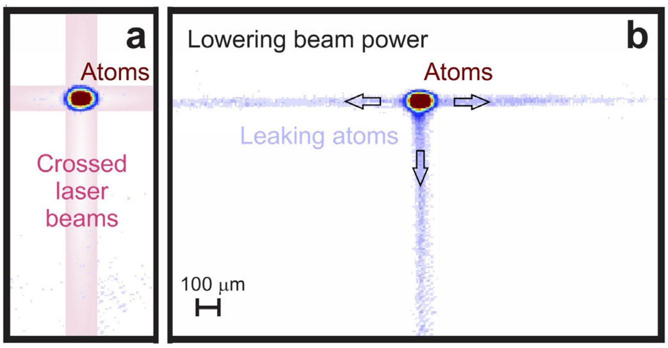

**Figure 5. Poking atoms with laser light. (a) Absorption image from an experiment showing $^{87}$Rb atoms trapped at the high-intensity intersection point of two laser beams with an optical frequency far away from any atomic transition. Laser beams have been added to illustrate the configuration. (b) The effect of lowering the optical power of the trapping beams. Atoms leak out of the trap and funnel away along the beams (no atoms escape in the upwards direction due to gravity). As it will be the most energetic atoms that escape, this process will lead to cooling.**

## Production of multiple Bose-Einstein condensates

By using an acousto-optic deflector, we can intersect a horizontal laser beam with several vertical beams to form multiple crossed dipole traps as illustrated in Figures 6a and 6b in the case of four traps, equidistantly spaced by 0.5 mm (Roberts *et al.* 2014). Figure 6c presents the effect of progressively lowering the horizontal beam power and thereby evaporatively cooling four ensembles simultaneously trapped in this configuration (Deb *et al.* 2014). We peek at the atoms by turning off all trapping laser

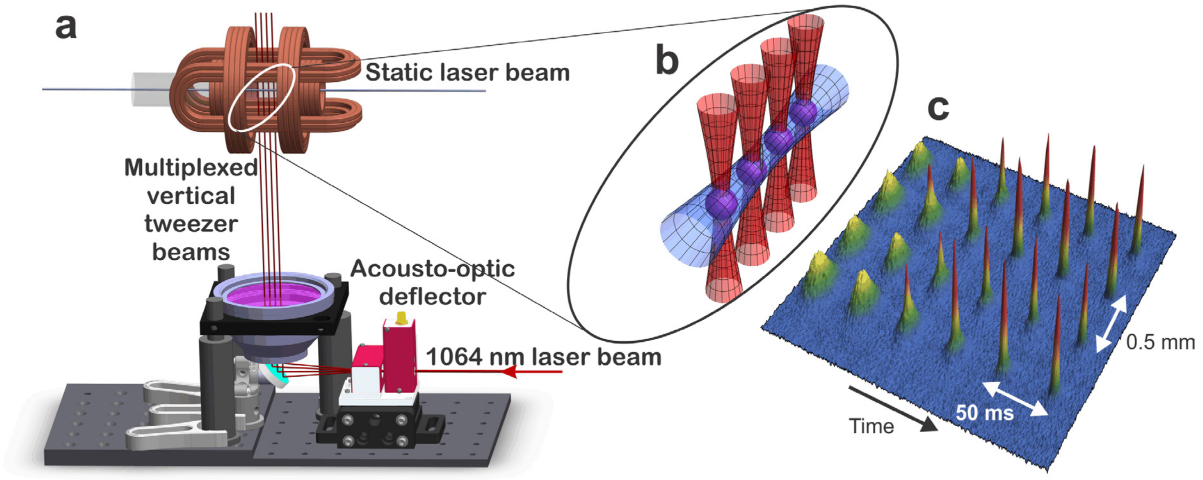

**Figure 6. (a) Experimental configuration for creating four simultaneous traps for ultracold atoms by intersecting a single horizontal laser beam with four vertical beams. The vertical beams can be spatially steered, which offers a possibility of positioning and accelerating atomic clouds. (b) Enlargement of the trapping region (inside an evacuated glass cell) illustrating trapping of atomic clouds at the beam intersections. (c) Development in the density distributions (inferred from absorption images – see Figure 4) for the four clouds as they are evaporatively cooled. The emergence of spiked density distributions from Gaussian blobs is a signature of Bose-Einstein condensates being formed.**

beams and let the clouds fall under gravity (as in Figure 4) for 18 ms while they expand before acquiring an absorption image. In a relatively hot cloud the atoms will expand more rapidly. The clouds in Figure 6c all have a temperature around a few hundred nanokelvin. We see that, as the atoms are cooled, the shape of the cloud dramatically changes. This results from a phase transition where the gas of atoms becomes a so-called Bose-Einstein condensate (BEC). Some of the many fascinating properties of BECs have previously been described in the present journal (Blakie 2005). A fuller account of the physics of BECs is outside the scope of the current exposition of light-based techniques for poking and peeking at atoms. Instead, I shall focus on an implementation of an optical collider for ultracold atoms.

## Steerable optical tweezers as a collider for ultracold atoms

The acousto-optic deflector scheme used to establish multiple traps for atoms along a horizontal confinement channel can be exploited to move and accelerate clouds of ultracold atoms. The ability to pinch a polarisable object and relocate it by means of a focused laser led Ashkin and Dziedzic to coin the term ‘optical tweezers’ when applying this technique to manipulate viruses and bacteria (Ashkin & Dziedzic 1987, Ashkin 2000). In our laboratory at Otago, we can pinch two ultracold clouds of atoms with laser tweezers and hurl them into each other along the direction of the horizontal guide beam (Rakonjac *et al.* 2012). Figure 7 shows examples of the scattering debris resulting from colliding clouds at two different collision energies. It is obvious that the angular scattering is radically different in the two cases. Experiments of this type, investigating the energy dependence of scattering, reveal the potentials through which two atoms interact and can corroborate the theoretical models describing the quantum scattering problems (Kjærgaard *et al.* 2004). Because our atoms have a temperature in the nanokelvin regime, we can conduct collision experiments at extremely low energies. So while atoms at room temperature move at sonic speeds, even our ‘high’ energy collisions lie in the pedestrian domain. For such low-energy scattering experiments, optical tweezer techniques have proven very versatile, opening the possibility for handling multiple species and quantum states of atoms together.

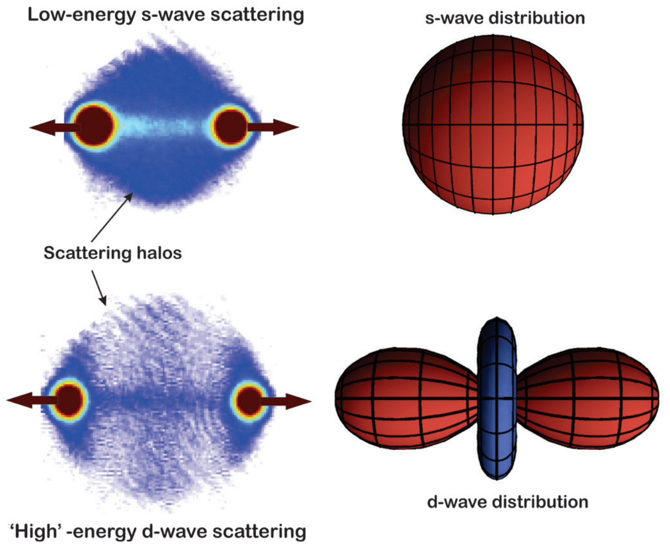

**Figure 7. Absorption images showing halos of scattered particles (left column) when steerable optical tweezers are used to accelerate and collide two clouds of ultracold $^{87}$Rb atoms. At low energies the angular scattering pattern is isotropic or “s-wave”. At comparatively high collision energies an anisotropic scattering pattern emerges, reflecting a “d-wave” distribution. Angular distributions (of electron probability density) for s- and d-waves are shown in the right column.**

## Conclusion

In this article I have tried to convey an impression of the central role light plays in manipulating and detecting atoms in modern atomic physics through a few illustrations from our laboratory at Otago. It is interesting to note that the exquisite control exercised over atomic particles by means of light today descends from a century-long evolution with humble beginnings in spectroscopy. Insights into how atoms interact with light paved the way for devising schemes such as laser cooling and dipole trapping of atoms. Within the last twenty years, no less than four Nobel Prizes have been awarded to the researchers who pioneered the field of cold atoms. Today, the ability to harness these atomic quantum systems has found a plethora of applications ranging from precision measurements to simulations of condensed matter systems. I refer the interested reader to the recent overview article ‘Cold atoms: A field enabled by light’ (Fallani & Kastberg 2015), which is freely available.

## Acknowledgments

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