1997 Nobel Prize for Physics: Laser cooling and trapping of atoms

The Nobel Prize in Physics for 1997 has been awarded jointly to Steven Chu of Stanford (USA), Claude Cohen–Tannoudji of the College de France (France) and W. D. Phillips of National Institute of Standards and Technology, Gaithersburg (USA) for their prolific work on laser cooling and trapping of atoms. Principles of laser cooling of atoms were propounded earlier than the work for which the award has been made. But it was the extensive experimental work of Chu and Philips which not only made laser cooling in three dimensions a practical reality for the first time, but also produced the astounding result that the temperatures achieved were systematically lower by an order of magnitude than the theoretical estimates. An explanation for such lower temperatures was provided by the theoretical work of the French and Stanford groups. Techniques of laser cooling and trapping have led to many applications of ultra-cold atoms which will be mentioned at the end of this article.

Doppler cooling

Consider a two-level atom with a ground state |g> and an excited state |e> separated by an energy $\hbar\omega_0$. The rate of absorption of photons by such an atom as a function of photon frequency is given by a bell-shaped curve called the Lorentzian shown in Figure 1 *a*. Absorption of a photon raises the atom from the ground state to the excited state. The atom has a mean life time τ in the excited state before reverting to its ground state by the spontaneous emission of a photon in a random direction. The half-width of the absorption curve, denoted by Γ, is of the order of a few MHz in frequency and is proportional to the reciprocal of the decay time τ.

If such an atom is placed between two counter-propagating laser beams tuned to a frequency ω_L slightly below resonance (i.e. $\omega_0 > \omega_L$, the detuning $\delta = \omega_L - \omega_0$ being negative; such a detuning is called *detuning to the red*), the following situation develops (Figure 1 *b*). If the atom is moving towards the right with a velocity v, the frequency of the photon travelling in the $-x$ direction gets Doppler shifted to a higher value $\omega^+ = \omega + \Delta\omega$, where

$$\Delta\omega = (v/c)\,\omega_L, \tag{1}$$

in which c is the velocity of light. The shifted frequency comes closer to the absorption frequency ω_0 and the absorption rate increases. On the other hand, the laser beam travelling in the $+x$ direction gets Doppler shifted to $\omega^- = \omega_0 - \Delta\omega$ and the absorption rate is reduced. The differential absorption rate is proportional to the atom velocity, for small values of the velocity. Since each photon carries a momentum $\hbar k$ ($k = 2\pi/\lambda$, where λ is the wavelength of the laser beam) in the direction in which it is travelling, the absorption of a photon causes the atom to acquire this momentum in the direction in which the photon is travelling. So the differential absorption rate causes a net force F on the atom which is proportional to its velocity but is *opposite* in direction to this velocity (Figure 1 *c*). This force is

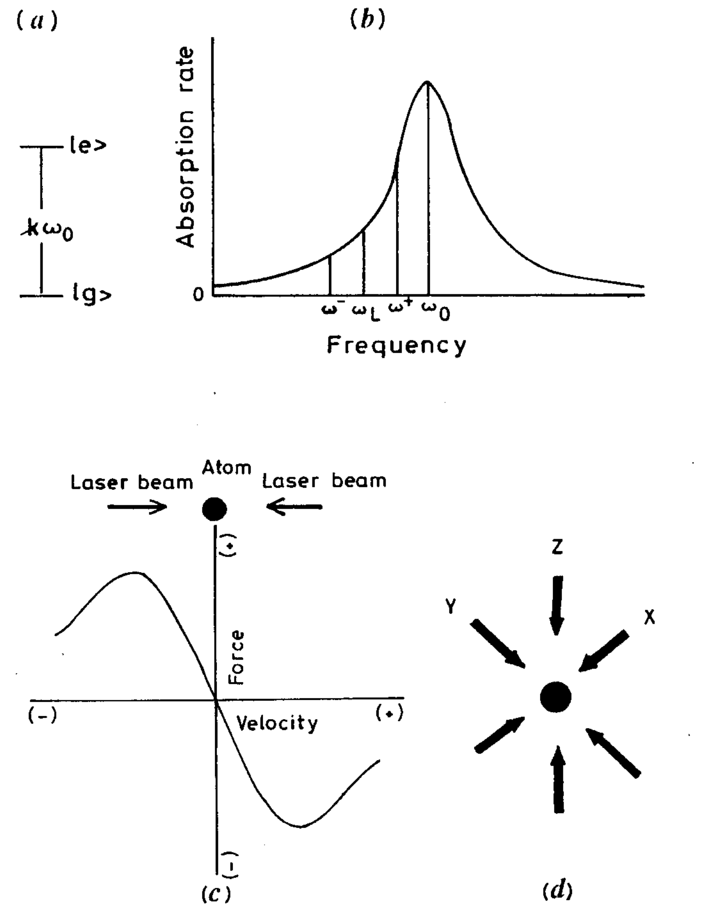

Figure 1. ***a***, A two level atom with the ground state |g> and the excited state separated by an energy difference $\hbar\omega_0$. ***b***, The absorption rate of such an atom follows a Lorentzian with a peak at the frequency ω_0. The half-width of the curve is Γ. When the atom moves towards the photon, the photon frequency is shifted to ω^+ and when it is moving away from the photon to ω^-. ***c***, When the atom is between two counter-propagating red detuned laser beams there is a force on the atom which is opposed to its velocity. ***d***, Three-dimensional optical molasses to slow down the atom.

similar to the viscous force that a ball dropped in a column of oil experiences. The atom slows down by this viscous force. By arranging three pairs of counter-propagating laser beams (derived from the same laser source) along the x, y, and z axes, all the three velocity components of an atom can be slowed down by this differential process of absorption (Figure 1*d*). Such a three-dimensional configuration of laser beams to slow down atoms is called *optical* molasses. The average kinetic energy of an atom is proportional to its temperature. The atom cloud therefore cools in the optical molasses.

The cooling rate by this Doppler shift-caused differential absorption is compensated by a heating rate arising from spontaneous emission of photons. Spontaneous emission causes the atom to acquire a momentum $\hbar k$ in a direction opposite to the direction of emission of the photon. In spontaneous emission photons are emitted in random directions. So the atom acquires momentum in steps of $\hbar k$ but in random directions. This random walk in momentum space causes the mean square of the momentum to increase linearly with time. This is equivalent to heating the atom at a constant rate. The final temperature attained is one at which the heating and cooling rates are balanced. Theory shows that the minimum temperature $T_{\min}$ attained is given by

$$T_{\min} = \hbar\Gamma/2k_B, \quad (1)$$

in which k_B is the Boltzmann constant. The minimum temperature is attained when the detuning of the laser beam is

$$\delta = -\Gamma/2. \quad (2)$$

The optical molasses arrangement was first realized by Chu and his collaborators[1] at AT&T laboratories in USA and the first experiments on a cloud of sodium atoms appeared to verify the predictions of Doppler cooling theory. Later careful experiments by Philips and his collaborators at NIST[2] showed that the temperatures attained were consistently lower by an order of magnitude than that predicted by Doppler cooling theory. In sodium, for example, the minimum temperature predicted by Doppler cooling theory is 240 μK while the lowest temperature achieved experimentally was around 40 μK. The minimum temperature was achieved when the detuning δ was close to -3Γ. It was also noted that the experiments were very sensitive to small residual magnetic fields. These results were confirmed by further experiments by other workers. These detailed experiments indicated that the *magnetic sub-levels* of the ground and excited states of the atom were responsible for achieving temperatures below the Doppler limit of equation (2).

Sub-Doppler cooling

It was recognized that in the optical molasses configuration, the polarization state of the electromagnetic field changes over a length scale of λ. The transition rate from a magnetic sub-level of the ground state to different magnetic sub-levels of the excited state depends on the state of polarization of the light at the site of the atom. If the state of polarization has a suitable value at a given location, a substantial difference in the population of the different magnetic sub-levels of the ground state can arise by a series of *absorption–emission* cycles. This phenomenon is called *optical pumping*. The *optical pumping time* τ_p is the time scale in which a steady

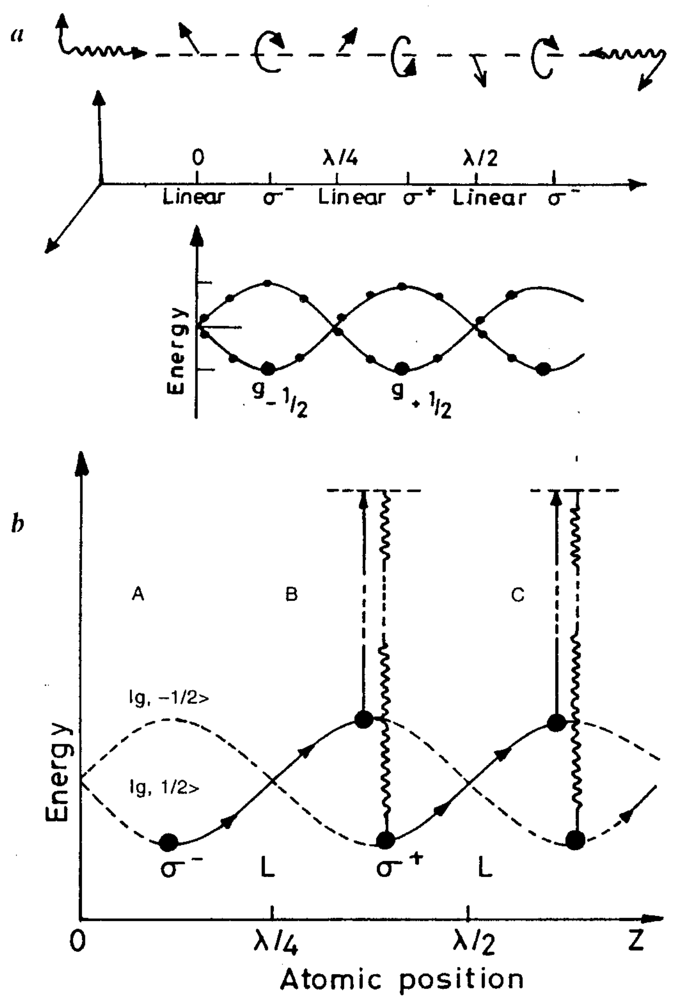

Figure 2. Two red-detuned laser beams polarized perpendicular to each other counter-propagate along the X axis. The variation of the resultant polarization in the top diagram ***a***. An atom with a ground state with two magnetic sublevels *Ig*, 1/2> and *Ig*, −1/2) is placed in the beam. The variation of populations with position is also shown in ***a***. The equilibrium populations in the two sub-levels are shown by the size of the closed circles on the corresponding curves. ***b***, Illustration of the Sisyphus cooling mechanism.

state differential population of the sub-levels is achieved through such absorption–emission cycles. Since the polarization state of the electromagnetic field changes over a length of the order of λ, the steady state population of the ground state sub-levels can vary over such a length scale. When the atoms move in such a changing polarization gradient, they change from the equilibrium ground state sub-level population at one location to the equilibrium sub-level population at another location, separated from the first by a length $\approx\lambda$, in a time scale of the order of τ_p.

There is a second effect arising from the interaction of the atom with the electromagnetic field. Such an interaction produces slight shifts in the energy of the magnetic sub-levels of the ground state, which are degenerate in the absence of a magnetic field. This shift is called *light shift*. The light shift also depends on the transition probability for excitation from a given magnetic sub-level and so will vary from position to position on a length scale of λ. Figure 2*a* shows such a situation in one dimension when the two counter-propagating laser beams are linearly polarized at right angles to each other and the ground state of the atom has two magnetic sub-levels |*g*, 1/2> and |*g*, −1/2>. The state of polarization of the light varies from linear to right/left circular back to linear as shown in Figure 2*a*. Here the light-shift as well as the equilibrium differential ground state population varies sinusoidally with a period $\lambda/2$ as shown in Figure 2*a*. The equilibrium relative population in the two states is indicated by the size of the black dots on the two curves representing the energy shift of the two magnetic sub-levels. Atoms moving with a velocity $v \cong \lambda/\tau_p$ will lose energy in the following way. Let us say that at the site A the atoms are in the magnetic sub-level |*g*, 1/2> which has a lower energy than the sub-level |*g*, −1/2>. As the atoms move to the location B, the energy of the sub-level |*g*, 1/2> increases. Since the total energy of the atom is a constant, the increase in its potential energy is accompanied by a decrease in the kinetic energy. When the atoms reach the location B a time τ_p later, optical pumping pushes all the atoms into the ground sub-level |*g*, −1/2> which has a lower energy at location B due to the change in polarization state at B. In this process the extra-potential energy of the atoms before pumping is carried away by photons. The atoms now in state |*g*, −1/2> at B with a lower kinetic energy start to climb the potential hill as they move to the point C where the process is repeated. This process is called *Sisyphus cooling* and is shown in Figure 2*b*. Thus the atoms keep slowing down. The theory of this process worked out by Cohen–Tannoudji and his group[3] showed that this effect is dominant over Doppler cooling especially for low velocity atoms and allows a much lower temperature to be reached than what is given by equation (2). Also the effect is more effective at a detuning much larger in magnitude than what is stated in equation (3). Subsequent careful investigations have validated these ideas[4].

Trapping of atoms

Atoms cooled in an optical molasses ultimately leak out of the molasses region as there is no confining potential to trap the atoms. The residence time of the atoms in the optical molasses is of the order of a second. This short residence time limits the density of the atomic cloud to 10^6 atoms/cc and the time is too short to carry out certain experiments with the cold cloud. A higher density of atoms and a longer residence time can be achieved using traps.

An inhomogeneous magnetic field can be used to trap atoms in certain magnetic ground sub-levels since the energy of the sub-levels will depend on the value of the magnetic field at a given location[5]. With steady state currents it will not be possible to produce magnetic fields with a local maximum. One can on the other hand produce steady state magnetic fields with a local minimum. At such a local minimum of the magnetic field one can trap atoms in magnetic sub-levels in which the Zeeman energy increases as the magnetic field increases. Such levels are called weak field seeking levels. However the potential barrier achievable with magnetic field gradients of a few hundred gauss/cm is not large enough to trap atoms at a temperature in the milli-Kelvin range. Such fields can be used to trap atoms with temperatures in the few tens of a micro-Kelvin range or lower.

The electrical susceptibility of an atom has a real and imaginary part. The imaginary part is responsible for the absorption of light and we have seen how differential absorption can be used to produce a force on the atom. The real part of the susceptibility also gives rise to a force when the electric field of the light is inhomogeneous, i.e. the intensity of the light is non-uniform. This force is called the *dipole* force. When the intensity of the light beam shows a spatial variation, this dipole force pushes an atom *towards a region of maximum intensity* if the laser light is *red detuned*, and *away from the region of maximum intensity* if the laser beam is *blue detuned* (δ is positive). Using a focussed red detuned beam with a detuning several times the natural line width Γ it is possible to trap atoms at the focus of the light beam[6]. The volume of the trapped region is small and fluctuations in the light intensity will tend to heat the trapped cloud of atoms.

The most successful trap for neutral atoms is the *magneto-optical trap* (MOT). To understand the principle of operation of MOT consider an atom in one dimension with two energy states |g> and |e>. Let the angular momentum quantum number F in the ground state be zero and F' in the excited state be 1. The ground state has a single magnetic sub-level |g, 0> and the excited state has three magnetic sub-levels |e, 1>, |e, 0> and |e, −1>. This atom is placed in a quadrupolar magnetic field varying linearly with the x co-ordinate and in two counter-propagating red detuned laser beams with opposite circular polarizations σ^+ and σ^- as shown in Figure 3 *a*. Due to the Zeeman interaction with the inhomogeneous magnetic field, the energy of the different sub-levels will vary with position as shown in the Figure. The σ^+ polarized beam will cause a transition from |g, 0> to |e, +1> state while the σ^- polarized beam will cause a transition from |g, 0> to |e, −1> state. If the atom is to the right of the origin, the energy difference between |e, 1> and |g, 0> levels comes closer to the laser frequency ω_L while the energy level difference between |e, −1> and |g, 0> levels goes farther away from ω_L. So the absorption rate of σ^+ photons coming from the right is more than the absorption rate of σ^- photons coming from the left. The atom experiences a net restoring force pushing it towards the origin. When the atom moves to the left of the origin, the absorption rates are reversed. Again there is a net restoring force pushing the atom to the origin. This force depends on the position and for small displacements is proportional to the displacement of the atom from the origin. So the atom finds itself in a harmonic oscillator potential. One can realize the same situation with a three-dimensional optical molasses with a quadrupolar magnetic field produced by a pair of coils symmetrically situated about the origin carrying currents in the opposite sense (see Figure 3 *b*). The three-dimensional harmonic oscillator potential has axial symmetry about the common axis of the two coils. The light beams are circularly polarized in suitable directions. With magnetic field gradients of about 10 gauss/cm one can realize trapping potentials large enough to trap atoms with temperatures of the order of a few milli Kelvin. The first MOT was realized by E. Raab *et al.*[7]. With magneto-optical traps it is possible to trap 10^{10} to 10^{11} atoms to a density of 10^{11} atoms/cc. It is not possible to increase the density further because the process of multiple absorption and re-emission of the photons by the atoms creates an effective repulsion between the atoms. The Doppler and Sub-Doppler cooling effects are also simultaneously active in the optical molasses. So one achieves cooling with trapping. The MOT has now been developed to such a stage that it is relatively simple to fabricate and use such traps[8].

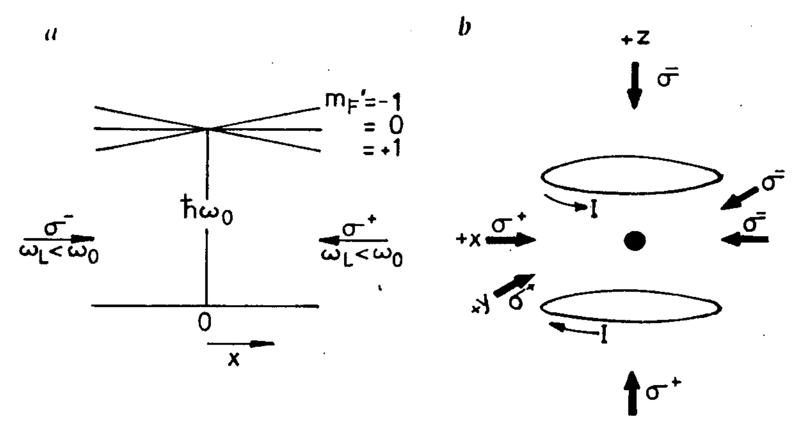

Figure 3. ***a***, An atom with a ground state with $F = 0$ and an excited state with $F' = 1$ is placed in a magnetic field varying linearly with X. The energies of the Zeeman split sub-levels are shown as a function of position. The counter-propagating laser beams are red-detuned with respect to the frequency $F = 0$ to $F' = 1$ in the absence of the magnetic field. The beam coming from the right is circularly σ^+ polarized while the beam from the left is circularly σ^- polarized. For an explanation of trapping see the text. ***b***, The three-dimensional magneto-optical trap.

Applications of ultra-cold atoms

Several fundamental experiments can be done with such ultra-cold atomic clouds. One can produce an atomic fountain of such a cloud by projecting it upwards with a small velocity of a few cm/s. This can be done by making the two counter-propagating laser beams in the z direction slightly different in intensity. One can also produce a moving standing wave in the z direction by making the two counter-propagating waves along the z direction to have slightly different frequencies. The projected cloud will reach a certain height and fall back in just the same way as a ball projected upwards under the action of gravity.

Using such an atomic fountain of caesium in a Ramsey type interference experiment with microwave beam, it is possible to measure the clock frequency of Cs more precisely than with existing techniques. The precision of the time standard can be improved[9] by three orders of magnitude to one part in 10^{16}. Using an atomic fountain of sodium and performing a Ramsey type experiment using optical beams, it has been shown[10] that the acceleration due to gravity could be measured to a precision of three parts in 10^8. Rotational frequencies as small as 5×10^{-13} radians/second can be measured[11].

It is possible to perform experiments to test the foundations of quantum mechanics. One can verify to what accuracy the magnitude of the charge on the electron and proton are equal. Phase changes introduced by fields on coherent atomic beams can also be measured.

Using laser cooling as the first stage and evaporative cooling as the second stage, Bose–Einstein condensation was first observed[12] in July 1995 in a cloud of two thousand ^{87}Rb atoms cooled below 170 nano Kelvin. Since then the number of atoms in the condensate has been increased to more than a million atoms and the properties of a weakly interacting Bose Condensate of alkali atoms have been measured and compared with theory. In 1997 the coherence of the Bose condensate was demonstrated[13] by producing interference between two condensates. The condensates were created in a double potential well and allowed to diffuse into each other by removing the confining magnetic field and the blue detuned laser beam. It has also been possible to couple a fraction of the condensate out of the trap making the first atom laser[14]. Using lithography with such beams it will be possible to achieve information storage densities far in excess of what has been achieved so far. The possibilities for new applications seem endless.

The phenomenon of laser cooling and trapping has reached the present level of maturity only through the seminal work of Steven Chu, Cohen–Tannoudji and W. D. Phillips. It is therefore appropriate that the Nobel Committee has chosen these three scientists for the award of the Nobel Prize for 1997.

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