# Nobel Prize in Physics – 1997

## Laser Cooling and Trapping

*Vasant Natarajan and R Srinivasan*

Vasant Natarajan is at the Department of Physics, Indian Institute of Science. His current research involves trapping of atoms to carry out high precision tests of fundamental physics. He has earlier worked on high precision mass spectrometry and on the focussing of atomic beams by laser fields.

R Srinivasan is a Visiting Professor at the Raman Research Institute after retiring as Director of the Inter-University Consortium for DAE Facilities at Indore. Earlier, he was at the Physics Department of IIT, Chennai for many years. He has worked in low temperature physics and superconductivity.

**This year's Nobel Prize in physics recognises the spectacular progress during the last decade in the cooling and trapping of atoms by the use of laser beams. The techniques exploit basic physical principles with great ingenuity and have very interesting applications in precision measurement and the study of new phenomena.**

This year's Nobel Prize in Physics has been awarded jointly to Steven Chu of Stanford University (USA), Claude Cohen-Tannoudji of College de France (France), and William D Phillips of the National Institute of Standards and Technology, Gaithersburg (USA). They have been cited for their seminal work in the use of laser light to cool and trap atoms. This award represents the recognition of more than two decades of work by many leading atomic physicists around the world. Indeed, several of the key ideas in this field did not originate solely in the laboratories of the above scientists. However, they have been chosen for the award because, in a remarkably productive period in the late 80's, these three researchers, working independently, discovered new experimental results that surpassed the predictions of existing theories of laser cooling. Soon after, they also developed new theories that explained the strange results and helped zero in on the best conditions for laser cooling. It is one of those rare instances in physics in which experiments have worked better than anticipated, which is a tribute to careful experimentation!

## Laser Cooling

The term 'laser cooling' sounds self contradictory since lasers are normally associated with intense heat. To the lay person, the word laser conjures up images, popularised by Hollywood thrillers, of a powerful red beam of light cutting through the thick metal door leading to the vault of a bank, or freeing the trapped hero and heroine from the hull of a sinking ship! Despite such images, lasers can be used to cool a cloud of atoms to extremely low temperatures. It happens because in the quantum world of atoms, the laws of physics are very different. To understand this better, let us review some of the relevant properties of light and its interaction with atoms. One is the Doppler effect (*Box 1*). The property that the energy of light comes in packets called *photons* is also well known since the days of the introduction of the light quantum hypothesis by Planck. Each photon carries an energy $h\nu$, where $h$ is the celebrated Planck's constant, whose presence is a sure sign that quantum physics is involved. But each photon also carries momentum equal to $h/\lambda$, where $\lambda$ is the wavelength of light. This implies that each time an atom absorbs or emits a photon, by the principle of *conservation of momentum*, the atom experiences a momentum change equal to $h/\lambda$. Absorption causes an increase in momentum by this amount, while emission causes the same decrease in the momentum of the atom.

Doppler effect plays an essential role in laser cooling of atoms.

**Box 1**

When there is relative motion between a source of waves and an observer, the frequency of the waves as measured by the observer is different from the frequency of the source at rest. This phenomenon is easily observable with sound. This is because the fractional change in frequency is equal to the ratio of the relative velocity of the source and the observer to the velocity of the waves in the medium. For sound the velocity in air is 330 m/s. One can reach terrestrial velocities which are a sizeable fraction of this velocity. For example when a train moves with a velocity of 100 km/hr, the fractional change in frequency is of the order of 8% and this is easily noticeable. When the train is approaching the observer the pitch of its whistle increases, while when it is moving away from the observer the pitch decreases. An observer can easily notice the sudden change in pitch of the whistle when the train passes him. The speed of light in vacuum is $3\times10^8$ m/s. So terrestrial speeds are a very tiny fraction of the speed of light and it is not easy to detect Doppler shift in this case. That is why the red light in the guard van does not appear to change its colour when the train rushes past the observer. However, gas atoms move with velocities of about 500 m/s at room temperature. They are also very sensitive to changes in frequency because of the very narrow absorption lines that they show.

When an atom absorbs or emits a photon it suffers a change in momentum of $h/\lambda$.

The next property we must understand is one that governs atom-photon interactions, the phenomenon of *resonance* (after which this journal is named!). Resonance is the reason why soldiers are asked to march out of step when crossing a suspension bridge, because if their marching frequency matches the oscillation frequency of the bridge, it can make the bridge oscillate with large amplitude and finally collapse. The condition that there is significant energy transfer only when the drive frequency matches the internal frequency is true for atoms also. The electric field of the incident light waves 'jiggles' the electrons in an atom, but the process is efficient at transferring energy (i.e. there is absorption of photons by the atom) only when the light frequency matches the internal frequency of the atom. The result is shown in *Figure 1*, in which we plot the photon absorption rate as a function of the light frequency. The shape of this curve is technically called a 'Lorentzian' and is a universal feature of resonance phenomena. The width of the curve is called the line-width, $\Gamma$, of the excited state and has a value of 10 MHz for a sodium atom absorbing yellow light.

One consequence of the Doppler shift discussed earlier is that the horizontal axis of the resonance curve in *Figure 1* can also be regarded as a velocity axis (remember that the change in frequency is related to the velocity). Thus, if the laser is tuned to the resonance frequency of the atom in the laboratory frame, only atoms with zero velocity will absorb photons at the maximum

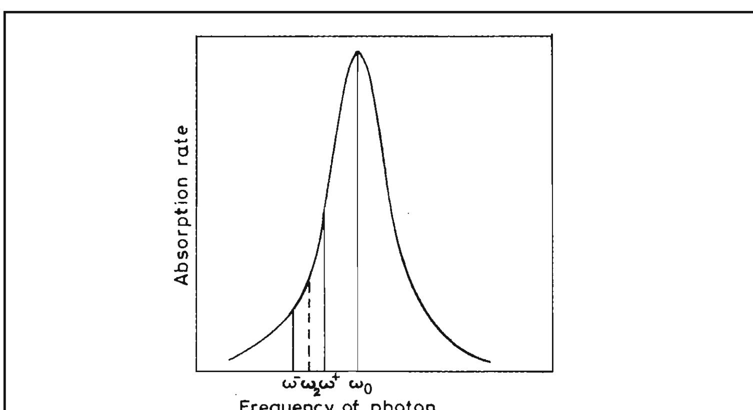


*Figure 1. The rate of absorption of photons as a function of frequency for a two level atom. Here $\omega_0$ is the natural frequency of the atom corresponding to the energy difference between the ground and excited states. The X axis is the frequency of the incident light. For a given frequency $\omega_L$ of the incident light red detuned with respect to $\omega_0$, for an atom moving towards the source the frequency $\omega+$ will be Doppler shifted towards $\omega_0$ and for an atom moving away from the source, the frequency $\omega$- will be Doppler shifted away from $\omega_0$.*

rate given by the peak of the curve. Any atom with a non-zero velocity in the laboratory frame will see a Doppler shifted frequency and consequently will absorb fewer photons. The narrow line width of the resonance curve also explains why the atoms are so sensitive to the Doppler shift. A sodium atom moving with a velocity of 30 m/s has a Doppler shift of 10 MHz, and will interact more weakly with a laser beam which is tuned to be resonant with an atom at rest.

The absorption rate for photons by an atom is maximum when the energy of the photon exactly matches the difference in the energies of the ground and excited states of the atom.

It is also useful to consider the absorption-emission process in some detail. Each absorbed photon takes the atom from the ground ( or stable) state to an excited state, with a concomitant momentum kick of $h/\lambda$ in the direction of the laser beam, as explained earlier. Before the atom can absorb another photon, it has to come down to the ground state; this it does through a process known as *spontaneous emission.*

Spontaneous emission is a random process and the photon can be emitted in any direction. So the momentum changes of the atoms in the spontaneous emission processes have the same magnitude $h/\lambda$ but random directions. *On an average,* the net change in momentum produced by spontaneous emission, which is a sum of vectors of equal magnitude but random directions, is zero. Thus, we see that absorption-spontaneous emission cycles result in a *net* momentum transfer to the atom in the direction of the exciting laser beam.

The Doppler cooling scheme can now be understood qualitatively based on the above concepts. For simplicity, we consider a one-dimensional case where the atoms are confined to move along the x-axis. The cooling configuration then consists of two identical laser beams propagating in the +x and –x directions, whose frequencies are chosen to be *slightly below the resonance frequency* $\nu_0$ of the atoms. To understand the cooling process, consider an atom moving in the +x direction with a small velocity v. The atom Doppler shifts the beam travelling in the –x direction to a higher frequency (closer to the peak of the

In spontaneous emission the photons are emitted in random directions.

An atom placed in two counter-propagating laser beams experiences a frictional force due to Doppler effect.

absorption curve in *Figure 1*) and the beam travelling in the +x direction to a lower frequency, further away from resonance. Therefore it preferentially absorbs (and spontaneous emits) photons from the beam travelling in the –x direction and gets more momentum kicks in this direction, which slows it down. The opposite happens for an atom travelling in the –x direction; it Doppler shifts the frequency of the beam moving in the +x direction closer to resonance and the frequency of the beam travelling in the +x direction farther away from resonance. It therefore experiences a force in the +x direction. The force, arising from differential absorption, is proportional to the velocity of the atom and acts in a direction opposite to the velocity. This is a frictional force and the atom would ultimately be brought to rest if this frictional force was the only consequence of the atom-laser interaction. The average force is the product of the differential absorption rate times the momentum transferred in each absorption-emission cycle. (This is a restatement of Newton's second law!) The result is shown in *Figure 2*. The force from the beam travell-ing along the +x direction is positive and has a peak at a negative velocity. The curve is a rescaled version of *Figure 1*, the x-axis being the velocity of the atom. The Doppler shift for an atom travelling with a negative velocity brings it closer to resonance. So the peak is centred around a negative velocity. Similarly , the force from the laser beam travelling in the –x direction has a peak at a positive value of the velocity of the atom. The net force is a sum of the two forces and is shown by the continuous curve. For small values of velocity, this force is proportional to the velocity and is opposed to it.

*Steven Chu*

*Claude Cohen-Tannoudji*

*William D Phillips*

At this stage two questions naturally appear in the mind of the reader. Firstly, how restrictive is our analysis of the one-dimensional case when extended to the three dimensions of real space? Well, it turns out that the scheme can be really extended by having three orthogonal pairs of counter-propagating beams (derived from the same laser) of the same intensity and detuning along the x, y and z axes. Since the velocity of the atom can be resolved into its orthogonal components and each component

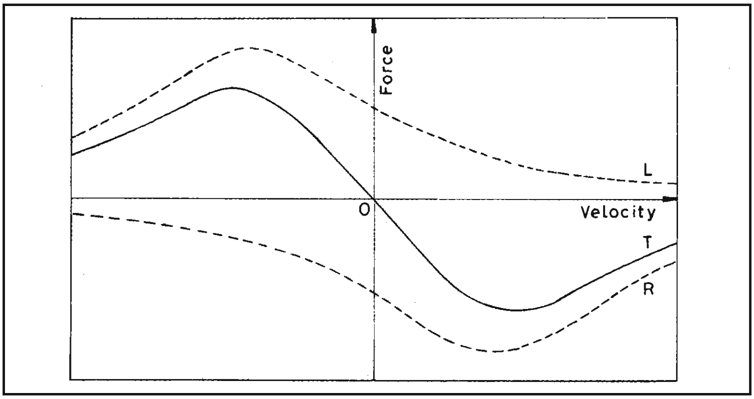


*Figure 2 The force on an atom plotted against its velocity for two counter propagating beams R (coming from the right) and L (coming from left) along the direction of the motion of the atom. The two light beams have the same frequency and intensity. The force due to light coming from the right is indicated by the curve with the label R and the force due to the beam coming from the left is indicated by the curve labelled L. The sum of the two forces on the atom is shown by the curve T. It is seen that the force is proportional to the velocity for small velocities and opposes the velocity. This is responsible for Doppler cooling.*

produces a force proportional to that component of velocity and opposing it, the net force is a frictional force proportional to and countering the velocity. Each component of the velocity will be brought to zero. Such a configuration of laser beams is called the *optical molasses* to convey the idea that the atoms are moving through a viscous medium. Experimentally, it was first demonstrated by Steven Chu and his collaborators at the AT&T Bell Laboratories in 1985.

The second question that arises is: "can the atom be really brought to rest?" Actually, this cannot be done for several reasons, one of which is that it would violate Heisenberg's uncertainty principle. Though the mean velocity of the atom can be zero, its mean square velocity is not. This is a well known result from the kinetic theory of gases. A gas at a finite temperature can have a finite root mean square velocity, which in fact is a measure of the temperature of the gas. Atoms at rest will correspond to a temperature of absolute zero which is unattainable. The atoms can be cooled to a finite, though low, absolute temperature. The key to understand this lies in the spontaneous emission process. Spontaneous emission results in no net transfer of momentum on the average. However, each individual emission event gives a momentum kick $h/\lambda$ to the atom, but in a random direction. This results in a random walk in momentum space in steps of $h/\lambda$ and the mean square momentum (ie.displacement in momentum space) increases

In spontaneous emission the atom receives momentum kicks in random directions. This leads to a heating of the atoms at a constant rate.

A stable temperature is attained when the cooling rate due to Doppler cooling balances the heating rate due to spontaneous emission.

linearly with time. Thus the atoms are getting *heated* at a steady rate. On the other hand the frictional force on the atom cools it. Under equilibrium conditions, when the heating and cooling rates become equal, the atoms attain a stable temperature T. Theory shows that the lowest temperature $T_{min}$ is obtained when the lasers are *detuned* half a line width ($\Gamma/2$) below resonance, and

$$T_{min} = h\Gamma/2\pi k_B$$

where $k_B$ is the Boltzmann constant. For a typical atom such as sodium for the yellow resonance line, this lowest temperature is 240 μK.

By the year 1986, researchers in many laboratories were able to demonstrate Doppler cooling using optical molasses in alkali atoms such as sodium. The energy levels of sodium are in the visible (the same yellow that you see from sodium vapour lamps in the streets), and were easily accessible with tunable dye lasers. The early results seemed to confirm the predictions of the above model, albeit without great accuracy. Soon after, scientists started doing careful experiments to measure the velocity distribution and temperature of the cloud of atoms under varying conditions of laser detuning, laser intensity, ambient magnetic field and so on. Startling new results were discovered. For example, in sodium, the lowest temperature reached was found to be much lower than the theoretically predicted minimum of 240 μK. The minimum temperature was found when the detuning of the laser beams was around 20–30 MHz and not around 5 MHz as predicted by theory. The final temperature attained was also sensitive to stray magnetic fields which were so small that they should not have caused any perturbation if the original model for cooling was correct.

Experiments consistently indicated that the final temperature attained was lower than that calculated theoretically.

A flurry of experimental activity followed with lower and lower temperatures being reported. An enormous amount of experimental data was accumulated before sufficient clues could be found to explain the 'anomalous' results. The basic flaw in the original model is the assumption that the ground and excited states of the atom are non-degenerate. In reality, each of the states is made up of several sub-levels which split in energy in a local magnetic field as in the familiar Zeeman effect. Also the interaction of the atom with the radiation produces small shifts of these different sub-levels called *light shifts*. The shift depends on the polarisation state of the light and the transition probability between the sub-level in the ground state and the sub-levels in the excited state for that polarisation of the light. When these factors are taken into account additional cooling mechanisms become available and one can theoretically account for the 'anomalous' experimental results. The ultimate limit to the lowest temperature attained appears to be set by the recoil velocity imparted to an atom by the spontaneous emission of a single photon. This would appear to be the fundamental limit since the uncertainty in the velocity of the atom should at least correspond to the velocity imparted to it by a single photon emission. After the new theoretical developments in laser cooling by Chu and Cohen-Tannoudji, temperatures close to the single photon recoil limit have indeed been measured. Scientists have even developed ingenious schemes to reach a spread in atom velocities lower than the single photon recoil limit.

The anomalous results are explained on the basis of degeneracy (presence of sub-levels) of the ground and excited levels and their energy shifts and optical pumping due to the polarisation gradient of the light in the optical molasses.

## Trapping of Atoms

The atomic cloud cooled in an optical molasses to a few tens of a micro-degree Kelvin has a diameter of a few millimetres. The root mean square velocity of the atoms is of the order of a cm/s. So the atoms will leak out of the molasses region in a time of about a second or less. This is insufficient to carry out experiments on the atomic cloud. One will have to trap the atomic cloud so that they reside in a confined region for times of several tens of seconds. This is done by creating a potential well in which the atomic cloud can be trapped.

There are several ways in which such a potential well can be created. One may apply a fairly large magnetic field which increases from a minimum value at some point outwards. As

In the optical molasses the atoms leak out in a time of the order of 1 second. To obtain much larger residence times in which experiments could be done the atoms have to be trapped in a potential well.

said earlier, generally atoms have many degenerate levels, whose degeneracy can be lifted with a magnetic field leading to magnetic sub-levels. Since there can be magnetic sub-levels in the ground state, the energy of which will increase with the magnetic field, atoms in such sub-levels will be trapped in an inhomogeneous magnetic field. This is called a *magnetic trap*. However the barrier heights in such a trap will not be very high unless one applies magnetic field gradients of the order of a few hundred gauss/cm. One may also focus a laser beam which is detuned to a lower frequency from the absorption line. In such a beam there is a force on an atom arising from the gradient of the light intensity. For a red detuned beam the minimum of the potential energy occurs where the intensity is a maximum i.e. at the focus. However the volume of the trapped region is very small and fluctuations in the laser intensity cause a heating of the trapped cold atoms.

The most useful trap in which a large number of atoms (about $10^{10}$ atoms) can be trapped to a density of about $10^{11}$ atoms/cc is the *magneto-optical trap*. (See *Figure 4*) In this trap one applies a *quadrupole* magnetic field whose magnitude increases linearly outwards, and laser beams in an optical molasses configuration. For simplicity consider a one-dimensional situation shown in *Figure 3*. The magnetic field increases from zero linearly with the x co-ordinate from the origin. At the same time the two counter propagating laser beams are circularly polarised in

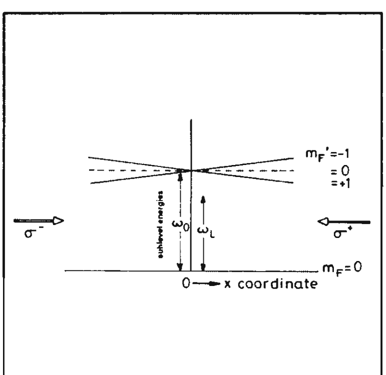


***Figure 3.** An atom in a magnetic field varying linearly with position and placed in two counter-propagating laser beams of polarisations $\sigma^+$ and $\sigma^-$. The ground state of the atom has an angular momentum quantum number $F=0$, $m_F=0$ and the excited state a quantum number $F'=1$ with three sub-levels $m_{F'}=+1,0,-1$. The variation of the energies of the different sub-levels due to the linearly increasing magnetic field is shown in the figure. $\omega_L$ is the frequency of the laser beams. It is red-detuned with respect to the absorption frequency $\omega_0$ of the atom in the absence of the magnetic field. For an explanation of the trapping action see text.*

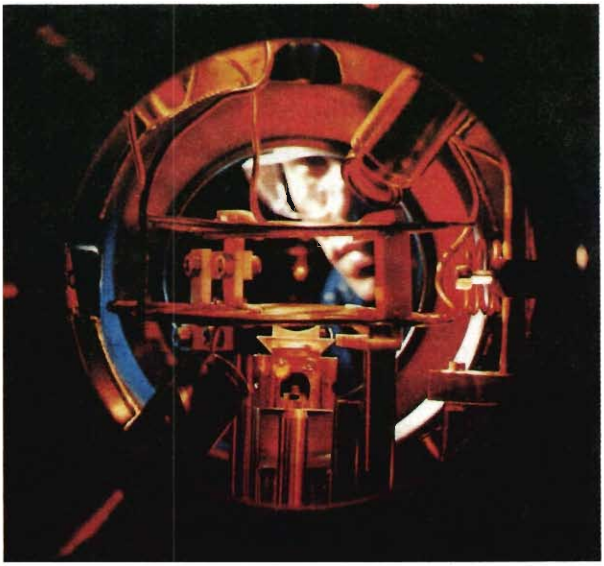

*Figure 4. A magneto-optical trap (MOT). The yellow dot is the cloud of sodium atoms. (Courtesy: Royal Swedish Academy of Sciences).*

opposite directions called $\sigma^+$ and $\sigma^-$ as shown in the figure. We consider an atom with a ground state having the angular momentum quantum number, F = 0 and an excited state with an angular momentum quantum number F' = 1. F is the total quantum number of a state including the orbital and spin angular momenta of the electrons and the spin angular momentum of the nucleus. Hence the ground state is non-degenerate and its energy is unaffected by the magnetic field. The excited state has three magnetic sub-levels ($m_F = -1, 0, 1$), and the interaction of the magnetic moment of the atom with the magnetic field causes the energy of the three sub-levels to vary with position as shown in the figure. The magnetic sub-level $m_F = 0$ is unaffected in energy while the energy level $m_F = -1$ increases linearly with x, and the energy of the sub-level $m_F = +1$ decreases linearly with x. The photon with $\sigma^+$ polarisation causes a transition from $m_F = 0$ to $m_F = +1$ while the photon with polarisation $\sigma^-$ causes a transition from $m_F = 0$ to $m_F = -1$. Since the laser beams are red detuned , when the atom is towards the right of the origin the energy level separation between $m_F = 0$ and $m_F = +1$ comes closer to the laser frequency thus increasing the absorption rate of $\sigma^+$ photons. On the other hand the energy separation between $m_F = 0$ and $m_F = -1$ increases as the atom moves towards the right and so the absorp-

A combination of optical molasses with circularly polarised light beams and a quadrupolar magnetic field yields the magneto-optical trap (MOT).

The magneto-optical trap (MOT) in conjunction with laser cooling enables one to perform novel experiments on atom clouds cooled to very low temperatures.

tion rate of $\sigma^-$ photons decreases. The differential absorption exerts a restoring force on the atom opposing the displacement. When the atom moves to the left from the origin more $\sigma^-$ photons are absorbed than $\sigma^+$ photons again producing a restoring force on the atom. The restoring force is proportional to the displacement but opposes it. The atom therefore finds itself trapped in a potential well. The frictional force arising from the Doppler effect cools the atom and the restoring force of the magneto-optical trap localizes the atom. This one dimensional situation can be extended to a three dimensional optical molasses by a suitable magnetic field and arrangement of circular polarisations of the counter propagating laser beams.

The magneto-optical trap (MOT) in conjunction with laser cooling enables one to perform novel experiments on atom clouds cooled to very low temperatures.

## Applications of Laser Cooling

It will not be possible to explain even cursorily all the different applications of ultra-cold atoms which have been realised to date.

It is possible to project the atomic cloud upwards like one would toss a ball. The cloud will reach a certain height and fall down due to gravity. This is called an *atomic fountain*. An artist's impression of such a device is on our front cover. The projection of the atom cloud upward can be done by arranging the two counter propagating beams in the vertical direction to have slightly different intensities or slightly different velocities. Once the atom acquires the required velocity, the laser beams are turned off and the atomic cloud executes a free fall under the gravitational acceleration due to the earth's pull.

One can use the atomic fountain to measure the acceleration due to gravity to a precision of 3 parts in $10^8$ and rotational frequencies as small as $5\times10^{-13}$ radians per second.

The transition between two hyperfine states of the ground level of the Caesium atom is used to define the standard of time ie. the second. Normally one uses Caesium atoms from an oven in measuring the clock frequency of the atom. These atoms have speeds of several tens of metres per second and this is responsible for limiting the precision of the time standard to one part in $10^{13}$. But with laser cooled atoms, the atoms in the fountain will have velocities of a few centimetres per second. The lower velocity substantially enhances the precision of the time standard by two to three orders of magnitude.

Using ultra-cold atoms one can improve the precision of the time standard, measure $g$ and rotational frequencies with very high sensitivity, produce Bose-Einstein condensation of atoms and carry out experiments to test the fundamental laws of quantum physics.

One can use the atomic fountain to measure the acceleration due to gravity to a precision of 3 parts in $10^8$ and rotational frequencies as small as $5\times10^{-13}$ radians per second.

Using laser cooled atoms and evaporatively cooling them further, temperatures as low as a few tens of a nK have been reached. It was possible for the first time in 1995 to observe Bose-Condensation in a cloud of $^{87}Rb$ atoms cooled below 170 nK (*Resonance*, February 1996). In the last two years the properties of such condensates have been investigated. In such a condensate the entire cloud of atoms behaves 'coherently' i.e. all atoms are in the same quantum state and behave similarly. Such a cloud of atoms can be used for new techniques of lithography to make high density integrated circuits and storage devices. The most optimistic of these scenarios promises to put an entire movie's worth of data in a disc the size of a small coin, or a computer that hides inside your palm!

It is tacitly assumed that the charge on a proton is exactly equal in magnitude but opposite in sign to the charge on an electron. This makes an atom electrically neutral. However if there is a slight difference between the magnitudes of the proton and electron charges, the atom will not be strictly neutral. Ultracold atoms can be used to verify how accurately the charge of a proton compensates the charge on an electron. Ultra-cold atomic clouds can be used to test some of the fundamental laws of quantum physics.

The list of potential applications seems endless. The Nobel Committee was probably well aware of this when they chose this year's winners.

*Address for Correspondence*
Vasant Natarajan
Department of Physics
Indian Institute of Science
Bangalore 560 012, India

R Srinivasan,
Raman Research Institute
C V Raman Avenue
Sadashivanagar
Bangalore 560 080, India