Laser cooling and trapping of ions and atoms

R. Srinivasan

Raman Research Institute, C. V. Raman Avenue, Sadashivanagar P.O., Bangalore 560 080, India

In the last fifteen years, techniques for laser cooling and trapping of atoms have been developed successfully and many new and important results in high resolution spectroscopy, atom beam interferometry and Bose–Einstein condensation have been obtained. In our country, a few groups are just embarking on these techniques. We describe here the essential components of a laser cooling and trapping set up for Rb using inexpensive diode lasers.

TECHNIQUES have been developed in the last fifteen years to use low power lasers (10 to 50 mW) tuned close to a resonant absorption frequency of an atom to reduce the average kinetic energy of a group of atoms at low pressure (about 10^{-8} to 10^{-10} Torr) to the kinetic energy appropriate to a few tens of a micro-degree Kelvin. The alkali atoms which have a lone electron in the outermost *s* shell (principal quantum number *n*) have a convenient resonant transition from $nS_{1/2}$ to $nP_{1/2}$ or $nP_{3/2}$. Sodium, rubidium and cesium have been the subjct of intensive investigations. Of these atoms, Rb and Cs have the resonant absorption at 780 nm and 852 nm respectively while Na has a resonant absorption at 589 nm. While an expensive dye laser is required to tune in to the resonant absorption of Na, relatively cheap diode lasers can be used with Rb or Cs.

After cooling the atoms, one would like to retain them in a confined region long enough to carry out experiments on them. This is achieved using traps. Ions are affected by electrical fields and one can produce a deep trap for ions relatively easily by the use of rf electrostatic fields (Paul trap) or steady electromagnetic fields (Penning trap). But neutral atoms are not affected by electrostatic fields and the pure magnetic traps produce a trap of low depth (of the order of a few mK) for weak field-seeking atoms. The most convenient trap is the magneto-optical trap (MOT), which uses a quadrupolar magnetic field in combination with appropriately circularly polarized laser beams tuned slightly to the red of the resonant absorption frequency of the atom. With such traps it will be possible to retain atoms and cool them to a temperature below a few hundred micro-Kelvin for times long enough to perform crucial experiments, if the background pressure of the atoms is low. A variety of important experiments have been done on such groups of atoms with a number of new results.

In this country we are just beginning to appreciate the importance of research in this area. Laser cooling and trapping can be achieved with relatively affordable expense if one chooses the appropriate atom for cooling and uses cheap diode lasers. This special section contains articles which, it is hoped, will stimulate the interest of workers in India to build such systems and start research in this area. In this introductory article some guidelines are given for setting up a laser cooling and trapping apparatus for ^{87}Rb. The reader is strongly advised to read refs 1, 2. They provide valuable practical tips for setting up such a laser cooling and trapping system for Rb.

A set-up for laser cooling Rb using a diode laser

The various components of a laser cooling and trapping set up for Rb will consist of the following:

(a) A grating stabilized tunable laser diode producing about 10 to 30 mW of power at 780 nm with optical components such as mirrors, lenses and quarter wave plates for producing cooling and trapping,

(b) A second grating stabilized laser diode of about 10 mW power to repump the atoms from a dark hyperfine ground state,

(c) Two magnetic field coils to produce a quadrupolar magnetic field for trapping,

(d) A tuned probe laser beam with a photomultiplier tube to measure the temperature of the cloud.

(e) A glass or metal UHV system to produce a vacuum of 10^{-7} to 10^{-9} Torr using an ion pump and a suitable source of Rb vapour.

Before describing the individual parts and their functions, let us first consider the energy level diagram of ^{87}Rb and make a few introductory remarks on laser cooling.

Energy level diagram of Rb^{87}

Rubidium is an alkali atom with one outermost electron in the 5*s* sub-shell. The atomic ground state of Rb (neglecting hyperfine interaction with the nucleus) is $5^2\ S_{1/2}$. The excited states are $5^2\ P_{1/2}$ and $5^2\ P_{3/2}$. The electron has a hyperfine interaction with the nucleus the strength of which depends on the nuclear spin I. There are two relatively abundant isotopes of Rb, namely ^{87}Rb and ^{85}Rb. The nuclear spin I of the former isotope is 3/2 and of the latter isotope is 5/2. Due to the hyperfine interaction any atomic energy level is split into hyperfine levels with a quantum number F taking integral values between $I + J$ and $|I - J|$. So for ^{87}Rb the ground atomic state is split into two hyperfine levels with $F = 1$ and 2. For ^{85}Rb the corresponding ground state hyperfine levels have the quantum numbers $F = 2$ and 3.

The splitting of the hyperfine levels is also different. The excited state $5^2P_{1/2}$ splits into two energy levels $F' = 1$ and 2 for ^{87}Rb and $F = 2$ and 3 for ^{85}Rb. The other excited atomic state $5^2P_{3/2}$ will split into four hyperfine levels with $F' = 3, 2, 1$ and 0 in ^{87}Rb and $F' = 4, 3, 2, 1$ in ^{85}Rb. The energy level diagram for the hyperfine levels of $5^2S_{1/2}$ and $5^2P_{3/2}$ of ^{87}Rb is shown in Figure 1, as this is the atomic transition that will be used for cooling. The hyperfine levels of $5^2P_{1/2}$ are not shown to avoid cluttering up the figure. The pumping diode laser for cooling will be tuned to the frequency corresponding to the transition from $F = 2$ to $F' = 3$. This corresponds to a wavelength of 780 nm approximately. The natural line width of this transition is 6 MHz. The pumping laser line width should be much less than the natural line width. It will be of the order of a few kHz to 1 MHz.

Brief theory of laser cooling and trapping

Let a group of ^{87}Rb atoms (about 10^7 atoms) at very low pressure (about 10^{-7} to 10^{-9} Torr) be placed between two counter-propagating laser pump beams (Figure 2 *a*) tuned slightly to the red of the absorption frequency corresponding to the pumping transition (i.e. $w_L < w_0$, where w_L is the angular frequency of the laser beam and w_0 the angular frequency of the transition from $F = 2$ to $F' = 3$). Let the intensity of the laser beam be small compared to the intensity required to saturate the absorption which is about 4.1 mW/cm^2. The absorption curve for the atom, as shown in Figure 2 *b*, will follow a

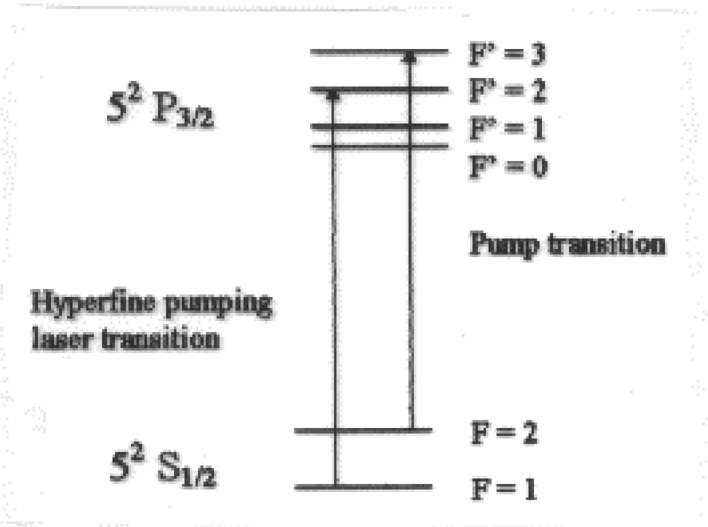

Figure 1. Energy level diagram for ^{87}Rb.

Figure 1. Energy level diagram for ^{87}Rb.

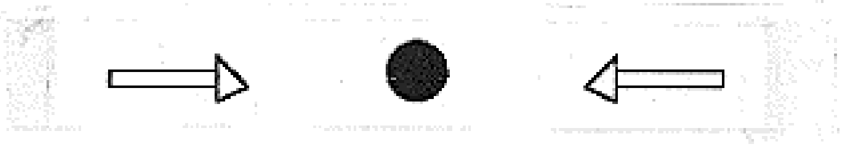

Figure 2. *a*, A cloud of ^{87}Rb atoms placed between two counter-propagating red detuned laser beams.

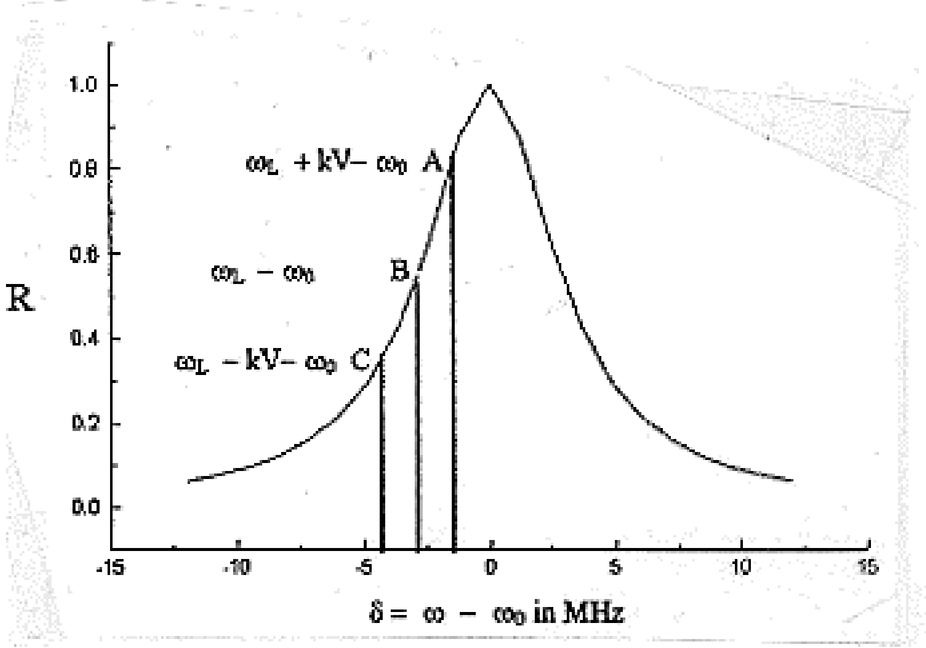

Figure 2. *b*, Normalized scattering rate as a function of detuning.

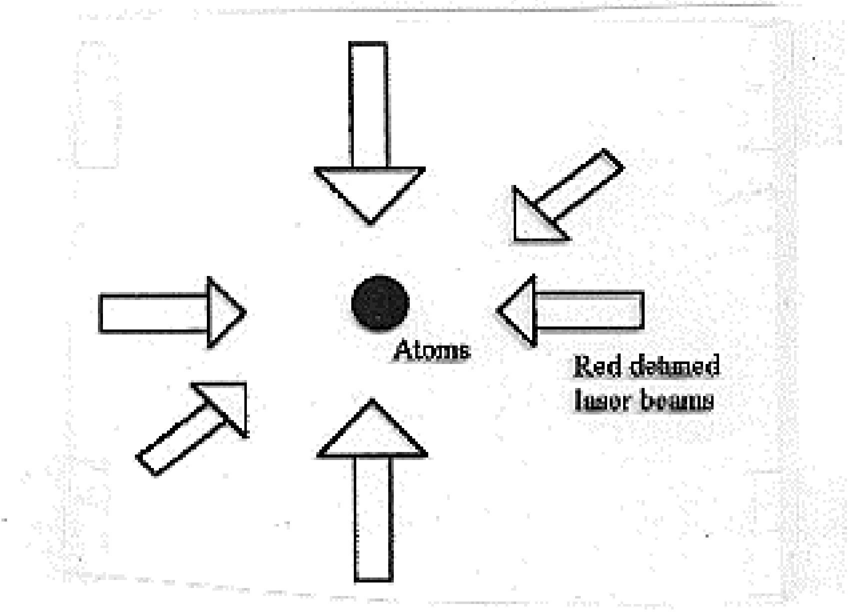

Figure 2. *c*, Three dimensional optical molasses.

Figure 2. ***a***, A cloud of ^{87}Rb atoms placed between two counter-propagating red detuned laser beams.

Figure 2. ***b***, Normalized scattering rate as a function of detuning.

Figure 2. ***c***, Three dimensional optical molasses.

Lorentzian shape with a peak at ω_0 and a full width at half maximum, Γ ($2\pi \times 6$ MHz). Γ is related to the life time τ of the excited state due to spontaneous emission by

$$\Gamma = 2\pi/\tau .$$

Let us for the moment disregard the multiplicity of the ground and excited states. An atom with a velocity V moving to the right will see the angular frequency of the laser beam coming from the right to be blue shifted to $\omega_1 = \omega_L + kV$ (the point A on the absorption curve) while the angular frequency of the laser beam coming from the left will be red shifted to $\omega_2 = \omega_L - kV$ (the point C on the absorption curve), where $k = 2\pi/\lambda_L$, is the wave-vector of the laser photon. Since ω_1 is closer to ω_0 than ω_2, more laser photons will be absorbed by the atom from the laser beam coming from the right than from the beam coming from the left. Absorption of a photon imparts a momentum $hk/2\pi$ in the direction of the beam. Here h is the Planck's constant. So the atom experiences a differential force proportional to $-V$, pushing it to the left and slowing the atom moving to the right. An atom moving to the left will absorb more photons from the beam coming from the left and less photons from the beam coming from the right. So it will also experience a damping force proportional to its speed. This damping force will slow down the atom. If the atomic transition is a strongly absorbing one, several thousand photons can be scattered in a second producing a strong damping force proportional to the speed of the atom. The damping force will be a maximum when the velocity of the atom is approximately given by $v \approx \Gamma/k$. On absorbing the photon, the atom goes to the excited state. From the excited state it comes down to the ground state mainly by spontaneous emission, since the intensity of the laser beam is much less than that required to saturate the absorption. The photon is emitted in a random direction and the atom acquires an equal and opposite momentum. Spontaneous emission corresponds to a random walk in momentum space with a momentum step of size $hk/2\pi$. This will increase the kinetic energy of the atom proportional to time and so it corresponds to heating. If we have three pairs of counter-propagating laser beams, as shown in Figure 2 *c*, *all derived from a single laser source and all equal in intensity*, the atom moving in any direction will experience a damping force proportional to its speed. The region of overlap of the three pairs of counter-propagating laser beams is called 'optical molasses'. Though the rare interatomic collisions at the low pressures prevailing in the molasses region are not important in achieving a Maxwellian distribution of velocities, such a distribution is achieved in a random walk problem with a damping proportional to the velocity. Hence one is justified in talking about a temperature for the cloud in the optical molasses. This mechanism of cooling is called the Doppler cooling mechanism. The lowest temperature that can be achieved by Doppler cooling is given under ideal conditions (i.e. the red detuning $\omega_L - \omega_0 = -\Gamma/2$) by

$$T_{\text{min}} = h/2k_{\text{B}}\ \text{t}\ ,$$

where k_{B} is the Boltzmann's constant. The final temperature achieved is independent of the intensity of the laser beam. For Na^{23} the minimum temperature is 240 µK.

The multiplicity of the ground and excited states produces two complications. The first is optical pumping. This implies a redistribution of population among the multiple levels (hyperfine levels or even Zeeman levels of a hyperfine level) due to a series of absorption emission cycles. The second is light shift. This refers to the shift in the energy levels of the different magnetic and hyperfine multiplets due to their interaction with the pumping light beam. This shift depends on (1) the intensity of the light beam and (2) the probability for transition from one of the ground state multiplets to another of the excited state multiplets. Both light shift and optical pumping will therefore also depend on the nature of the polarization of the light at any point in the optical molasses. Since six linearly polarized light beams overlap in orthogonal directions in the optical molasses, the state of polarization of the electromagnetic field in the optical molasses varies rapidly over a length scale of the order of l_{L}. In the presence of such a polarization gradient in the molasses, other mechanisms of cooling involving optical pumping and light shifts take place which operate more effectively on slower-moving atoms to produce a final temperature much lower than what can be realized by Doppler cooling[3]. For these mechanisms to act effectively, the splitting of the magnetic sub-levels of a hyperfine level by a residual magnetic field must be much smaller than the light shifts. To achieve the ultimate minimum temperature with the help of sub-Doppler cooling, the optical molasses region will have to be very well shielded from any residual magnetic field. But for cooling to a few hundred micro-Kelvin, such a shielding is not required.

The cooled atoms will diffuse out of the optical molasses within a time of the order of a second or less. In order to build a sufficiently large number of laser-cooled atoms confined within a region of the order of a cubic millimetre with a lifetime of about 100 seconds, it is necessary to trap the neutral atoms. This is not the place to discuss the different ways to trap neutral atoms. These are discussed briefly in ref. 3. Suffice it to say that by using a quadrupolar magnetic field producing a field gradient of a few Gauss/cm and using appropriately circularly polarized counter-propagating laser beams tuned to the transition from F to $F¢ = F + 1$, it will be possible to produce a trap of depth from 0.1 to 1 K in which the neutral atoms can be trapped. The quadrupolar field is produced by having two coaxial coils through which a current of one to two amperes can be sent in opposite directions. The position of the zero of the magnetic field should coincide nearly with the centre of the optical molasses. Such a trap is called a magneto-optical trap (MOT). The restoring force is produced by the differential absorption of counter-propagating beams between magnetically split Zeeman levels of the atom. Near the point where the magnetic field is zero, the restoring force is linearly proportional to the distance. The trapping force is accompanied by the damping produced by the Doppler and sub-Doppler cooling mechanisms. So the potential is an axially symmetric overdamped harmonic potential. The mechanism of trapping and a detailed description of the MOT will be presented in the accompanying article by Jagatap.

In the MOT, the number of atoms trapped does not depend sensitively on the actual depth of the trap or on the exact alignment of the counter-propagating beams. The equality of intensity of counter-propagating beams is also not a sensitive parameter. The misalignment of the optical beams or slight differences in the intensities of the beams only distort the shape of the cloud without seriously affecting the number of atoms trapped or the temperature of the cloud. So it is not very difficult to achieve laser cooling and trapping of the Rb cloud.

In the case of ions it is possible to use electrostatic forces (Paul trap) or electromagnetic forces (Penning trap) to trap them in a deep trap. In an accompanying article, ion traps with special reference to Paul trap will be discussed by Menon.

Characteristics of a laser diode

It is necessary to procure a diode laser giving an output power between 10 and 50 mW and lasing at approximately 780 nm for laser cooling and trapping Rb atoms. AlGaAs index-guided laser diodes are available at a cost of a few hundred dollars for a thirty mW diode. The diode will lase when the injection current exceeds a threshold value. The power output increases approximately linearly with injection current above the threshold. The active region has a height which is a fraction of a micron, a width of about 1 micron and a length of a fraction of a millimetre. A detailed account of the characteristics and operations of diode lasers is given in refs 4, 5. The following characteristics of the diode laser are important for our purpose:

> a) The diode laser can oscillate in the TE or TM mode. In the former, the electric field is parallel to the plane of the active region whereas in the latter the electric field has a component perpendicular to the plane of the active region. Since the TE mode has a higher reflectivity than the TM mode at the faces of the cavity, the lasing threshold power for the TE mode is less than that of the TM mode. So the TE mode is preferentially excited as the lasing current crosses the threshold. The output beam is nearly linearly polarized with the electric vector parallel to the plane of the junction.
>
> b) The single mode diode laser spectrum is dominated by a single Lorentzian line with a spectral width of 10 to 100 MHz. The single mode is accompanied by weaker features, corresponding to relaxation oscillations, approximately 2 to 3 GHz away from the single mode frequency.
>
> c) The frequency of the single mode can be tuned either (a) by varying the temperature or (b) by varying the injection current. The injection current tuning arises because of the heating produced by the current. Changes in index of refraction due to the injection current also play a role in tuning. The tuning curve of a diode laser is not continuous but

has a staircase pattern. The continuous segments in the staircase correspond to changes in cavity length for the single mode due to temperature changes while discontinuous changes correspond to switching between different longitudinal cavity modes due to the shifting of the gain curve (see the accompanying paper by Santa Chawla). These different modes are separated by about 170 GHz or 0.35 nm in a typical AlGaAs index-guided diode. One may therefore change the temperature of the diode by ten to twenty degrees above or below room temperature to achieve a limited range of tuning over a few nm for AlGaAs lasers. The higher the temperature of the diode, the shorter its lifetime.

Due to the breaks in the tuning range, it may happen that a single diode may not tune in to the required transition even by changing its temperature. It will therefore be necessary to buy a few diodes stated to lase around a particular wavelength to find the right diode to tune in to the atomic transition. The dependence of the lasing wavelength on the injection current allows the possibility of amplitude or frequency modulating the diode output to scan the laser quickly over a range of frequencies.

d) It is necessary to reduce the line width of the laser to 1 MHz or below and to stabilize the frequency. This can be done by using optical, electronic or combined feedbacks and the methods of frequency stabilization are dealt with in the accompanying article by Santa Chawla. It is only necessary to mention that the temperature of the diode and the external cavity should be controlled to within a milliKelvin to prevent changes in length of the cavity causing a destabilization of the frequency.

e) In using a diode laser, care must be taken to see no other spurious external feedback occurs due to light reflected at the surface of the optical components retracing its path back to the laser. Such a feedback will shift the laser frequency and cause instability in the operation of the laser. One may use an optical isolator for this purpose.

f) The laser should be protected against transient voltages and currents which will damage the laser. Suitable protection circuits must be provided.

g) A laser diode will change its lasing frequency and its tuning characteristics with time.

Due to the small transverse dimensions, the laser beam emerging from the diode has a considerable divergence. It is generally elliptical in nature with a divergence angle of about 30° perpendicular to the plane of the junction and 10° in the plane of the junction. The beam can be collimated using a plastic lens of small focal length. The beam can be made to have a Gaussian profile within about 10% using inexpensive lenses and spatial filtering.

Optical elements

A schematic diagram of the laser cooling arrangement is shown in Figure 3. The output of the laser beam from the frequency-stabilized laser diode (1) is expanded by a two lens telescope arrangement (3). The numbers in the brackets refer to the numbers in Figure 3. The expanded beam will have an elliptical cross-section with the major axis nearly three times the minor axis. The beam should be expanded so that the minor axis is about 1.5 cm or more. By using dielectric coated mirrors (4, 6, 7, 9, 10 and 11) it will be possible to divide the incident beam into three beams of nearly equal width and equal intensity travelling in three mutually orthogonal directions in the trapping cell. Two of these directions can be arranged parallel to the plane of the lasing junction. Let us call this the horizontal plane. This is advantageous for the following reason. Light coming out from the laser will be polarized with the electric vector in the horizontal plane. Linearly polarized light reflected by a mirror will retain its linear polarization if the polarization of the incident light is either *parallel* or *perpendicular* to the plane of incidence. So the two horizontal beams generated by the mirrors 4 and 7 will remain polarized in the same orientation as the incident beam. However to get the vertical beam, one will have to use a combination of mirrors at which the planes of incidence will not be parallel or perpendicular to the direction of polarization of the laser beam. Thus the vertical beam will be elliptically polarized. However as long as the ellipticity is less than 10%, this will not matter. The state of

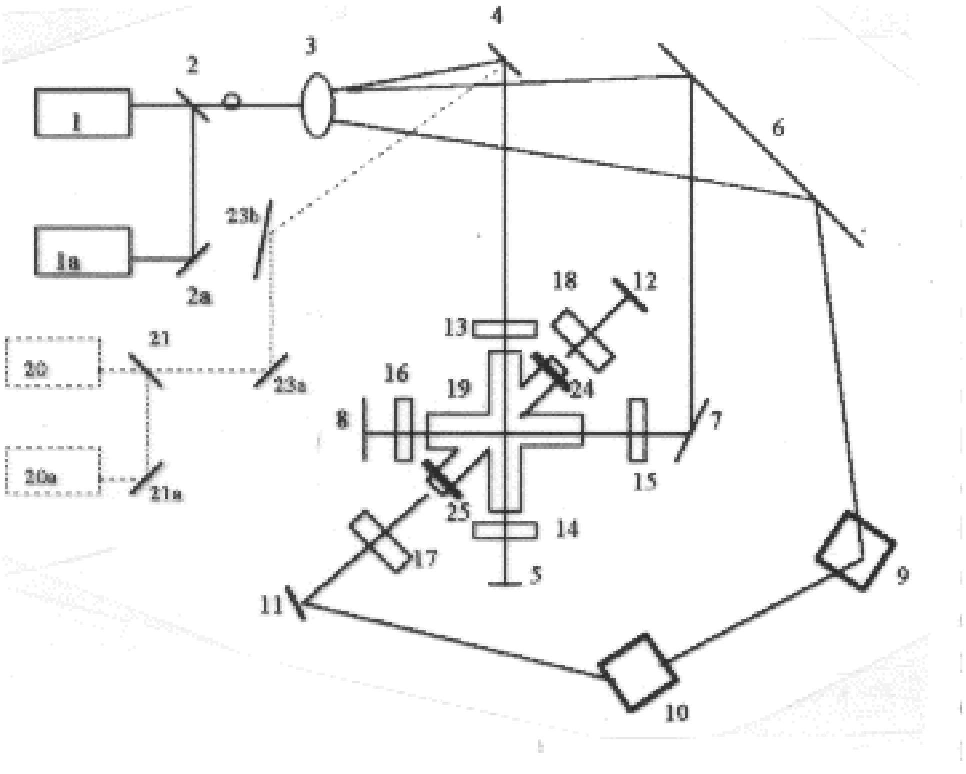

Figure 3. Schematic of a laser cooling and trapping set-up.

Figure 3. Schematic of a laser cooling and trapping set-up.

polarization of the light can be tested by using an analyser and looking at the extinction on rotating the analyser.

For the magneto-optical trap the beams will have to be *circularly polarized*. The two beams perpendicular to the axis of the magnetic field will have to be circularly polarized in the same way looking towards the beam. The beam along the axis of the magnetic coils should be circularly polarized in the opposite direction. This is achieved by setting the axes of the four quarter wave plates 13, 14, 15 and 16 rotated + 45° clockwise relative to the direction of polarization of the light beams and the axes of the other two quarter wave plates 17, 18 at an angle of –45° to the major axis of the slightly elliptically polarized beam. One will have to see if the atoms are trapped by switching on the current in the two magnet coils. It may be necessary to reverse the current in the coils to achieve the trapping condition with the given setting of the states of circular polarization of the laser beams. The circularly polarized light beams along the three orthogonal directions pass through the quarterwave plates (14, 16, and 18) before they are retro-reflected by the three mirrors (5, 8 and 12). They again pass through the same three quarter wave plates. This changes their states of circular polarization to be opposite to those of the forward beams. The three mirrors (5, 8 and 12) should not be set to reflect the beams back exactly along their original directions. In such a case the reflected light will get back to the laser in the absence of an optical isolator and will shift the frequency of the laser considerably. So the mirrors are set to offset slightly the forward and reflected beams. However by keeping these mirrors close to the trapping cell, one can still achieve a considerable overlap of the forward and retro-reflected beams in the trapping cell. The larger the volume of this overlap in the optical molasses, the greater the number of atoms trapped.

Hyperfine repumping laser

One out of thousand atoms pumped into $F' = 3$ state will end up in the ground hyperfine state $F = 1$. The energy level difference between $F = 1$ and $F = 2$ is of the order of a GHz. Since the pumping laser line has a width of less than 1 MHz, such a laser cannot excite the atoms in the $F = 1$ ground hyperfine level to any of the excited hyperfine levels. So in course of time all the atoms will collect in the $F = 1$ ground hyperfine level and there will be no further absorption of the pump laser photons. To avoid this situation, we have to pump back the atoms collected in the $F = 1$ ground state to the $F = 2$ hyperfine level. This explains the necessity for using two laser diodes, one for cooling and one for pumping the atoms from the dark ground hyperfine level. This is done by using a second laser diode tuned to the broad transition from $F = 1$ to the four excited hyperfine levels. The power of this laser can be low, about ten milliwatts. The frequency stabilized hyperfine laser beam from the laser diode (20), is reflected by the pair of mirrors (23a) and (23b) onto the mirror (4) which reflects it to the trapping cell. The alignment of this laser beam is not very critical.

Trapping cell and vacuum system

The trapping cell is most conveniently made of glass. It is a cross with six arms to which optical windows are fused. There is a separate side arm to connect the UHV pumping system and another closed side arm to contain a source of Rb. Such a glass cell is shown in Figure 4. An all-glass cell has the advantage that it can be baked and one can achieve a vacuum of 10^{-9} Torr without much problem. The glass cell is connected on one side to a turbo-pump to create initially a vacuum of 10^{-6} Torr or better. The glass cell can then be isolated by closing the UHV valve. For achieving lower pressures and pumping out the Rb vapour, an ion pump of about 40 l/h pumping speed can be used. The current through the ion pump itself is a measure of the vacuum achieved.

A convenient source of Rb vapour is a Rb getter. This is a rubidium compound mounted inside a stainless steel oven and is commercially available. The oven is mounted on a UHV compatible feed through. By passing a current of a few amperes through the oven, one can build up enough Rb pressure to see the fluorescence in the laser beam. By adjusting the current the background pressure in the cell can be adjusted.

Magnetic coils

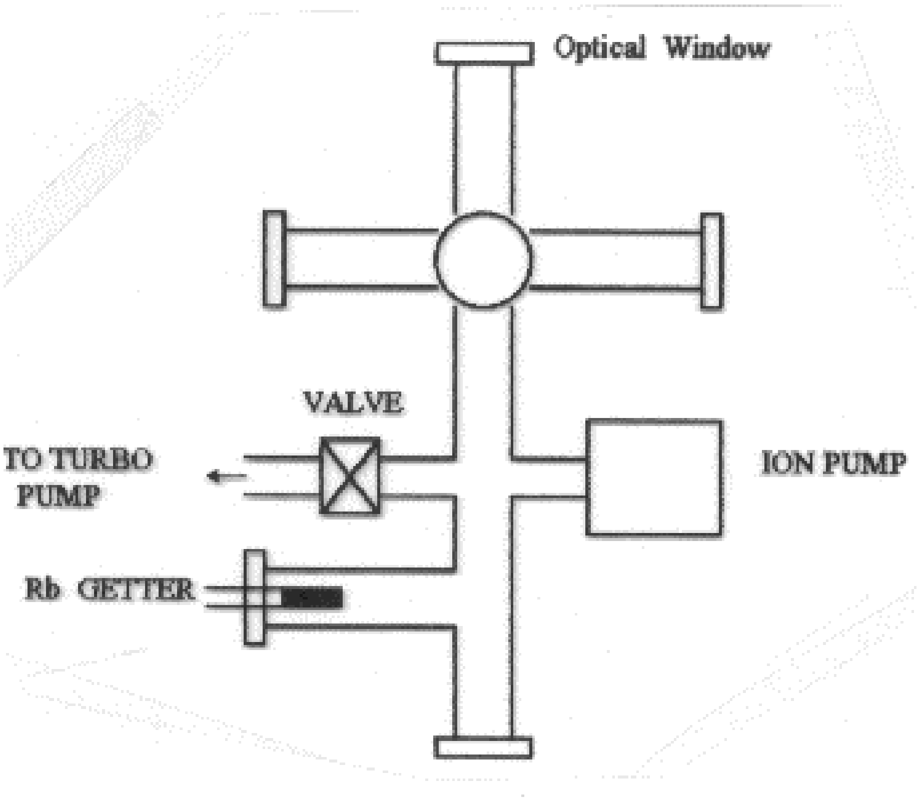

Figure 4. Trapping cell and vacuum system.

Figure 4. Trapping cell and vacuum system.

To produce a quadrupolar magnetic field, two circular coils (24 and 25 in Figure 3) of about 3 cm diameter wound with twenty turns of copper wire are mounted coaxially on the two opposite arms of the trapping cell at equal distance, 3 to 5 cm, from the centre of the optical molasses. By passing a current of few amperes in opposite directions in the two coils, one can generate a magnetic field gradient of about 10 to 20 G/cm at the centre of the trap. The field gradient along the axis is twice as large in magnitude as the radial field gradient. This produces an axially symmetric harmonic trap in which the axial frequency is $\sqrt{2}$ times as large as the radial frequency.

Operation of the trap

It is convenient to have a closed circuit television camera and TV monitor to observe the laser beams. The alignment of the laser beams is facilitated by having an IR luminiscent card. The beams are first aligned without the trapping cell in position to ensure the proper overlap of the beams at the location of the cell. The cell is then put in position. The cooling laser is operated at low power. The heating current on the rubidium getter is turned on and the current is adjusted till the pressure in the cell builds up to see the fluorescence of the rubidium vapour. Then the power of the laser diode is raised to the required value and the repumping diode is turned on. The current through the magnetic coil is switched on. One will be able to see a bright cloud of rubidium vapour trapped at the centre of the trap. If no cloud is seen, the current in the magnetic coils may not have the proper sign relative to the circular polarizations of the counter-propagating laser beams in the cell. If the current through the magnetic coils is reversed, one will be able to see the cloud.

To make an estimate of the number of atoms in the cloud, a quantitative measurement of the intensity of the fluorescence is required. This may be obtained either by using a photomultiplier tube or, less expensively, using a photo-diode with an unobstructed view of the trapping region. There will be a background fluorescence which is measured by looking at the signal from the detector in the absence of the magnetic field. The magnetic field is now turned on. If it is in the correct orientation, a significant increase in the signal will result. Knowing the efficiency of the detector and the solid angle subtended by the detector at the centre of the trapping region, and calculating the rate of atomic scattering from the formula

$$R = (I/I_s)/[1 + (I/I_s) + 4(\mathrm{d}/\mathrm{G})^2],$$

where I_s is the saturation intensity (4.1 mW/cm^2), I the sum of the intensities of the six trapping beams, d is the detuning of the laser from the peak of the curve and G the natural line width (6 MHz), one can get an approximate number of atoms in the trapped region. This will be of the order of 10^6 to 10^7 atoms and the size of the trapped cloud will be of the order of a cubic millimeter. If the intensity of one of the beams is slightly reduced or the magnetic field gradient, changed, the shape of the cloud changes.

To measure the lifetime of the atoms in the trapped region, one measures the fluorescence intensity as a function of time after switching on the magnetic field. The resulting curve shows an exponential growth leading to saturation from which the lifetime can be measured. If the partial pressure of background atoms other than Rb is negligible compared to the partial pressure of Rb, then both the rate of filling of the trap and the rate at which the Rb atoms leave the trap by collision with untrapped high velocity Rb atoms will be proportional to the partial pressure of Rb. So the final number of Rb atoms collected in the trap will be independent of pressure while the lifetime in the trap will increase inversely with the background pressure. These facts can be verified experimentally.

Applications

Laser-cooled atoms have negligible Doppler shift because of their low velocity. High resolution spectroscopic investigations can be carried out on such a cold cloud of atoms. In addition, such a cloud of cesium or other atoms can be used for improving the accuracy of the time standard. Interferometric experiments with a beam of cold atoms can be used to measure precisely the acceleration due to gravity and angular frequencies of rotation. Such interferometric experiments can also be used to test the foundations of quantum mechanics. Using laser cooling as the first stage of cooling and evaporative cooling to reduce the temperature of the cloud further, Bose–Einstein condensation of the cloud can be achieved. In the accompanying article by Vasant Natarajan, some of these applications will be dealt with.

---

1. MacAdam, K. B., Steinbach, A. and Wieman, C., *Am. J. Phys.*, 1992, **60**, 1098–1111.
2. Wieman, C., Flowers, G. and Gilbert, S., *Am. J. Phys.*, 1995, **63**, 317–330.
3. Srinivasan, R., *Curr. Sci.*, 1998, **74**, 106–110.
4. Camparo, J. C., *Contemporary Phys.*, 1985, **26**, 443–477.
5. Wieman, C. E. and Hollberg, L., *Rev. Sci. Instrum.*, 1991, **62**, 1–20.

ACKNOWLEDGEMENTS. I thank Dr N. Kumar, Director, Raman Research Institute, for his support in initiating laser cooling activity in the Institute. I acknowledge my indebtedness to my colleague, Dr Hema Ramachandran, for her help in preparing the manuscript.

BACK TO NON-FRAMES CONTENTS
BACK TO FRAMES CONTENTS