Chapter 3

Laser Cooling and Trapping of Neutral Atoms

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3.1 Cold Atoms

At room temperature the atoms of a gas move at a speed ∼300 m/s. It leaves us with a very short observation time and hence there is broadening in spectral lines. For more precise measurements slow atoms are needed. This can be done by lowering the temperature of the gas. At normal atmospheric pressure, gases condense at lower temperatures. It will first liquefy and then turn into a solid if cooled further. However, if the gas is cooled in vacuum, it remains in gaseous phase thereby making it convenient to study their properties. This is where unconventional cooling method like *laser cooling* emerged. Undoubtedly, the development of techniques for cooling and trapping of neutral atoms using laser is one of the ground-breaking scientific achievements of modern Physics [17].

["*Steven Chu, Claude Cohen-Tannoudji and William D. Phillips were awarded the Nobel Prize in 1997 for the development of methods to cool and trap atoms with laser light.*"]

It provides unique tool for precision spectroscopy, study of fundamental physics, frequency standard, etc. Depending on the technique used, finally achieved temperature can be in mK, μK or even in nK regime [18–20]. At these temperatures, the atoms follow the laws of quantum mechanics. In this viewpoint, laser cooled atoms has promising prospect for the new age quantum technologies including quantum computer and quantum simulator. Some of the applications of ultra-cold atoms are given below.

1. Bose–Einstein condensation (BEC) [21]. This macroscopic quantum system provides a unique medium, leading to matter wave application, quantized vortex, slow light propagation, optical information storage, quantum information processing and qubit.

2. Ultra-precision spectroscopic measurements by the elimination of Doppler broadening. It can overcome the transit time broadening to unprecedented level. For example, frequency standard in cold atom based optical clocks [22].
3. Ultraprecise measurement of gravitational fields based on the Doppler shift of free-falling cooled atoms on Bloch oscillations [23].
4. Lithography with cold atomic beams to form precisely controlled micro structures [24].
5. Quantum Computation (QC) is one of the most important application of ultra-cold neutral atoms. In particular, thousands of ultra-cold atoms can be loaded in optical or magnetic micro traps to create large array. This feature inherently offer scalability which is one of the key requirements of QC. Other important aspects of cold atom-based QC include feeble interaction with environment and long coherence time. These two are must criteria for error correction and disruptive computation paradigms in QC [25, 26].

["*The 2001 Nobel Prize in Physics was awarded to E. A. Cornell, W. Ketterle and C. E. Wieman for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates.*"]

3.2 Basic Principle of Laser Cooling

When an object scatters resonant light, the light exerts a force on that object. The pressure associated with this force is called ‘Radiation pressure’. This mechanical action of the light can be used to slow down atoms of a gas. Slowing down the atoms results in reduction in the associated temperature. This is the basic concept behind laser cooling of atoms. General perception is that when laser beam is incident on an object, it tends to heat the object, not cool. So in that sense laser cooling is counter intuitive. The ideas underlying laser cooling is illustrated in Fig. 3.1.

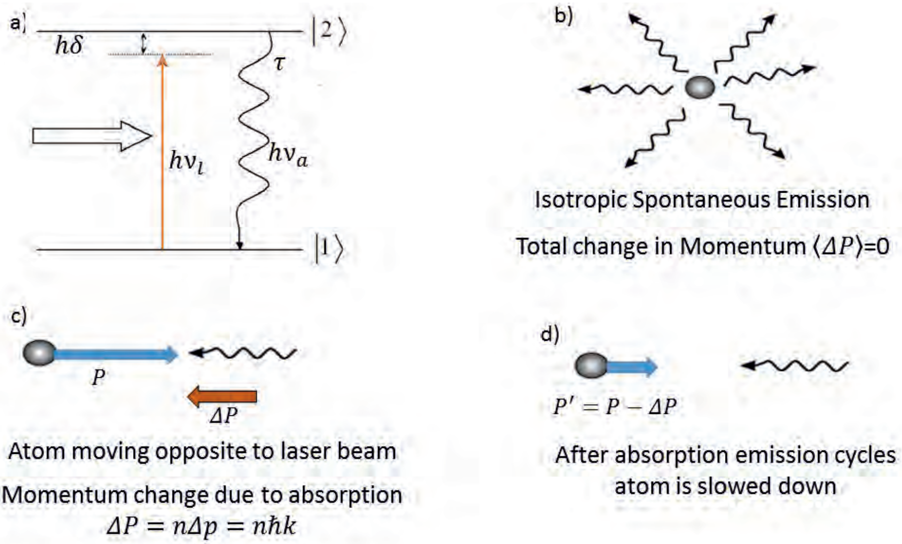


Figure 3.1: Basic mechanism behind laser cooling.

["*The radiation pressure is the reason behind the fact that a comet tails always point away from the sun.*"]

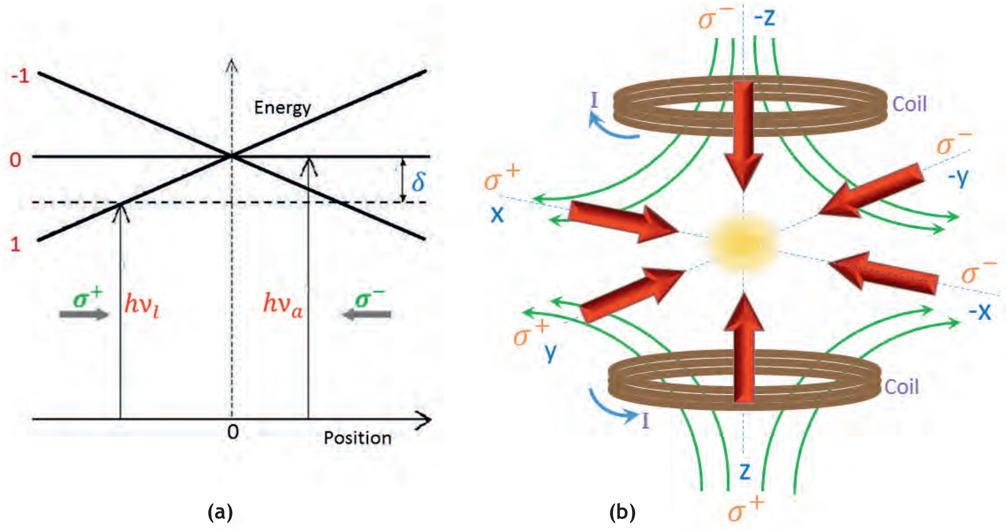
For simplicity consider a two-level atom with a ground state and only one excited state. The energy separation between these two states is $\Delta\mathrm{E} = \mathrm{h}\nu_a$. The atom is illuminated by a laser beam which is propagating along opposite direction of the atomic velocity $\vec{v}$. The laser frequency ν_l is tuned to near the atomic resonance frequency ν_a. Each laser photon, although massless but carries a momentum of $\hbar k_l$ ($k_l = 2\pi\nu_l/c$). On absorption of a laser photon the atom goes to the excited state. At the same time it also gets a momentum kick $\Delta\mathrm{p}$ which is equal to laser photon momentum $\hbar k_l$ along the direction of laser propagation. Since the excited state has finite lifetime (τ) the atom goes back to ground state by spontaneous emission of a photon. This emission of photon also gives a momentum kick by an amount of $\Delta\mathrm{P}$. However, this momentum change has no preferred direction because spontaneous emission is isotropic. So if one considers a large number (say n) of absorption emission cycles, the total change in momentum of atom due to absorption accumulates to $\Delta\mathrm{P} = n\Delta\mathrm{p} = n\hbar k$, while the change in momentum due to emission averages to zero.

["*The rms velocity of Cs atom at room temperature (300 K) is ∼240 m/s. If a laser is tuned to D_1 transition (i.e. wavelength is ∼852 nm) absorption of one laser photon would change the velocity by ∼3.5 mm/s. Therefore, typically 67500 photons are required to make the rms velocity of Cs close to zero. However there are typically 10^7 absorption emission cycles of photons per second. So the atom could be stopped within few milliseconds using the laser. This corresponds to deceleration of the order of 10^4 g !*".]

The net result is that the momentum of atom along the laser propagation direction is reduced by $\Delta\mathrm{P}$. This may be viewed that an atom is acted upon by a force. This force is called 'scattering force'. In consequence, the average kinetic energy E_k of the atom is reduced. This results in reduction in temperature according to $\frac{1}{2}k_BT = E_k$ The scattering force can be used to decelerate a beam of neutral atoms by opposing its velocity using a laser beam. For a gas a single laser beam is not sufficient. However, if the atoms are illuminated by a set of counter propagating beams there would be net force opposing the velocity of the atoms. Say for example, laser beams illuminate an atomic sample along ±x direction, tuned to red of the atomic absorption. An atom moving with a velocity $+v_x$ will be in resonance with the beam along –x but will be out of resonance for the beam along +x direction. Consequently, the atom is more likely to absorb a photon from +x beam and experience scattering force in that direction. Similarly the atom moving along –x direction with velocity $-v_x$ will experience scattering force along +x direction. Overall effect is that the atoms are slowed down in 1D. In 3D, six laser beams along ±x, ±y and ±z are required to offer a net damping force to slow all the atoms in the intersection region and reduces its temperature. This Doppler effect dependent cooling is also called as Doppler cooling.In this configuration the atoms experience a force $\vec{F} = -\alpha\vec{v}$ where α is the damping coefficient. The value of α depends on the laser intensity, laser frequency and lifetime of the excited state. The atomic motion in the field of laser beams is just like a motion of a particle in a viscous fluid. That's why a such a system of cold atoms confined by six laser beams is labeled as 'Optical molasses'. The above equation of force may imply that all atoms should decelerate to $\vec{v} = 0$ and the sample reach T = 0 which is unphysical. There is a limit to fall in temperature because there exists heating mechanism. The origin of the scattering force is the exchange of momentum in steps of $\hbar k$ between the atoms and the laser photon. The atomic recoils due to spontaneous emission are in completely random directions. The atomic sample is thereby heated. The equilibrium between cooling and heating mechanism provides the temperature limit known as Doppler cooling limit given by $T_D = \hbar\Gamma/2k_B$.

3.3 Magneto Optical Trap for Cold Atoms

The 'scattering force' can be used for cooling but this force alone cannot be used to trap the cold atom. Among many techniques, magneto-optical trap (MOT) is widely used for cooling



(a) (b)

Figure 3.2: Basic principle of MOT.

and trapping of neutral atoms. It has found extensive use in a vast variety of experiments in atomic, molecular, and optical physics [27]. It allows cooling of neutral atom gases down to temperature around ∼100 μK. A MOT can be realised by overlapping three pairs of opposing polarized laser beams along with a quadrupole magnetic field. The basic principle of MOT in one dimension is illustrated in Fig. 3.2a with one atom undergoing $J_g = 0 \rightarrow J_g = 1$ transition. In presence of a weak inhomogeneous magnetic field $B(x) = \rho x$ the energy level are split by energy difference $\Delta E = \mu\, m B(x)$ (Zeeman effect) where μ is the Bohr Magneton and magnetic quantum number of the level is labeled as m. The atoms are illuminated by two counter propagating laser beams with polarization σ^+ and σ^-, propagating along +x and –x direction respectively. Both laser beams are red detuned. Atoms located at -x (+x) region, preferentially absorb photons from $\sigma^+(\sigma^-)$ laser beam and experience a force along +x (-x) direction i.e. towards the centre.In effect the atoms experience a net time averaged force directed towards origin. This position dependent force along with velocity dependent force results in simultaneous cooling and trapping of atoms. The concept of 1D MOT may be extended to 3D MOT as illustrated in Fig. 3.2b. It involves six laser beams propagating along ±x, ±y and ±z directions. A spherical quadrupole magnetic field is produced by two current carrying coils in ‘anti-Helmholtz’ configuration.

[‘*In MOT, the atoms experience a force* ($\vec{F}$) *which is proportional to its velocity* ($\vec{v}$) *as well as its position* ($\vec{r}$) *i.e.* $\vec{F} = -\alpha\vec{v} - k\vec{r}$. *This is equation of motion of a damped harmonic oscillator.*’]

3.4 Atomic Species

Over the last few decades, many theoretical and experimental studies have been devoted to laser cooling of atoms and its application in research and industry. Many atomic species have been laser cooled including alkali atoms (Na, K, Rb, Cs, Fr), Alkaline earth metal atoms (Mg, Ca, Sr, Ra) and metastable noble gas atom (Ne, Ar, Kr). A few of these laser cooled neutral atoms have been listed in table 3.1 along with some relevant parameters including transition wavelength and Doppler cooling limit.

Table 3.1: Few relevant parameters including transition wavelength and Doppler cooling limit.

Elements	λ (nm)	T_D (μK)
^{1}H	121.6	2389
^{7}Li	670.9	142
^{23}Na	589.1	240
^{39}K	766.7	146
^{40}Ca	422.8	832
^{52}Cr	425.5	134
^{85}Rb	780.2	143
^{88}Sr	460.8	768
^{133}Cs	852.3	124
Fr	718	182

[*"Very recently laser cooling and trapping of anti-Hydrogen is also achieved [28]."*]

Alkali-metal atoms are a popular choice for laser cooling and trapping based experimental activities. The excitation frequency from the ground state to first excited state is in visible region. So, the experiments can be conducted with relatively cheaper visible range lasers.

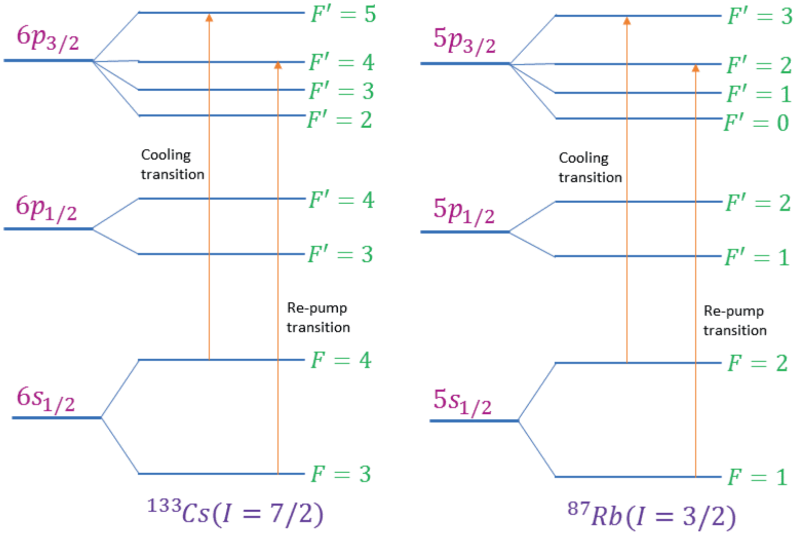


Figure 3.3: Energy levels diagram of ^{133}Cs and ^{87}Rb (not according to scale) relevant for laser cooling and trapping.

Another reason is that the alkali metals have a large vapour pressure at room temperature. It is easy to generate an atomic beam of alkali metals with atoms kept in a reservoir with small opening. Neutral ^{133}Cs and ^{87}Rb atoms are used for cooling and trapping in the ultra-cold atom based experimental facility in BTDG. Owing to the non-zero nuclear spin I = 7/2 for ^{133}Cs, the transitions are split into hyperfine levels labeled by quantum number

F. The relevant energy level diagram is shown in Fig. 3.3. For laser cooling of Cs atoms, the cooling laser is tuned to the red of the $6s_{1/2}F = 4 \rightarrow 6p_{3/2}F = 5$ transition (cycling or cooling transition). For laser cooling to continue without interruption, the Cs atoms should remain in these two states during repeated absorption and emission cycle. However, a fraction of atoms reaches $6p_{3/2}F' = 4$ level from $6s_{1/2}F' = 4$ level which eventually ends up in the $6s_{1/2}F = 3$ level by spontaneous emission. These atoms cannot absorb the cooling photon which is detrimental towards cooling. For efficient cooling, these atoms should be back to cycling transition. This is achieved by using an additional laser tuned to $6s_{1/2}F = 3 \rightarrow 6p_{3/2}F' = 4$ transition (re-pump transition). This laser is called re-pump laser and it pumps the population from $6s_{1/2}F = 3\ to\ 6p_{3/2}F' = 4$. ^{87}Rb (I = 3/2) has a similar hyperfine structure. The cooling and re-pumping transition for ^{87}Rb are $5s_{1/2}F = 2 \rightarrow 5p_{3/2}F' = 3$ and $5s_{1/2}F = 1 \rightarrow 6p_{3/2}F' = 5$ respectively.

3.5 Thermometry at Micro-Kelvin

Of all the attributes of cold atoms, perhaps temperature is the most important one. Measuring the temperature of cold atom cloud in vacuum is not easy. Many specialized techniques have been developed for this purpose. Among these, Release and Recapture (RR) method and Time of flight (TOF) method are most frequently used. Other important methods include forced oscillation of the cloud, Fluorescence spectrum analysis etc. RR method is based on repeated release and recapture of atoms from the MOT. This is achieved by sequence of 'off' and 'on' periods of the cooling beams. Just before the 'off' period of duration t_{off} of the cooling beams, the cloud is in steady state (ss) in MOT with steady state fluorescence intensity I_{ss}. This intensity I_{ss} is proportional to the steady state number N_{ss}. When cooling beams are switched off there is no trapping force. The expanding cloud also falls under gravity, as a result, the atoms are lost from the cloud. After time t_{off} the cooling beams are brought back and the florescence intensity I_{t_off} is proportional to the remaining number of atoms N_{t_off}. The fraction of atoms remaining is given by

$$f_r = \frac{N_{ss}}{N_{t_off}} = \frac{I}{I_{t_off}} = \frac{1}{\pi^{3/2}} \int_0^{v_c/v_T} 4\pi.e^{-u^2} u^2 du \qquad (3.1)$$

$v_T = \sqrt{(2k_B T/M)}$ is the thermal velocity of the atom at temperature T and $v_c = R_c/t_{off}$ is the velocity at which atoms reach the position $R_c$at time t_{off}. The integration is a function of t_{off}. For different t_{off}, f_r can be generated experimentally and can be compared with the theoretical value to get the value of v_T and hence the value of T. TOF method is considered to be most reliable method to measure the cold cloud temperature. In TOF, cold atom cloud is released by turning off the lasers. The cloud expands ballistically and falls due to gravity. The expansion can be measured by a probe laser beam which is positioned several cm below. From the expansion the Gaussian radius σ_v of the velocity distribution can be estimated. The temperature (T) of the cloud is related to σ_v as $T = M\sigma_v^2/k_B$.

3.5.1 Expansion of cold atom cloud in presence of photon field.

A novel technique to measure the temperature of the cold atom cloud is developed in the laser cooling laboratory, BTDG, BARC. In a cold atom cloud, spontaneous emissions results in random atomic recoils. Fluctuations originating due to this gives rise to diffusive spreading of velocities. In MOT, there exists additional mechanisms which gives rise to the fluctuation such as the difference between the number of photons absorbed from each of the counter propagating laser beams, instantaneous dipole force, force arising due to radiation trapping, and the magnetic force. As a result of these fluctuations, the evolution of the atomic momentum looks similar to a random walk. A diffusion coefficient can be defined in analogy with the classical Brownian motion. It is related to the steady state kinetic temperature according to Einstein relation. The experimental schemes discussed here provide measurements of the temperature [29] and atomic dynamic parameters like velocity diffusion coefficient [30]. Also, experimental observation provides an evidence for the existence of the radiation trapping force. The schematic of the experimental set up is given in Fig. 3.4. An external cavity diode laser (ECDL) of wavelength 852 nm in master oscillator power amplifier (MOPA) configuration is used for cooling. Another ECDL of same wavelength is used as a re-pump laser. The experimental facility contains two distinct areas. The first area is 'control area' and the second one is 'MOT area'. This is done to ensure any change in optical alignment in one area doesn't affect the alignment in other. Frequency and amplitude adjustment of both cooling and re-pumping laser, laser locking etc. are done in the control area. The output of cooling laser is incident on a 10% reflection beam splitter (BS). The reflected beam is used for frequency analysis and laser stabilization purpose. The frequency of the cooling laser is tuned to the red of desired hyperfine transition by means of saturation absorption spectroscopy (SAS) [14]. The frequency tuning is done by changing the grating angle inside the laser. The movement of the grating is controlled by applying a precise voltage to a piezoelectric translator (PZT). From the SAS profile, the frequency of the laser is locked by a software-based locking provision developed in the lab. The 90% transmitted beam is passed through an acoustic optic modulator (AOM). It is modulated by an RF generator. The first order beam from AOM is then coupled to a single mode polarization maintaining optical fiber using a 'free space to fiber' coupler and transmitted to the MOT area for trapping and cooling. The output of the fiber is incident on a telescopic arrangement to expand the beam diameter. This is required to increase the number of trapped atoms in the capture region in MOT. Since the output of the diode laser is vertically polarized, a quarter wave plate

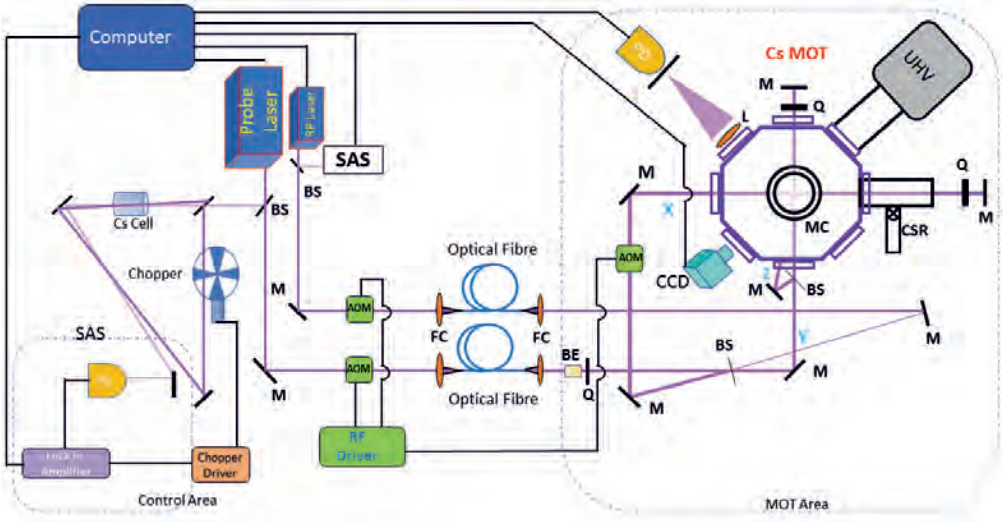


Figure 3.4: Schematic of ultra-cold atoms based experimental facility. Here, SAS: Saturation absorption spectroscopy, UHV: Ultra high vacuum, CSR: Cs atoms reservoir, RP Laser: Repumping Laser, BE: Beam Expansion arrangement, Q: Quarter wave plate, AOM: Acoustic Optic Modulator, Computer: Facility for data acquisition, data analysis and laser locking, BS: Beam Splitter, M: Mirror, MC: Magnetic coil, FC: Fiber coupler, PD: Photodiode, and CCD: Charged coupled device.

(QWP) is used to make the cooling beam circularly polarized. As described in section 4, the six directional arrangement of the cooling beam is achieved by the following alignment. After the QWP the beam is split using 33% reflection BS. The reflected beam is sent through the ultra-high vacuum MOT chamber along +x axis. After exiting from the MOT chamber, the beam is passed through a QWP and retro reflected back (along –x direction) to the chamber using a mirror. The 66% transmitted beam is further split into two equal parts by a 50% reflection BS. The reflected and transmitted beams are sent into chamber along +y and +z direction. After the exit from the chamber, these beams passed through a QWP and retro reflected back into the chamber along –y and –z direction respectively. All these alignments are so adjusted that maximum overlap region among the six beams is achieved. Almost similar alignment has been done for the re-pumping laser including SAS and coupling to a single mode fiber for sending it to MOT area. The re-pumping beam is then combined with

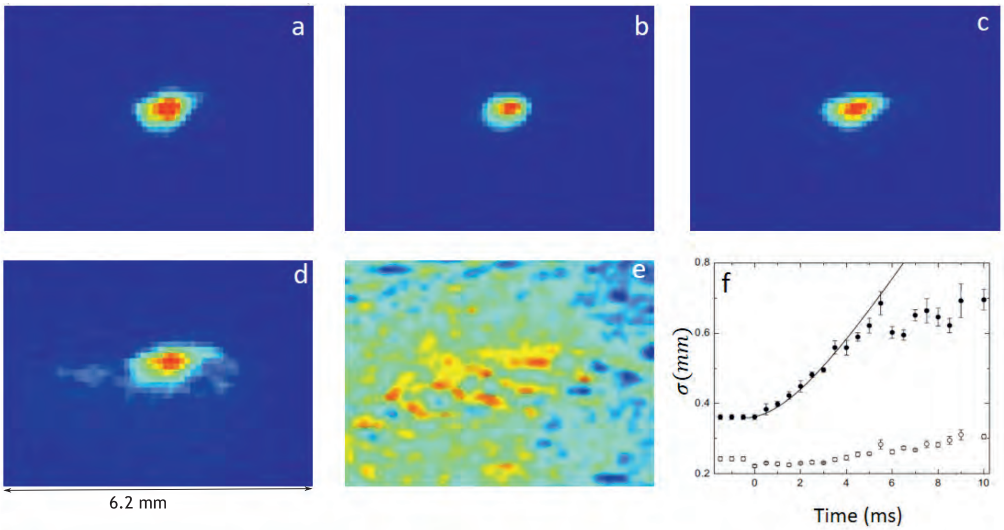


Figure 3.5: Fluorescence images of an expanding cloud at (a) Steady state, (b) t = 0 ms, (c) t = 3 ms, (d) t = 7.5 ms, (e) t = 20 ms, and (f) The temporal evolution of $\sigma_x(t)$ (solid circles) and $\sigma_z(t)$ (hollow circles) obtained from the analysis of the fluorescence images of the expanding cloud. Source: Ref. [29].

the cooling beam by the 33% reflection BS and is sent to the MOT chamber as shown in Fig. 3.4. Two identical coils are placed on the top and bottom of the MOT chamber in 'Anti-Helmholtz' configuration to generate spherical quadrupole magnetic field. The filed gradient along the radial direction is ∼10 G/cm. The MOT chamber is connected with an ultra-high vacuum pumping station. A vacuum of $\sim 10^{-9}$ torr is maintained within the chamber on day-to-day basis. The alkali metal is stored in a specially designed reservoir. The Cs vapour is introduced to the ultra-high vacuum MOT chamber in a controlled way using a valve. The fluorescence from the cold atom cloud at the centre of the MOT is monitored by a CCD camera. The experimental observations are involved the expansion of the cold atom cloud in ±x direction. For this purpose, the trapping laser beams along ±x directions only are switched off (keeping other four beams along the ±y and ±z directions intact) by means of amplitude modulation. The modulation generates dark and bright intervals for the beams along ±x directions for duration t_{on} and t_{off} respectively. During t_{on} the cloud grows and attain a steady state fluorescence. During t_{off} the cloud is confined in 2D (±y and ±z direction) and expands along ±x direction. The fluorescence images of the cloud at steady state is shown in Fig. 3.5a. The figure is taken from Ref. [29]. The images of expanding cloud at time t = 0 ms, t = 3 ms, t = 7.5 ms, t = 20 ms are shown in Figs. 3.5b-3.5e respectively. Immediately (t = 0) after switching off the beams along ±x direction, the cloud size gets reduced compared to its steady state size (Fig. 3.5b). This is followed by an expansion of the cloud along x direction for $0 < t \leq 5$ ms as shown in Fig. 3.5c. At long enough times, i.e., t = 20 ms, apparently an exploding cloud is observed (Fig. 3.5e). The stochastic evolution of the rms size of the could along x direction ($\sigma_x(t)$) is given as

$$\sigma_x^2(t) = \sigma_x^2(0) + \frac{k_B T}{M} t^2 + \frac{2}{3} D_v t^3 \tag{3.2}$$

where k_B is Boltzmann constant and M is the mass of Cs atom, $\sigma_x(0)$ is the rms size of the cloud at t = 0. The second and third term on the right-hand side of the equation represent the ballistic expansion, and the stochastic heating due to the fluctuations respectively. From Eq. (3.2), it can be observed that at least in the initial time regime ($0 < t \leq 4$ ms) the expansion of the cloud is ballistic. One can neglect the stochastic term which become dominant only in long time regime. With this approximation, 1D expansion along x-direction the equation takes the form as

$$\sigma_x^2(t) = \sigma_x^2(0) + \frac{k_B T}{M} t^2 \tag{3.3}$$

$\sigma_x^2(t)$ and $\sigma_x^2(0)$ are measured from the analysis of florescence imaging of the cold atom cloud and fit $\sigma_x(t)$ vs t to the Eq. (3.3) governing ballistic expansion (Fig. 3.5f). The measured T is ∼168 μK with fitting error of ∼1%. This result is consistent with the temperature measurement carried out using RR method.

3.5.2 Study of atomic dynamics

In Eq. (3.1) one can put the temperature T = 168 μK as measured from ballistic expansion of the cloud. Setting the values of $\sigma_x^2(0)$ and fitting the experimental data $\sigma_x^2(0)$ vs t one obtains value of velocity diffusion coefficient D_v from the coefficient of the t^3 terms. The measured value is $D_v = 1.4 \times 10^4 cm^2 s^{-3}$ with a fitting error of 8%. The plot of the rms size along z direction $\sigma_z(t)$ is also shown in Fig. 3.5f. It is evident that for t < 5 ms, the cold cloud expands along the x direction only, while its size along the z direction remains intact. The plot shows a dip of $\sigma_z(t)$ at t = 0. This corresponds to the contraction of the cloud immediately after switching of the trapping beam along ±x direction as seen in Fig. 3.5b. The same situation arises for y direction also (plots not shown). However, there is no appreciable contraction in $\sigma_x(t)$. So the initial contraction of the cloud is due to reduction in $\sigma_z(t)$ and $\sigma_y(t)$ only. The reason is the following. There exist a strong long-range force resulting from the multiple scattering of cooling photon in the cloud called 'radiation trapping force' (F_r). SWW model shows $F_r \propto I_t$ where I_t is total laser intensity seen by the atom cloud. In the steady state of the MOT, $I_t(ss) = 6I$. After switching off a pair of trapping beams along ±x, $I_t(0) = 4I$. Consequently $F_r(ss) < F_r(0)$ and this results in the contraction in $\sigma_z(0)$ and $\sigma_y(0)$.

3.6 Enhanced Loading of MOT

A large number of trapped atoms N (exceeding 10^{10}) is desirable for any further experiments involving cold atom. Different techniques have been reported for the enhancement of trapped atoms. Here, the enhancement in N in a MOT is realized by means of an auxiliary laser, hereafter termed as 'control laser'. A small fraction of the capture volume in MOT is illuminated by the control laser which is scanned over cooling transition frequency i.e. $6s_{1/2}(F = 4)\ to\ 6p_{3/2}(F' = 5)$. The increase in N by presence of control laser is found to be a near-resonant phenomenon. Maximum enhancement is achieved when the laser is slightly blue detuned from the resonance transition [31]. The schematic is as shown in Fig. 3.6. N is measured from the analysis of fluorescence intensity (I) of the cold cloud. The extent of the enhancement is denoted by a factor $E = I^c_{ss}/I^0_{ss} = N^c_{ss}/N^0_{ss}$, where the subscript ss means steady state and superscript c and 0 means the corresponding values with and without control lasers respectively. The variation of E as a function of the frequency detuning of the control laser (δ_c) from the resonance transition in Fig. 3.7a with background density (n_b) as a parameter. For far red or blue detuning ($|\delta_c| > 40$ MHz) the control laser has no measurable effect on N_{ss}. Maximum enhancement is achieved when the control laser is slightly blue

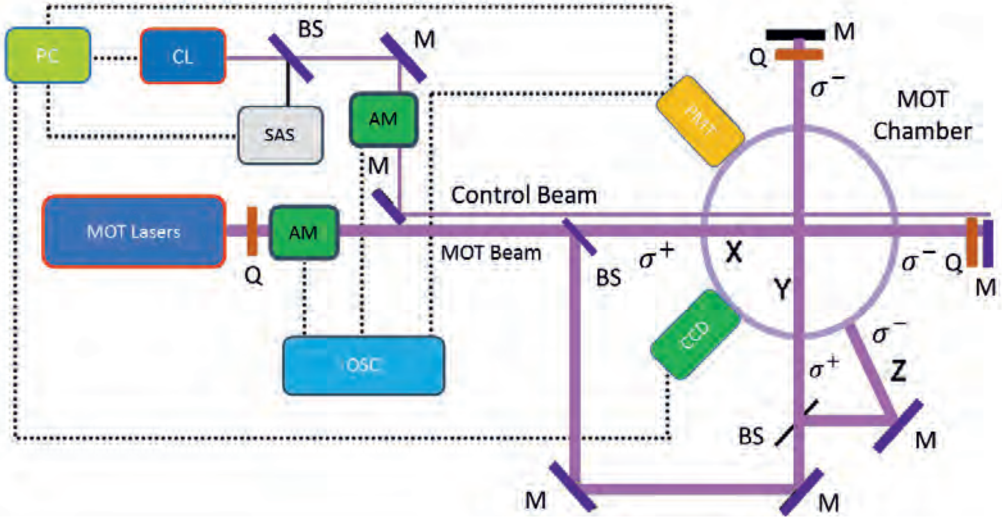


Figure 3.6: Schematic of the experimental set-up for enhanced loading of the MOT. MOT lasers include two diode lasers. The frequencies of these lasers are locked to cooling and re-pumping lasers transitions. Here, CL represents control laser, PC: Computer for control and data acquisition, SAS: Saturation absorption spectroscopy, OSC: Oscilloscope, BS: beam splitter, AM: Amplitude modulator, Q: Quarter wave plate, and M: Mirror.

detuned (~6 MHz) from the cooling transition. The capture rate (R) in a vapour cell MOT is proportional to $v_c^4.d^2$ where v_c is the capture velocity of the atoms being cooled, and d is the effective diameter of the MOT beams. Atoms having velocity below v_c, entering the trapping beams interaction volume will be trapped. In a MOT away from the trap centre, the Zeeman shifts of the transitions $|F,\ M_F\rangle \rightarrow\ |F',\ M_{F'}\rangle$ are large. As a result, the atoms may land in some magnetic states which is out of resonance with the trapping beams. Hence, R effectively depends on the magnetic field gradient. The presence of the control laser in the experiments probably brings these atoms, inaccessible to the trapping beams, back into the cooling transition. This results increase in R and, thus, in N_{ss}. The enhancement is also observed to be dependent on the control laser intensity (I_c) as shown in Fig. 3.7b. It attains the maximum value for I_c ~1.7 mW/cm^2. At higher intensities it decreases rather sharply. This indicates the near-resonant nature of the observed phenomenon.

3.7 Conclusions

The potential application of ultra-cold atoms in traps in the field of quantum optics, frequency standards, quantum computation etc. are discussed briefly. The basic principles of

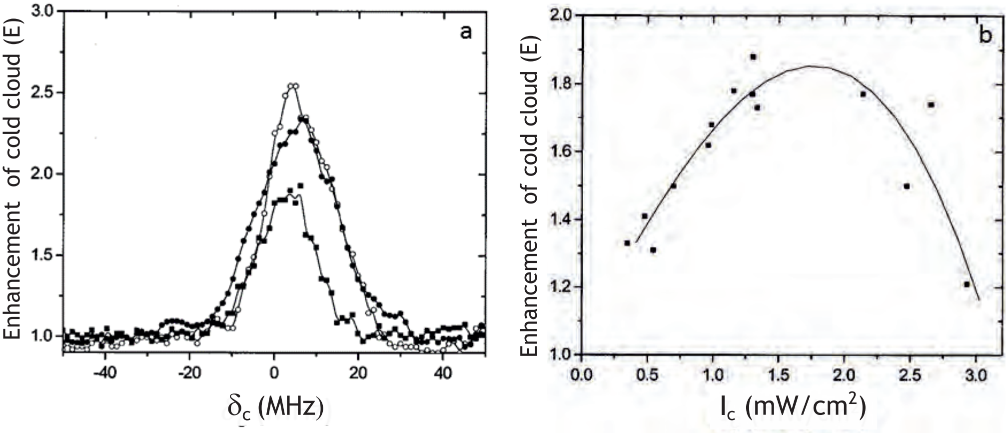


Figure 3.7: Variation of enhancement of cold cloud (E) as a function of δ_c and I$_c$: (a) detuning δ_c of the control laser from the F = 4 to F$'$ = 5 transition for different background densities, n$_b$ ($8.2\times10^7/cc$ for hollow circle, $3.3\times10^8/cc$ for solid circle and $7.4\times10^8/cc$ for solid square), and (b) the intensity of control laser (I$_c$) for $n_b = 7.0 \times 10^8/cc$ and δ_c ~3 MHz.

laser cooling and MOT are described. A technique for characterization of cold atom like measurements of cold atom temperature, velocity diffusion coefficient is discussed. It is based on the observation of the one-dimensional expansion of a cold ^{133}Cs cloud carried out by modulating a pair of counter propagating beam. The experimental results provide deeper insight of the basic concept like radiation trapping force, associated velocity diffusion and super ballistic expansion. In many of the utilities of cold atom in MOT one needs to increase the number of trapped atoms. In this view, enhancement in the number of trapped atoms in a Cs MOT by a near-resonant control laser has been discussed.

Frequently Asked Questions

Q1. Why alkali atoms are popular for laser cooling?

Q2. Why re-pump laser is required in laser cooling?

Q3. What is scattering force?

Q4. What is optical molasses?

Q5. What is Doppler cooling?

Q6. What limits the ultimately achievable temperature in Doppler cooling?

Q7. What is radiation trapping force?

Q8. What makes ultra-cold neutral atoms a promising candidate to implement quantum computer?