T.3: Laser cooling and trapping of Rb atoms

Vibhuti Bhushan Tiwari (vbtiwari@rrcat.gov.in)

Last two decades have seen the techniques related to laser cooling and trapping [1] play an important role in the advancement of modern atomic physics by achieving better control over the external degrees of freedom (position and velocity) of atomic systems. The perturbing effect due to thermal motion of atoms can significantly limit the accuracy of spectroscopic measurement of atomic energy levels. Cold atoms, observable over much longer durations, have therefore proven over the time their usefulness in high resolution spectroscopy, frequency standards and atomic clocks. The first suggestion for laser cooling of neutral atoms came from T. W. Hansh and A. L. Schawlow (1975) and, independently for trapped ions, from D. Wineland and H. Dehmelt (1975). Since its first experimental realization by S. Chu and his co-workers at the Bell Laboratories, New Jersey in 1985, the field of laser cooling has grown with a tremendous speed. The advancement in the field of laser cooling has been well recognized by award of Nobel prize in Physics (1997) to Steven Chu, Claude Cohen-Tanoudji and William D. Phillips. Later on, one of the foremost application of laser cooling turned out to be the achievement of Bose-Einstein condensation in dilute alkali gases which resulted in award of Nobel prize in 2001 to Eric A. Cornell, Carl E. Wieman and Wolfgang Ketterle. The field of laser cooling is actively progressing to further explore the basic quantum properties of atoms for applications in a new generation of practical measurement devices and quantum information processing.

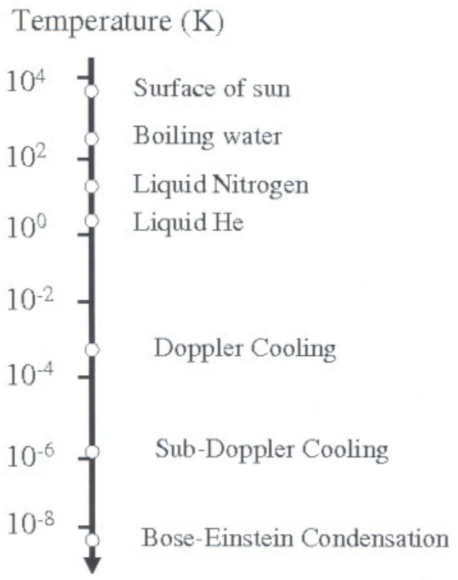

Fig. T.3.1 Kelvin temperature scale

It is interesting to figure out where a laser cooled atomic sample is placed on a Kelvin temperature scale on which the absolute zero roughly corresponds to -273.15 ^{0}C. Fig.1 shows a logarithmic scale of absolute temperatures. The scale starts with the temperature at the surface of the sun which is roughly ~5000 K. Decreasing this temperature by nearly a factor of one order of magnitude, we reach near the range of familiar room temperatures (~300 K). Another two orders of magnitude down the temperature scale leads us to a few degrees Kelvin, the domain of traditional low-temperature physics. Such temperatures are associated with quantum physics phenomenon such as superconductivity and superfluidity. Thanks to the advances in laser cooling techniques, a temperature of millionth of a degree Kelvin and even lower is possible on this scale for atomic systems. At these extreme temperatures, the thermal atomic de Broglie wavelength becomes comparable to the wavelength of the visible and near infra-red light. Therefore, it becomes possible to exploit wave nature of atoms using light in this wavelength range leading to the development of atom optical elements such as atom mirrors and lenses. Further lowering of the temperatures for atomic samples is possible by adopting laser cooling techniques followed by evaporative cooling. At these ultra-low temperatures, atoms having integral spin known as bosons undergo a transition called Bose-Einstein condensation where atoms begin to occupy the same lowest energy state of the trap. As such, the condensate can be thought of as forming a new state of matter, a quantum gas behaving as a macroscopic system of a million or so atoms, all evolving in a coherent way. Therefore, laser cooling techniques have helped to attain temperatures where new physical phenomenon can be studied.

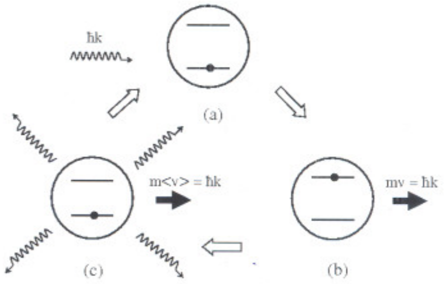

Fig. T.3.2 (a) a two level atom, initially in the ground state, absorbs a photon with momentum hk/2π, (b) the velocity of the excited atom is increased by hk/2πm in the direction of incident beam, (c) spontaneous emission of photon in a direction described by symmetric probability distribution such that average velocity change is zero. The atom returns to the ground state, ready to repeat the cycle.

The basic idea behind laser cooling is the transfer of momentum to an atom moving in a light field due to scattering of photons (Fig. 2). Each photon moving with a momentum of hk/2π after getting absorbed, gives a kick to the atom along its direction of propagation. When the photon is spontaneously emitted, the emission is equally probable in all the directions. The net change of momentum due to spontaneous emission over a large number of emission-absorption cycles is, therefore, zero. In this process, however, the moving atom's momentum is changed by the amount of momentum of a single photon multiplied by the number of absorbed photons. The resulting force is known as the scattering force.

In case of a moving atom, the well known Doppler effect plays an important role in deciding this force. For the laser frequency detuned below the atomic resonance frequency by about a few linewidths, the Doppler effect shifts the atom closer to resonance with the beam propagating in the opposite direction. At the same time, the frequency of the beam moving along the direction of the atom is Doppler shifted further away from the resonance. This force slows the atom down whichever direction it moves in. For red detuning of the beam, the net force opposes the velocity and therefore viscously damps the atomic motion. In three-dimensions, an atom experiences a damping force at the intersection of three mutually orthogonal counterpropagating pair of beams, as if it is moving in a viscous fluid. This technique of cooling atoms in three dimensions was first demonstrated by S. Chu and co-workers in 1985 and is since then known as optical molasses. Accompanying this cooling by the scattering force there is always some diffusion or heating which limits the lowest temperature which can be reached. The diffusion arises from the recoil of the atom from the spontaneous photons. The minimum temperature T_D achievable using Doppler effect is known as the Doppler cooling limit. For example, Na atom has T_D = 240 μK whereas for Rb atom, T_D = 140 μK. Temperatures well below the Doppler cooling limit were reported shortly after the first successful demonstration of three dimensional optical molasses with Na atoms. It was soon realized that the real atoms have degenerate sublevels in the ground and excited states and therefore can not be explained by a simple two-level model. Moreover, the superposition of the laser beams produces a resultant polarization which changes over a distance of less than a wavelength. In addition to causing the light shifts which change in space these polarization gradients affect the atom through optical pumping. The optical pumping is a process in which atomic population is transferred to a particular ground-state sublevel through absorption of polarized light and subsequent spontaneous emission. Due to optical pumping process, atoms at rest in a steady state condition have population distributed over the different ground-state sublevels which in turn determine the ground-state orientations. Due to sub-Doppler cooling process, atoms are left with a residual momentum of the order of hk due to random spontaneous emission. The temperature T_{rec} corresponding to a single spontaneous emission event is known as the recoil limit. For most of alkali metal atoms, T_{rec} is nearly a fraction of 1 μK. The de Broglie wavelength of the atom becomes comparable to the wavelength of the cooling radiation at the recoil limit, suitable for atom optics experiments. The recoil limit can be circumvented by putting the atom into a final state which does not absorb photons from the radiation field. For example, in a method called `velocity selective coherent population trapping', atoms get optically pumped into a non-absorbing `dark' state, obtained by a coherent superposition of two ground states sublevels.

Magneto-optical trap (MOT)

Trapping a particle means to confine it to a region of space by a position dependent force. The three dimensional laser cooling in optical molasses is achieved by using only a velocity dependent force. In absence of a position dependent force, laser cooled atoms diffuse out of the molasses region. The problem is well addressed by a trap which employs both optical and magnetic fields, widely known as the magneto-optical trap (MOT). The laser beams passing through the center of the trap in presence of a weak inhomogeneous magnetic field provide the spatially dependent radiation pressure force. The magnetic field is a spherical quadrupole configuration with gradients of several gauss per centimeter about the zero of the magnetic field, which is the center of the trap. The field has a linear gradient in all three directions, permitting the use of three mutually perpendicular pairs of oppositely circularly polarized laser beams that are detuned a few natural linewidths below a strong atomic transition. Therefore, the laser light, in addition to three-dimensional confinement, also provides suitable conditions for Doppler and sub-Doppler cooling of the atoms.

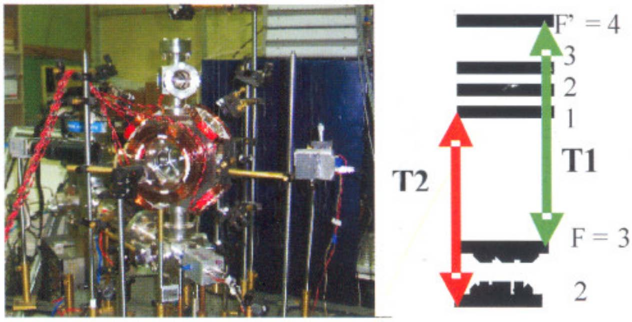

Fig. T.3.3 Picture of experimental MOT setup with relevant energy levels of ^{85}Rb. T1: cooling transition to obtain cold atoms in F=3 state. T2: cooling transition to obtain cold atoms in F=2 state.

Alkali atom traps have usually been operated with trapping force provided by cycling transition from the upper hyperfine level of the ground state. In our MOT setup (Fig. T.3.3), we could not only use this T1 transition for cooling and trapping of ^{85}Rb atoms but also successfully operated for the first time using cycling transition from the lower hyperfine level of the ground state indicated by T2 transition in (Fig. T.3.3). The number and temperature are important parameters to characterize a cold atomic sample. We estimated the number of trapped atoms by imaging the fluorescence from the trapped atoms onto a photodiode [2,3]. The fluorescence emission power at the photodiode is proportional to the number of trapped atoms. The temperature of the cold atoms was estimated using free-expansion method ((Fig. T.3.4). In this method, atom cloud expansion rate after release from the MOT is measured which is correlated to the initial temperature of the cloud. As an example, for magnetic field gradient, dB/dz = 10 G/cm, and single trapping beam intensity 8.4 mW/cm^2, the value of number of trapped atoms using T2 transition was equal to 4.2 x 10^6 optimized around trap laser detuning of Δ_L = -12 MHz. The corresponding density and temperature of the atom cloud was measured to be around 2 x 10^8 cm^{-3} and 4.4 mK, respectively [4,5].

The possibility of trapping an atom using different sets of transitions may be useful in cold atom collision studies, enhancing the number of trapped atoms for achieving Bose-Einstein condensation and quantum optics related experiments

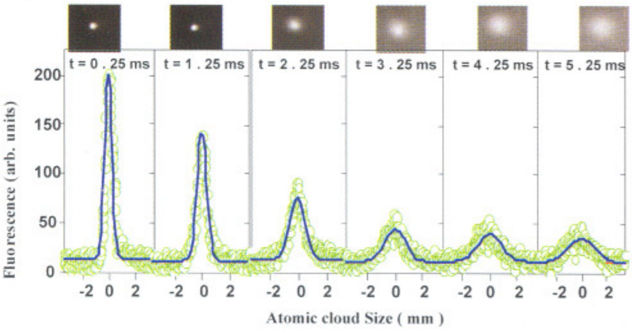

Fig. T.3.4 Fluorescence images of atom cloud at T = 250±40μK, undergoing free expansion and corresponding spatial profiles in radial direction with their best Gaussian fit.

Frequency Stabilization of lasers used in MOT setup

A typical experimental set up for laser cooling and trapping of atoms employs several frequency stabilized lasers tuned to different frequencies near resonance of the appropriate transitions. Laser cooling experiments now widely use semiconductor diode lasers having advantage in terms of reliability, miniature size, low power consumption and availability of emission wavelength suitable for alkali atoms. Moreover, wide wavelength tunability can easily be achieved by using external cavity diode lasers (ECDLs). These tunable external cavity diode laser systems consist primarily of a semiconductor laser diode, collimator for coupling the output of a diode laser and a grating which provides optical feedback for single-mode operation and tuning of the wavelength over the whole range of gain bandwidth. It is important to stabilize the diode's injection current and the temperature which determine the output frequency of an ECDL. A fluctuation in temperature, injection current or mechanical stability of the system may result in a long term frequency drift. This drift can be reduced by locking the laser frequency to an external reference using an electronic control system. This electronic system with the servo loop, measures the deviation of the laser frequency from a preselected reference value and tries to bring it to near zero as quickly as possible. Usually, this active stabilization of the laser frequency is achieved by comparing the operating frequency of diode laser with a frequency reference. For laser cooling experiments, it is convenient to employ narrow spectral features corresponding to the atom to be cooled as the frequency reference. It is easy to identify the transition used for cooling and set the appropriate detuning. For example, polarization spectroscopy (PS) presents a very attractive and sensitive technique for generating a frequency reference. However, the conventional PS signal contains background level which is susceptible to the fluctuations in the laser intensity and temperature changes. To avoid this problem, we proposed and implemented a new scheme based on polarization spectroscopy for laser frequency stabilization [6-9].

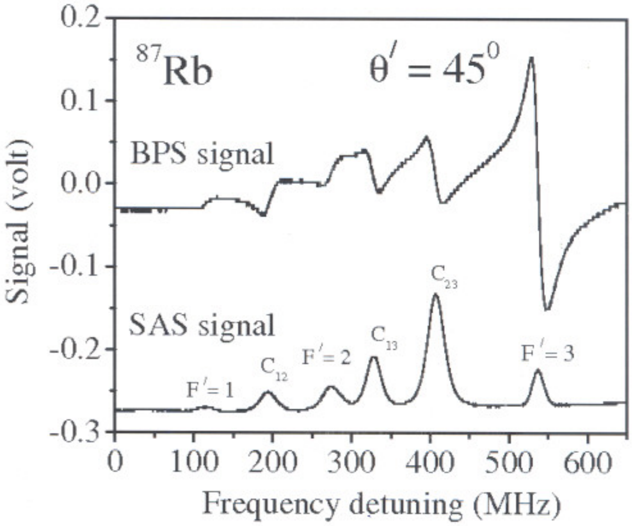

Fig. T.3.5 The BPS spectrum of $5^2S_{1/2}$ (F=2) to $5^2P_{3/2}$ (F') transition of ^{87}Rb for angle between polarizer and analyzer of 45^0 alongwith a simultaneously recorded saturated absorption spectroscopy (SAS) signal.

In this scheme, two parallel laser beams of identical linear plane of polarization used as probes are overlapped with two counter propagating oppositely circularly polarized pump laser beams in a vapour cell. The difference in intensities of the two probe laser beams passing through an analyzer results in the reference signal to be used for frequency stabilization. We call this signal the bi-polarization spectroscopy (BPS) signal (Fig. T.3.5). The signal is large, near symmetric, background-free and dispersion-like which makes it very useful for peak locking especially for closed transitions. Using the BPS signal as a frequency discriminator error signal, we were able to lock a semiconductor diode laser at the exact line centre of the closed atomic transition $5^2S_{1/2}$ (F=2) to $5^2P_{3/2}$ (F'=3) of ^{87}Rb. The measured frequency fluctuation and the drift rate of the locked laser frequency were found to be less than 0.3 MHz and 0.05 MHz, respectively, for observation period of more than 3 hours.

Study of trap dynamics with cold atoms

The investigations on MOT dynamics have primarily aimed at achieving optimum performance of the trap in terms of high number density and low temperature for cold atoms. These studies are not only useful in achieving better control over trap operation but also helpful in understanding other similar systems such as plasma and astrophysical systems with appropriate scaling. The trap dynamics essentially depends on the number of trapped atoms. For a small number of trapped atoms ($N<10^5$), the atoms are non-interacting in the MOT. In this ideal-gas or temperature-limited (TL) regime, the density distribution is Gaussian with a radius that remains constant as more trapped atoms are added to the MOT. For a large number of trapped atoms ($N>10^5$), the MOT operates in a constant density or multiple scattering (MS) regime. In this regime, repulsive force due to the reabsorption of scattered photons leads to an increase in the cloud size while the density remains constant. In the MS regime, different atom cloud shapes such as ring and ring with core can be obtained for misalignment of trapping beams and number of trapped atoms exceeding a critical value. Moreover, highly populated traps can show cloud shape instabilities in the form of oscillations of the cold atomic cloud. These instabilities arise due to the attenuation effect in the thick cold atomic cloud. A magneto-optical trap with large number of trapped atoms ($N\sim10^{10}$) can also show self-sustained oscillations. The origin of these oscillations lies in the competition between the confining force of the trap and the repulsive interaction associated with multiple scattering of light inside the cold atomic cloud. To understand the various aspects of the trap dynamics, the measurement of trap parameters such as damping coefficient and spring constant is important. Moreover, these studies can be used to verify different models of the processes creating forces in the trap. Various techniques have been used to measure these trap characteristics. The spring constant of the trap, for example, can be obtained by measuring the displacement of the atom cloud due to intensity imbalance created in a pair of counterpropagating beams. However, the experimental uncertainty in this method is increased due to the attenuation effect prominent near the MS regime. The equipartition theorem based method of simultaneous measurement of temperature and spatial profile of the atom cloud forms another method to measure spring constant. This method also suffers from the radiation trapping effect near the onset of the MS regime. Therefore, a more direct method based on the atom cloud oscillation is better suited for the measurement of the trap characteristics around the MS regime. In our work we have investigated impulsive light-force induced dynamics of cold ^{85}Rb atoms in a MOT operating near the MS regime with various trap parameters such as trapping laser intensity, detuning and magnetic field gradient (Fig. T.3.6) [10,11]. Depending on the magnitude of initial drift velocity of the atom cloud, either oscillation or escape of the atoms from the trap was observed. The oscillations of cold atom cloud in our MOT setup were observed as follows. After a predecided trap loading time, a saturated resonant forcing laser beam of variable pulsewidth (50 μs - 250 μs) was used to hit the trapped atom cloud in vertical direction during which trapping beams were switched off momentarily. For pushing beam width in the range of 50 μs - 70 μs, the atom cloud was displaced in linear region such that the displacement was linear in velocity. The trapping beams were switched on simultaneously with the switching off of the forcing beam resulting into an oscillatory motion of the atom cloud.

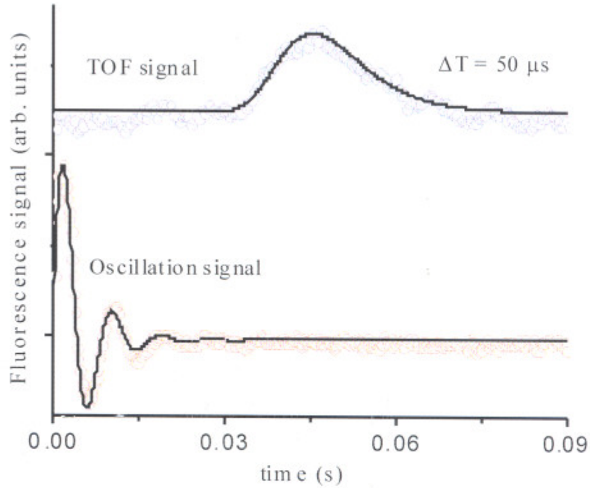

Fig. T.3.6 Experimentally observed TOF and atom cloud oscillation signals denoted by open circle alongwith theoretically fitted solid curve for forcing beam pulsewidth ΔT = 50 μs.

The time-of-flight (TOF) method was used for our experiment, to estimate drift velocity and velocity width of the atom cloud pushed by a pulsed forcing laser beam of variable width. The pushing force on the atom cloud was applied immediately after trapping beams were switched off. The fluorescence from atoms, falling on a thin sheet of probe beam placed below the trap, as a function of time provided the TOF signal (Fig. T.3.6). By fitting the experimentally observed

TOF signal with that calculated numerically, the drift velocity and the variance of the velocity distribution of the forced atom cloud was estimated. For example, the drift velocity and the standard deviation of axial velocity for 50 μs forcing beam pulsewidth were found to be (3.88±0.16) m/s and (0.93±0.06) m/s, respectively. Fig.T.3.6 also shows a typical example of experimentally observed oscillation fluorescence signal alongwith the theoretical results for trap laser detuning of $\Delta_L = -2\Gamma$ where $\Gamma = 2\pi \times 5.9$ MHz is the natural line-width of the cooling transition. The single trapping beam intensity of 2.5 mW/cm^2 and magnetic field gradient of 12.5 G/cm have been used. The spring constant κ and damping coefficient α of the trap were used to best fit the experimentally observed oscillations. For example, we obtained spring constant $\kappa = (8.02\pm0.11) \times 10^{-20}$ N/m and damping coefficient $\alpha = (6.19\pm0.27) \times 10^{-23}$ Ns/m for trap laser detuning of $\Delta_L = -2\Gamma$. Using this technique it was also possible to measure the escape velocity of atom cloud $v_{z,e}$ at which 90 % of the trapped atoms escape from the trap along the forcing beam direction. For single trap beam intensity of 3.2 mW/cm^2, trap laser detuning $\Delta_L = -2\Gamma$, magnetic field gradient of 12.5 G/cm, and 1/e^2 radius of the trap laser beam of 2 mm, we experimentally obtained the optimum value of $v_{z,e} = 15$ m/s. Our results showed that near the multiple scattering regime the trap characteristics which were responsible for the confinement in MOT got affected by saturation effects which resulted in a nearly constant density of trapped atoms.

Electromagnetically induced transparency (EIT) in cold atoms

The optical properties of atomic and molecular gases are fundamentally related to their intrinsic energy levels. In presence of strong laser excitation, atomic coherence plays an important role in the evolution of the atom-field system. For example, the coherent evolution in a two-level atomic system takes place in terms of population oscillations between the two states known as Rabi oscillations. A suitable generalization of this coherent preparation of states to a three-level atomic system provides an interesting quantum interference effect known as electromagnetically induced transparency (EIT). The absorption of a weak probe beam passing through an EIT medium becomes almost zero in presence of a strong coupling field making the medium effectively transparent to the probe beam. Moreover, the transparency of the EIT medium is attained with strong dispersive and non-linear effect.

Therefore, after its first experimental realization in 1991 by S. E. Harris and co-workers at Stanford University, California, EIT effect has found applications in various fields such as low light level nonlinear optics, ultra-slow group velocities and storage of light, sensitive magnetometer, quantum-optical switches, laser frequency stabilization, and spectroscopy of Rydberg states. Many such EIT related studies involve three-level atomic configuration known as, Λ-type system with dipole forbidden transition between the two lower states. Due to minimum coherence dephasing rate compared to other three level atomic configurations, the Λ-type EIT system produces the strongest EIT signal. The Λ-type scheme can be easily implemented using alkali atoms including Rb atoms where transition between the two ground state hyperfine levels is dipole forbidden. To perform EIT experiments in a Doppler broadened medium, the coupling Rabi frequency should be greater than the inhomogeneous spectral width of the system which therefore, necessitates the use of pulsed lasers with high peak power with intensity > 1 MW/cm^2. However, low power CW lasers can still be used by employing Doppler-free configuration in an atomic vapour cell. However, atomic collisions in the thermal atomic vapour contribute towards the dephasing rate of the dipole forbidden transition.

Laser-cooled atoms can provide an ideal medium for studying EIT since collisional dephasing is greatly reduced compared to a room temperature vapour cell. The advantage of studying EIT in cold atoms is due to the absence of Doppler broadening and a relatively smaller collisional dephasing rate in such a medium. Using cold atoms, a much stronger EIT signal has been observed compared to that resulting from a vapour cell for comparable coupling laser intensity. The relative alignment of coupling and probe beams in a Doppler-free medium of cold atoms is also free from any restriction allowing a much simpler experimental arrangement. Cold atoms have therefore, provided an ideal homogeneous medium to perform EIT related experiments. In alkali atoms, the formation of an EIT system often involves hyperfine energy states. The degenerate magnetic sub-levels of these hyperfine states play an important role in deciding the strength of the EIT signal. As long as all the magnetic sub-level transitions are connected with the coupling transitions, the Λ-type system can be treated as complete. For this complete system, large transparency depth of the EIT signal can be obtained for moderate coupling intensities.

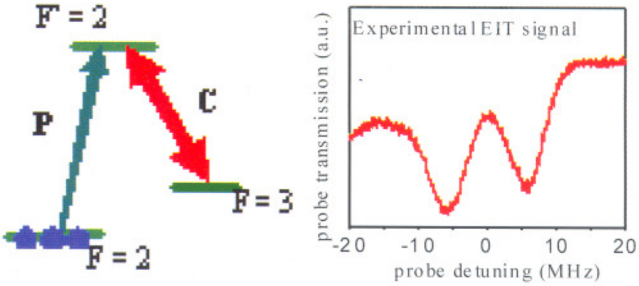

Fig. T.3.7 Λ-type system with cold atoms trapped in F = 2 state. EIT signal for coupling field tuned to exact resonance with the $5^2S_{1/2}$ (F=3) to $5\,^2P_{3/2}$ (F'=2) transition and coupling Rabi frequency of 11.7MHz.

We have studied EIT effect in a cold sample of ^{85}Rb atoms obtained from a steady state magneto-optical trap (MOT) [12]. The cold atomic sample prepared either in the ground state hyperfine level F = 3 or F = 2 of 5 $^2S_{1/2}$ of ^{85}Rb atoms was used to investigate EIT signal for Λ-type configuration of hyperfine levels of the D2 line. We have obtained a complete Λ-type system for cold atoms trapped in F=2 state and coupled from F=3 to F'=2 level (Fig. T.3.7). The EIT peak height was observed to be near maximum for coupling Rabi frequency of ~10 MHz.

Conclusions

We have presented here our work related to magneto-optical trapping of Rb atoms for performing various kinds of studies with cold atoms. The work included in-house development of a MOT set-up to produce cold Rb atoms. We have prepared, for the first time, a cold ^{85}Rb atomic sample trapped in ground hyperfine F = 2 state. We demonstrated new laser frequency stabilization techniques based on polarization spectroscopy which provided frequency drift of less than MHz over several hours of measurements during laser cooling experiments. A novel methodology based on impulsive light force was adopted to perform measurements on the dynamics of a MOT around the multiple scattering regime. We also investigated electromagnetically induced transparency using a steady-state cold atomic sample of ^{85}Rb atoms trapped either in the hyperfine level F = 3 or F = 2 of 5 $^2S_{1/2}$ ground state. A closed Λ-type system was realized for atoms trapped in F = 2 state with coupling transition F = 3 to F' = 2. A steady state sample of cold ^{85}Rb atoms obtained in the lower hyperfine level of the ground state with a closed Λ-type energy level configuration can have practical applications in making quantum optical devices such as quantum interference switches.

Acknowledgements

The author wishes to extend his sincere and deep gratitude to Dr. S. C. Mehendale for constant guidance and encouragement during the course of this work. The work presented here would not have shaped in its present form without enthusiastic participation and sustained cooperation from colleagues including Dr. H. S. Rawat, Dr. S. R. Mishra, Dr. M. P. Singh and Mr. S. Singh. Valuable technical help was received during this work from colleagues of different laboratories at RRCAT, particularly Mr. A. Kak for fabrication of glass chamber for initial testing of MOT, Mr. H. S. Vora for developing image capturing and processing software and Mrs. L. Jain, Mr. M. Joshi, Mrs. J. Khanwalkar, Mr. S. Krishnan and Mr. C. Rajan for electronics and instrumentation.

References

1. "Laser cooling and trapping of atoms", H. J. Metcalf and P. van der Straten, J. Opt. Soc. Am. B, 20, 887 (2003).
2. "Characterization of a Magneto-optic Trap for ^{87}Rb atoms", V. B. Tiwari, S. R. Mishra, H. S. Rawat, S. Singh, S. P. Ram, and S. C. Mehendale, Proc. National laser Symposium, Mumbai, January 10-13 (2005), p-382.
3. "Laser frequency stabilization and large detuning by Doppler-free dichroic lock technique: Application to atom cooling", V. B. Tiwari, S. R. Mishra, H. S. Rawat, S. Singh, S. P. Ram, and S. C. Mehendale, Pramana - J. Physics, 65, 3, 403 (2005).
4. "Magneto-optical trap for ^{85}Rb atoms in the ground hyperfine F = 2 state", V. B. Tiwari, S. Singh, H. S. Rawat, and S. C. Mehendale, Proc. National laser Symposium, Delhi, January 7-10 (2009), p-90.,
5. "Cooling and trapping of ^{85}Rb atoms in the ground hyperfine F = 2 state", V. B. Tiwari, S. Singh, H. S. Rawat, and S. C. Mehendale, Phys. Rev. A, 78, 063421 (2008).
6. "Bi-polarization spectroscopy in atomic vapour: Application to laser frequency stabilization", V. B. Tiwari, S. Singh, S. R. Mishra, H. S. Rawat, and S. C. Mehendale, Int. conf., CDAMOP, New Delhi, March 21-23 (2006), p-129.
7. "Laser frequency stabilization using Doppler-free bi-polarization spectroscopy", V. B. Tiwari, S. Singh, S. R. Mishra, H. S. Rawat, and S. C. Mehendale, Opt. Commun., 263, 249 (2006).
8. "Laser frequency stabilization using light-induced birefringence in atomic vapor", V. B. Tiwari, S. Singh, S. R. Mishra, H. S. Rawat, and S. C. Mehendale, Int. conf. and Humboldt Kolleg, SCPCBGM, Varanasi, November 28-30 (2005), p-20.
9. "Laser frequency stabilization using a balanced bi-polarimeter", V. B. Tiwari, S. Singh, S. R. Mishra, H. S. Rawat, and S. C. Mehendale, Appl. Phys. B: Lasers Opt., 83, 93 (2006).
10. "Cold atomic pulses from a magneto-optical trap", V. B. Tiwari, S. Singh, H. S. Rawat, M. P. Singh, and S. C. Mehendale, Proc. National laser Symposium, Baroda, December 17-20 (2007), p-411.
11. "Measurements on impulsive force-induced dynamics of cold ^{85}Rb atom cloud in a magneto-optical trap", V. B. Tiwari, S. Singh, H. S. Rawat, and Manoranjan P. Singh, J. Phys. B: At. Mol. Opt. Phys., 41, 205301 (2008).
12. "Electromagnetically induced transparency in cold ^{85}Rb atoms trapped in ground hyperfine F = 2 state", V. B. Tiwari, S. Singh, H. S. Rawat, Manoranjan P. Singh, and S. C. Mehendale, J. Phys. B: At. Mol. Opt. Phys., 43, 205301 (2010).