Evaporative Cooling of Atoms to Quantum Degeneracy in an Optical Dipole Trap

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Abstract. We discuss our experimental results on forced evaporative cooling of cold rubidium $^{87}{\text{Rb}}$ atoms to quantum degeneracy in an Optical Dipole Trap. The atoms are first trapped and cooled in a magneto-optical trap (MOT) loaded from a continuous beam of cold atoms [1]. More than $10^{10}$ atoms are trapped in the MOT and then about $10^8$ atoms are transferred to a Quasi-Electrostatic Trap (QUEST) formed by tightly focused CO$_2$ laser ($\lambda = 10.6\mu m$) beams intersecting at their foci in an orthogonal configuration in the horizontal plane. Before loading the atoms into the dipole trap, the phase-space density of the atomic ensemble was increased making use of sub-doppler cooling at large detuning and the temporal dark MOT technique. In a MOT the phase-space density of the atomic ensemble is six orders of magnitude less than what is required to achieve quantum degeneracy. After transferring atoms into the dipole trap efficiently, phase-space density increases by a factor of $10^3$. Further increase in phase-space density to quantum degeneracy is achieved by forced evaporative cooling of atoms in the dipole trap.

The evaporative cooling process involves a gradual reduction of the trap depth by ramping down the trapping laser intensity over a second. The temperature of the cold atomic cloud was measured by time-of-flight (TOF) technique. The spatial distribution of the atoms is measured using absorption imaging. We report results of evaporative cooling in a single beam and in a crossed double-beam dipole traps. Due to the large initial phase space density, and large initial number of atoms trapped, the quantum phase transition occurs after about 600 ms of evaporative cooling in our optimized crossed dipole trap.

1. Introduction

Evaporative cooling is the key technique and the most efficient way for producing a Bose-Einstein condensate in both magnetic and optical dipole traps. Evaporative cooling is based on the removal of the most energetic atoms from the trap which is followed by a rethermalization of the remaining atoms by elastic collisions resulting in the reduction of the overall temperature of the system. Evaporation technique for cooling has been widely used in low-temperature physics where cooling is done by evaporating liquified gases. Evaporative cooling technique was first proposed by Harald F. Hess in 1986 [2] for spin-polarized atomic hydrogen for producing a Bose-Einstein condensate. This technique was implemented on alkali atoms in 1994 to produce the first Bose-Einstein condensates [3, 4, 5] in magnetic traps, and evaporative cooling in an optical dipole trap, first demonstrated in 1995 [6], was implemented in 2001 for Bose-Einstein condensation in an all-optical dipole trap [7]. The great potential of evaporative cooling technique is evident from the fact that it can increase the phase-space density by six orders of magnitude.
Evaporative cooling is most effective in dark traps where there is absence of near-resonant light. The main disadvantage of using near-resonant light for trapping is that there is a limit to the minimum temperature that can be achieved due to a significant probability of photon scattering and recoil. In near-resonant traps with high atom number density, the collision rate between atoms is large. Due to the presence of near resonant light, the fraction of atoms in the excited state increases and inelastic collision between atoms with one of the atoms in the excited state (S+P collisions) occurs resulting in inelastic energy exchange between the atoms which causes loss of atoms from the trap. Hence near-resonant light should be completely avoided in order to reach very low temperatures well below the single photon recoil limit. For efficient evaporative cooling, it is important to have a large ratio between the elastic collisions and the inelastic collisions since elastic collisions enable thermalization and lowering of temperature by evaporation whereas inelastic collisions causes loss of atoms from the trap along with heating due to inelastic energy exchange between atoms. The inelastic collisions include collisions with the background gas and three-body recombination. The other inelastic processes which affect the evaporative cooling process are dipolar relaxation and spin relaxation.

The efficiency of evaporative cooling [8] which depicts the temperature decrease per particle lost is defined as

$$\alpha = \frac{d(\ln T)}{d(\ln N)} = \frac{\dot{T}/T}{\dot{N}/N}$$

where $T$ and $N$ are respectively the temperature and the atom number in the trap. If $\alpha$ remains constant during the evaporation process, the reduction of temperature of the atoms follows the relation

$$\frac{T(t)}{T(0)} = \left(\frac{N(t)}{N(0)}\right)^\alpha$$

The truncation parameter $\eta$ for the evaporation process is defined as

$$\eta = \frac{\epsilon_t}{k_B T}$$

where $\epsilon_t$ is called the truncation barrier and atoms having energy higher than $\epsilon_t$ are preferentially removed from the trap during the evaporation process. In case of spontaneous evaporation, $\epsilon_t$ remains constant and elastic collisions between atoms produces atoms with energies higher than the truncation barrier $\epsilon_t$ which evaporate out of the trap spontaneously. As the temperature reduces due to this ‘plain’ evaporation process, the value of the truncation parameter increases whereas $\epsilon_t$ remains constant, and the rate of evaporation, which is proportional to $e^{-\eta}$, is supressed. Hence, to maintain a continuous cooling process, forced evaporative cooling has to be implemented such that $\eta$ is kept constant during the evaporative cooling process.

The rate of evaporation of atoms from the trap is given by

$$\dot{N} = -N \gamma_{el} \eta e^{-\eta}$$

where $N$ is the total number of atoms in the trap, $\gamma_{el}$ is the rate of two-body elastic collision between the atoms in the trap given by

$$\gamma_{el} = n_0 \sigma_{sc} \bar{v}_{rel} = N (8 \sqrt{\frac{2 \sigma^2 m}{\pi k_B}} \bar{\omega}^3) \frac{\bar{\omega}^3}{T}$$

$n_0$ is the peak density of atoms in the trap, $\sigma_{sc}$ is s-wave scattering cross-section which is the collision cross-section for low energy collisions. $a$ is the s-wave scattering length, $m$ is the mass of the atom, $\bar{\omega} = (\omega_x \omega_y \omega_z)^{1/3}$ is the mean trap frequency, and $\bar{v}_{rel}$ is the average relative velocity between two atoms in the trap. The peak atom number density is given by

$$n_0 = N \left(\frac{m \bar{\omega}^2}{2 \pi k_B T}\right)^{3/2}$$
The phase-space density is defined as \( n \lambda_{DB}^3 \) where \( n \) is the atom number density in the trap and \( \lambda_{DB} = \sqrt{\frac{2\pi \hbar^2}{mk_B T}} \) is the thermal de Broglie wavelength of the atoms in the trap. Bosonic atoms form Bose-Einstein condensate when their phase-space density exceeds 2.612. The typical value of phase-space density in a magneto-optical trap is around \( 10^{-6} \) which implies that the phase-space density of atoms has to be increased by six orders of magnitude for producing a Bose-Einstein condensate after magneto-optical trapping (The phase space density in the thermal vapour of Rb is, in contrast, only \( 3 \times 10^{-19} \), which shows the great importance of magneto-optical trapping and cooling as an intermediate step towards Bose-Einstein condensation). Phase space density can be increased by both increasing the atom number density and reducing the temperature of atoms in the trap. Density of atoms in a MOT can be increased by implementing spatial or temporal dark MOT technique or magnetic compression. The temperature can be reduced to a few times the single photon recoil limit by using sub-doppler cooling; however for further cooling to the BEC transition temperature, evaporative cooling is essential.

Two kinds of dark traps are used for evaporative cooling of atoms: magnetic traps and optical dipole traps. Evaporative cooling in magnetic traps relies on the selective removal of the higher energy atoms using a radio-frequency (RF) ‘knife’ where the rf radiation flips the spin-state of an atom from a low-field seeking state (trapping state) to a high-field seeking state (non-trapping state) thereby expelling the atom from the trap. In optical dipole traps, such a method for evaporative cooling is not applicable since optical dipole trapping is independent of the magnetic spin-state of the atoms. Evaporative cooling in optical dipole traps is done simply by lowering the trap depth by lowering the intensity of the trapping laser beams. The main advantage of optical dipole traps over magnetic traps for evaporative cooling is that the evaporative cooling occurs at a much faster rate in optical dipole traps. Typically, evaporative cooling to produce a Bose-Einstein condensate in a tightly confining crossed optical dipole trap takes only about 2 seconds whereas the typical time for reaching the BEC transition temperature in magnetic traps is about 20 seconds. This relaxes, by at least a factor of 5, the stringent requirement for ultra-high vacuum that is essential for very long trap life-times.

In contrast with magnetic traps which are based on the interaction of the permanent magnetic moment of atoms with the inhomogeneous magnetic field of the trap, optical dipole traps are produced as a result of the interaction of the induced electric dipole moment \( \mathbf{p} \) in the atoms with the spatially varying electric field \( \mathbf{E} \) of the trapping light which induces the electric dipole moment. This interaction can be represented as \( \mathbf{p} = \alpha \mathbf{E} \), where \( \alpha \) is the frequency dependent atomic polarizability of the trapped atoms.

To create dark optical dipole traps for atoms it important to avoid near-resonant light to prevent optical excitations which may lead to heating of the atoms and loss of atoms from the trap since these traps are much shallower as compared to the near resonant traps like the magneto-optical traps. Hence the detuning of the trapping laser in optical dipole traps is kept as large as possible. Optical dipole traps can be divided into two categories depending on the extent of detuning of the trapping light: (1) far-off resonant traps (FORT) [9] and (2) Quasi-electrostatic traps (QUEST) [10].

In a FORT, the range of detuning \( \Delta \) of the trapping light is about several tens of nanometers such that the condition \( |\Delta| = |\omega - \omega_0| \ll \omega_0 \) holds good, where \( \omega \) and \( \omega_0 \) are the optical transition frequency of the atoms and the trapping laser frequency respectively.

In a QUEST, the detuning is kept extremely large such that \( \omega \ll \omega_0 \). The corresponding optical dipole potential \( U_{dip} \) and the scattering rate \( \Gamma_{sc} \) in a QUEST is given by

\[
U_{dip}(r) = \frac{3\pi e^2 \Gamma}{\omega_0^4} I(r) = -\frac{\alpha_d}{2\varepsilon_0 c} I(r)
\]
and the scattering rate is given by
\[ \Gamma_{sc} = \frac{2\Gamma}{\hbar \omega_0} \left( \frac{\omega}{\omega_0} \right)^3 U_{dip}(r) \]  
(8)

where \( \alpha_{st} \) is the static polarizability of the trapped atoms.

To maximize the efficiency of the evaporative cooling, it is essential to prevent heating processes in the trap like optical excitations. Hence, it is more beneficial to use a Quasi-Electrostatic trap (QUEST) for evaporative cooling where the optical excitation rate is lower than \( 10^{-3} \) s. In our experiment for evaporative cooling of \(^{87}\)Rb atoms, we have used a 50 Watt CO\(_2\) laser with wavelength 10.6 microns to form a Quasi-Electrostatic trap in both single beam and crossed beam configuration.

Efficient evaporative cooling requires high atom number density in the trap so as to enable fast thermalization by the elastic collisions between atoms in the trap. Since a large number of atoms are lost during the evaporative cooling process, there is a need to start with a large initial number of atoms in the trap. For this reason, in our experiment we have started with a magneto-optical trap with the number of atoms exceeding \( 2 \times 10^{10} \) loaded within 1 sec from a cold atomic beam with a high flux of \( 2 \times 10^{10} \) atoms/sec from a 2D\(^+\) MOT which we have reported about recently [1]. The cold atomic beam with a mean longitudinal velocity of 15 m/sec and low divergence of 25 mrad enables efficient loading of the 3D-MOT produced in the main experimental chamber. The initial atom number density achieved in the magneto-optic trap was about \( 1.5 \times 10^{11} \) atoms/cm\(^3\), which is at the limit of the atom number density that can be obtained in a near resonant magneto-optical trap due to density limiting factors such as photon rescattering [11] and light-assisted collisional losses [12, 13]. The temperature of the atom cloud in the MOT is about 200 \( \mu \)K which is higher than the temperatures in a typical Rb MOT with around \( 10^{7} \) atoms. This is consistent with the fact that the trap contains more than \( 1 \times 10^{10} \) atoms and the temperature of the atom cloud in a 3D-MOT scales as \( N^{1/3} \). For efficient transfer of atoms into the optical dipole trap, the temperature of the atoms in the magneto-optic trap was reduced and the atom number density was increased using the temporal dark MOT technique which will be described in detail in a subsequent section.

In this paper, we present the experimental results from evaporative cooling of \(^{87}\)Rb atoms in both single beam and crossed beam Quasi-Electrostatic trap formed by focussing a 50 Watt CO\(_2\) laser of wavelength 10.6 \( \mu \)m where evidence of Bose-Einstein condensation was observed after evaporative cooling in the crossed dipole trap for less than a second.

2. Experimental set-up

The experimental set-up consists of a two-chamber vacuum system connected through a differential pumping duct. One is a cuboid chamber operating in the vacuum range \( 3 \times 10^{-8} - 3 \times 10^{-7} \) mbar, in which the high-flux atomic beam from a 2D\(^+\) MOT is produced. The experimental set-up for producing the 2D\(^+\) MOT is described in detail in [1]. The other is a multi-port UHV chamber (Kimball Physics) where the pressure is maintained below \( 7 \times 10^{-11} \) mbar. The three dimensional Magneto-Optical trap (3D-MOT) is produced in the second chamber with the atoms captured from the cold atomic beam from the 2D\(^+\) MOT source. The atomic beam passes to the UHV chamber through the differential pumping hole. After loading about \( 2 \times 10^{10} \) atoms into the 3D-MOT, the atoms are further cooled by sub-doppler cooling at large detuning and made into a 40 times more denser sample by going through a temporal dark-MOT phase for 60 msec. Two orthogonal CO\(_2\) laser beams, with a frequency difference of 80 MHz between them, tightly focussed at the centre of the dark-MOT were kept on at full power of 18 Watts each during these phases and the cold atoms get transferred into the dipole potential formed by the focussed CO\(_2\) laser beams. In the dipole trap atoms are spontaneously evaporated and lost at a very fast rate, nevertheless we can routinely retain more than \( 5 \times 10^{7} \) atoms in the dipole trap.
50 msec after switching-off all near-resonant light and magnetic fields. Afterwards, the intensity of the CO$_2$ laser beams are non-linearly ramped down for several hundred msecs and absorption pictures of the remaining atoms are taken.

![Figure 1.](image.png)

**Figure 1.** (Color online) The schematic diagram of the experimental arrangement to produce the cold atomic beam from a 2D$^+$/MOT which loads atoms into a 3D-MOT. The two CO$_2$ laser beams in crossed configuration in horizontal plane focussed at the center of the 3D-MOT is also shown in the figure.

For the 3D-MOT six independent cooling laser beams instead of three retro-reflected beams were used to avoid radiation pressure imbalance due to significant light absorption by the large number of atoms in the MOT. The cooling laser beams was red-detuned $2\Gamma$ away from the $^5S_{1/2}, F = 2 \rightarrow ^5P_{3/2}, F = 3$ transition. Each of the laser beams had a waist of 10 mm and were appropriately circularly polarized. The magnetic field gradient used for the MOT was 5 Gauss/cm.

### 2.1. Single beam trap

A commercial radio-frequency excited CO$_2$ laser (Gem Select-50, Coherent Inc.) provides a maximum of 60 Watts at $\lambda = 10.6\mu m$. Initially, the full power was used to trap atoms in a single beam optical dipole trap. The laser beam was allowed to expand in free space using its natural divergence of 7.5 mrad for 2 meters without using any beam expander in order to simplify the optical alignment of the trapping CO$_2$ beam. The CO$_2$ laser beam was expanded to a waist diameter of 15 mm starting from an initial waist of 2 mm and focussed to a waist diameter of less than 100 microns at the centre of the MOT using a ZnSe meniscus lens of diameter 38 mm and focal length 100 mm kept just outside the vacuum chamber. The lens was mounted on a X-Y-Z stage for fine adjustment of the focal spot at the MOT centre.

### 2.2. Crossed beam trap

For the crossed beam configuration of the CO$_2$ laser Quasi-Electrostatic trap, the initial laser beam output was split using a 50-50 beamsplitter and then each of the beams were passed through Acousto-optic modulators (AOM) (Intra-action Corp.). Each of the AOMs introduces a frequency shift of 40 MHz in the laser beams. For one of the beams, the Bragg angle of the AOM was adjusted for obtaining maximum power in the $+1^{th}$ order diffracted beam and the
other AOM was adjusted for maximizing the power in $-1^{\text{th}}$ order diffracted beam. Hence a frequency difference of 80 MHz was introduced between the two beams used for the crossed dipole trap so as to prevent any standing wave effect between them. Each of the two beams were then expanded in free space for 3.5 meters to a beam waist of about 20 mm each before focussing at the MOT centre in a right angle configuration in the horizontal plane. The lenses used for focussing each of the beams have a focal length of 100 mm and diameter 38 mm and the focus was done to a waist diameter of less than 100 microns. Both the lenses were mounted on X-Y-Z stages for the fine adjustment of the focal spots.

3. Detection system

In this section we shall discuss about our detection system to detect the cold atoms in the traps and in free motion. We employ both time-of-flight detection scheme to measure the velocity distribution of cold atoms and absorption imaging technique to observe the spatial distribution of the cold atoms after releasing the atoms from the trap.

3.1. The time-of-flight detection scheme

In order to measure the temperature of the cold atomic sample accurately we employ a time-of-flight detection scheme. A probe beam of total power 20 $\mu$W was derived from the MOT laser beam and brought to resonance with respect to $^5S_{1/2}, F = 2 \rightarrow ^5P_{3/2}, F = 3$ transition of $^{87}$Rb atoms using acousto-optic modulator. Then the probe beam was expanded using cylindrical lens pairs to form a sheet of probe beam and aligned horizontally 7 mm below the MOT centre. The width of the probe beam is 1.5 mm and it is expanded to 2 cm waist size in horizontal direction. The probe beam is retro-reflected so as to ensure that the atoms do not encounter unbalanced scattering while passing through the probe. The probe beam is made to fall on a photo-detector and the signal of the photo-detector is taken to a lock-in-amplifier (SRS) after passing it through a photodiode signal amplifier (Toptica, PDA-S).

The MOT laser beam and thus the probe beam was modulated at a frequency of 5 KHz. The modulation signal is used as the reference of the lock-in-amplifier. The output of the lock-in amplifier is detected as the time-of-flight signal. The time-constant of the lock-in-amplifier was kept at 3 msec. The temperature was determined by fitting the TOF signal with the formula [14] given by

$$S(t) = \frac{a}{\sqrt{\sigma_a^2 + \sigma_v^2 T^2}} \exp \left[ \frac{- (g(t_0^2 - t^2))}{2 \sqrt{2} \sqrt{\sigma_a^2 + \sigma_v^2 T^2}} \right]$$

where $\sigma_a = \sqrt{\sigma_0^2 + \sigma_p^2}$, $\sigma_0$ is the cloud size and $\sigma_p$ is the width of the thin sheet of probe beam and $t_0$ is the free fall time. $\sigma_v^2 = k_B T/m$ where T is the temperature of the trapped atoms, m is the atomic mass and $k_B$ is the Boltzmann constant.

3.2. Absorption imaging of cold atoms

In order to observe the spatial distribution of cold atoms we employ a direct absorption imaging technique. A probe beam of total power of 8 $\mu$W and intensity 15$\mu$W/cm$^2$ was brought to resonance with respect to $^5S_{1/2}, F = 2 \rightarrow ^5P_{3/2}, F = 3$ transition of $^{87}$Rb atoms using acousto-optic modulator. This probe beam was expanded to a waist size of 10 mm using a pair of spherical lenses. The probe beam was aligned through the centre of the atom cloud and retro-reflected for a balanced detection. The centre of the atom cloud is imaged onto a CCD camera (EMCCD iXon DV887, Andor Technologies) using a 35 cm focal length meniscus lens. The lens is kept at 2f distance away from the centre of the atom cloud and the camera is kept another 2f distance away from the lens. This way the atoms are imaged without any magnification. For
imaging the cloud the probe beam is pulsed for 1 msec within the camera exposure time-window, set to 2 ms.

The intensity of the absorption probe beam was kept much below the saturation intensity (1.6 mW/cm² for rubidium) so that the probe beam absorption is proportional to the atom number density in the cloud and independent of the probe beam intensity. The transverse intensity profile of the probe beam in the x-y plane after passing through the atom cloud and propagating in the z-direction is given by

\[ I(x, y) = I_0(x, y) \exp(-n_c \sigma_{ab}) \]  

where \( n_c = \int n(x, y, z) \, dz \) is the column density, \( \sigma_{ab} \) is the on-resonance absorption cross-section and the optical density \( D \) of the cloud at location \( (x, y) \) is given by

\[ D = \sigma_{ab} n_c(x, y) = -\ln T(x, y) \]  

where \( T(x, y) \) is the relative transmission of the probe beam which is determined by comparing the probe beam intensity profile with and without the presence of atoms in the path of the probe beam. Denoting the probe absorption image signals with and without the presence of atoms as signal image \( S_{\text{sig}}(x, y) \) and reference image \( S_{\text{ref}}(x, y) \) respectively and a background image \( S_{\text{bg}}(x, y) \) without the probe beam, the optical density is determined as

\[ D(x, y) = -\ln \frac{S_{\text{sig}}(x, y) - S_{\text{bg}}(x, y)}{S_{\text{ref}}(x, y) - S_{\text{bg}}(x, y)} \]  

The subtraction of the background image is done to eliminate the effect of stray scattered light and electronic noise.

The velocity distribution of the atoms in the cloud in the optical dipole trap corresponds to the spatial distribution of the atomic cloud after releasing the atomic cloud by switching off the dipole trap and allowing the atomic cloud to expand freely. The temperature of the atoms trapped in the optical dipole trap was determined by measuring the size of the atomic cloud at various times after switching off the dipole trap. The temperature of the trapped atoms can be determined according to the equation

\[ T = \frac{m}{k_B} \left( \frac{\sigma_2^2 - \sigma_1^2}{t_2^2 - t_1^2} \right) \]  

where \( \sigma_1 \) and \( \sigma_2 \) are defined as the sizes of the atomic cloud at times \( t_1 \) and \( t_2 \) respectively.

In order to obtain the optical density from these images we take another picture of the probe beam alone \( (S_{\text{ref}}) \) after 100 msec when atoms have fallen-off from the field of view, then this image is divided by the image containing atoms \( S_{\text{sig}} \) and a logarithm of the resulting image is taken. A third image \( S_{\text{bg}}(x, y) \) was taken by switching off the probe beam. Absorption imaging was used for detecting the atoms trapped in the MOT both before and after the temporal dark MOT phase to estimate the density enhancement. Also the atom number and density of atoms trapped in the optical dipole trap in both single beam and crossed beam configuration were estimated from absorption images. Finally, the BEC transition was detected from the absorption image of atoms after evaporative cooling to below the BEC transition temperature.

4. Phase-space density enhancement: Temporal Dark-MOT

The density of the cold atomic sample captured in the MOT is \( 1.5 \times 10^{11} \text{ atoms/cm}^3 \) at a temperature of about 200 \( \mu \text{K} \). This translates to a phase space density of \( 10^{-6} \), i.e six orders of magnitude below the phase space density required for the quantum phase transition. In
this section, we shall discuss about the technique for enhancement of phase-space density for optimized dipole trap loading.

Initially, the MOT was loaded from the cold atomic beam from 2D+MOT to an atom number of about $2 \times 10^{10}$ atoms within 1 sec. The dipole trap was then switched on followed by the temporal dark MOT phase to maximize the transfer of atoms into the dipole trap. In the temporal dark MOT technique, first the intensity of the repumping beam was lowered to 1 percent of its initial value and then after 20 msecs, the cooling beam detuning was increased from 12 MHz to 40 MHz to enable sub-doppler cooling process. After 40 msecs, the repump beam was shut off and after 2 ms the cooling laser beams and the magnetic field was switched off. The lowering of the repump intensity and then switching it off 2 msecs before the cooling beams results in transfer of more than 95 percent of the trapped atoms into the lower $F=1$ hyperfine ground state. This process is crucial for the dipole trap loading for the following reasons: (1) It increases the atom number density of the trap significantly by preventing the density-limiting processes such as photon rescattering, light-assisted collisional losses by transferring atoms to the lower hyperfine ground state or the (classical) ‘dark’ state where the atoms go out of resonance from the cooling light. (2) The life-time of the atoms in the trap increases in the $F=1$ state since in the upper hyperfine state $F=2$, atoms are greatly affected by the hyperfine-changing collisional losses [12, 15] which can be prevented by transferring them to lower $F=1$ state. (3) The temperature of the trapped atom reduces significantly due to the sub-doppler cooling process. For example, in our experiment the temperature of the atoms was reduced from 200 $\mu$K to 40 $\mu$K after the temporal dark MOT phase combined with sub-doppler cooling.

After the atoms are trapped and cooled in the MOT and then then phase space density of the cold atomic sample is increased in temporal dark MOT, about 0.5% of these atoms are transferred into the optical dipole trap formed by the focussed CO$_2$ laser. the atoms trapped in the dipole trap were detected using both time-of-flight (TOF) and absorption imaging technique.

5. Trap frequency measurement
The vibrational frequencies in the dipole trap were measured using the parametric resonance method [16]. According to the classical description of parametrically driven harmonic oscillator, the equation for the parametric oscillations including damping can be written as

$$\ddot{x} + \beta(t)\dot{x} + \omega^2(t)x = 0$$

(14)

where $\beta(t)$ and $\omega(t)$ are the time-dependent damping coefficient and natural frequency of the oscillator respectively. When the natural frequency is modulated as $\omega^2(t) = \omega_0^2(1 + f_0 \sin(\omega_m t))$ where $f_0$ and $\omega_m$ are the amplitude and the frequency of modulation. The energy of the oscillator increases exponentially when the modulation frequency is close to twice the trap frequency $2\omega_0$ or close to subharmonic frequencies $2\omega_0/n$. There is resonant amplification when $\omega_m = 2\omega_0$. When $f_0 \ll 1$, the width of the resonance is given by $f_0 \omega_0$. The quantum description of the parametric heating in harmonic potentials also gives the same results[17]. The parametric resonance frequencies in atom traps are measured by driving parametric excitations and when the driving frequency equals twice the trap frequency ($2\omega$) or subharmonics ($2\omega/n$) of the trap frequency, the atoms get heated up and they are lost from the atom trap.

In our experiment for trap frequency measurement, the power of the trapping laser beam is modulated by modulating the RF power in the AOM so that the trap depth, $U_0$, is also modulated. For the measurement, the modulation was done at a lower power of 15 W so that the variation of the deflection efficiency of the AOM with input RF power is in the linear region. The atom number remaining in the dipole trap after the modulation was measured by time-of-flight technique. At the parametric resonance frequencies especially at $2\omega$, the atoms are strongly heated out of the trap. Hence, to determine the trap frequencies, the atom number left in the single beam CO$_2$ laser trap was measured as a function of the modulation frequency.
The fraction of atoms remaining in the trap after driving the parametric oscillation for 300 msec is shown in Fig. 2. The power in the single beam CO\textsubscript{2} trap is 15 Watts and the modulation amplitude is 13.5\% of the total power. From Fig. 2 the measured trap frequency ($\nu_r$) is 800 Hz ($\pm 7$ Hz) in the radial direction. Similarly in the axial direction the trap frequency is measured to be 49 Hz.

In case of the single beam trap with full power of 18 Watts, the trap frequencies in the radial and axial directions were estimated to be $\nu_r = 910$ Hz and $\nu_a = 60$ Hz respectively. Since the trap frequency $\omega \propto \sqrt{U_0}$ and since $U_0$ scales linearly with the total power of the trapping laser beams, the mean trap oscillation frequency in the crossed dipole trap produced by crossing two identical single beam traps in the horizontal plane is estimated to be $\bar{\nu} = 1.3$ kHz. From this value of trap frequency the initial collision rate is estimated to be 140 kHz. While the measured trap frequencies are comparable to those in other similar experiments [7, 18], the estimated initial collision rate is an order of magnitude larger owing to a factor of 20 higher initial atom number in our crossed dipole trap.

![Figure 2](image)

**Figure 2.** Plot of the fraction of atoms remaining in the dipole trap versus the trap modulation frequency in the single beam dipole trap. The experimental data is fitted with a lorentzian (solid line).

6. Evaporative cooling

In this section we shall discuss about the evaporation of cold atoms from the optical dipole trap. The elastic collision rate between the atoms are very high in a tightly focussed optical dipole trap as compared to the collision rate between the atoms trapped in a magnetic trap and both elastic and inelastic collision contribute to the loss of atoms from the dipole trap. The initial rate of elastic collisions in tightly confining dipole traps can typically be between 10 and 150 kHz whereas typical initial elastic collision rates in magnetic traps are below 300 Hz. Elastic collisions are very important for re-thermalization process of the cold atom cloud. Initial peak densities which can be attained in a tightly confining optical dipole trap are around $10^{14}$ atoms/cm\textsuperscript{3} whereas those in magnetic traps are around $10^{11}$ atoms/cm\textsuperscript{3}. This makes the initial conditions for evaporative cooling very favourable in tightly confining optical dipole traps.

6.1. Spontaneous evaporation

It was observed that when the atoms were kept trapped in the optical dipole trap for some time, there was rapid initial evaporation of atoms from the trap in the first 500 msecs which happened spontaneously without any forced evaporative cooling. The rapid plain evaporation
process was then followed by a slow decay process over several seconds as shown in Fig 3. Simultaneously, the temperature of the atoms also decreased from the initial 32 μK to 14 μK as shown in Fig. 4. This phenomenon can be explained as follows: The initial rapid loss of atoms occurs due to the spontaneous evaporation of the atoms with higher energy from the trap followed by rethermalization by elastic collision, thereby reducing the overall temperature. But this temperature reduction reaches a lower limit where the rate of loss of atoms from the trap reduces significantly when the losses due to collisions with background ‘hot’ atoms takes over; hence there is no further reduction of temperature without the implementation of forced evaporative cooling.

![Figure 3. Plot of the number of atoms versus the trapping time in a single beam dipole trap.](image)

![Figure 4. Plot of the temperature of the atoms versus the trapping time in a single beam dipole trap. The points are the experimental data and the continuous line is an exponential fit to the data serving as a guide to the eye.](image)

6.2. Forced evaporative cooling in single beam dipole trap
Forced evaporative cooling in dipole traps is done by ramping down the intensity of the trapping laser and thereby the trap-depth using an accousto-optic modulator. For forced evaporative cooling in a single beam Quasi-electrostatic trap, the initial CO$_2$ laser beam of 50 Watt was split into two parts using a 50-50 beam-splitter and one of the 25 Watt beam was passed through
an AOM for variation of the laser beam intensity. The intensity of the trapping beam was varied by varying the RF power given to the AOM which in turn varies the power in the first order diffracted beam which is used as the trapping light for the single beam dipole trap. The forced evaporative cooling was done using both linear and non-linear ramps. For linear evaporation ramp, the optimized cooling was obtained for $U(t) = U_0(1 - t/\tau)$ where the time constant $\tau = 1.2$ sec, $U_0$ and $U(t)$ are the initial and final dipole potential trap depth respectively after a ramping time $t$. The temperature of the atoms trapped in the dipole trap after the evaporation ramp was measured using time-of-flight (TOF) detection technique. As the ramping time was increased, progressive cooling was observed as shown in Fig. 5.

In the case of non-linear ramp, the evaporative cooling was optimized when the potential depth $U_0$ was reduced according to the formula: $U(t) = U_0(1 + t/\tau)^{-\beta}$ where $\tau = 0.3$ sec and $\beta = 1.5$. The evaporative cooling progresses efficiently during the non-linear evaporation ramp as shown in the plot of the final temperature of atoms versus the total ramping time in Fig. 6.

In Fig. 6, the temperature seems to saturate at around 2 $\mu$K temperature, which is mainly due to the resolution limitation of the time-of-flight detection system in our experiment. The width of the TOF probe beam is 1.5 mm which contributes to the increase in width of the TOF signal as evident from eqn. (6). (The apparent increase in the width of the TOF signal due to the filter time-constant of the lock-in-amplifier, set at of 3 msec during the measurements, was subtracted out to obtain the correct estimate of the temperature). Due to this, there is a lower limit to the width of the TOF signal as depicted in Fig. 6. Nevertheless, the temperature

**Figure 5.** Plots of the TOF signals for various evaporation ramping time in a single beam dipole trap. The signals are recorded after an expansion time of 38 msecs.
seems to reduce well below 2 microkelvin by looking at the initial rate of the evaporative cooling till 250 msecs.

**Figure 6.** Plot of the final temperature of the trapped atoms versus the evaporation ramping time in a single beam dipole trap. Efficient evaporative cooling was observed accompanied by corresponding loss of atoms from the trap until the measured temperature reached a constant lower value limited by the resolution of the TOF detection system. From the trend of the evaporative cooling before reaching the lower limit of the detection system, the temperature seems to reach well below 2 µK and may even have reached the BEC transition temperature.

6.3. Forced evaporative cooling in crossed dipole trap
The main advantage of dipole trap in crossed beam configuration is that the trap is isotropic as compared to the highly anisotropic trap in the single beam configuration. The crossed trap has balanced tight confinement in all directions whereas the single beam trap which has weak confinement along the propagation axis of the trapping laser beam. This feature is evident in the large difference in the axial and radial trap frequencies of the single beam trap, as discussed earlier.

Optical dipole traps have a disadvantage as compared to the magnetic traps that evaporative cooling in dipole traps typically do not reach a ‘runaway regime’ where the evaporative cooling accelerates itself as the temperature decreases. As the evaporative cooling progresses in an optical dipole trap by relaxing the dipole potential, the trap depth also reduces thereby decreasing the atom number density which causes a reduction in the elastic collision rate which is vital for the evaporative cooling. Also, dipole traps provide smaller trapping volumes as compared to that in magnetic traps. However a large initial phase-space density can be attained in the optical dipole traps (typically 0.001-0.01) before the evaporative cooling as compared to that in magnetic traps (typically 10⁻⁶) due to much tighter confinement which enables rapid evaporative cooling to BEC transition in tightly confining optical dipole traps.

The mean trap oscillation frequency in the crossed dipole trap was estimated to be  \( \nu = 1.3 \) kHz using parametric resonance method. The peak density of atoms in the crossed dipole trap was determined to be \( 1.0 \times 10^{15} \) atoms/cm³ from eqn. (6). The initial temperature of the cold atoms in the trap after spontaneous evaporation for 50 msecs was measured to be 25 µK. The estimated elastic collision rate is \( 140 \times 10^3/s \) which is much higher than the trap oscillation frequency which enables efficient evaporative cooling due to rethermalisation by elastic collision between atoms. This high elastic collision rate can be explained as due to the high atom number in the dipole trap which is 20 times more than other similar experiments [7] and the elastic collision rate is proportional to the atom number in the trap. The initial phase-space
density in the crossed dipole trap after spontaneous evaporation for 50 msecs was estimated to be 1/100.

After a plain evaporation phase of 50 msecs in the dipole trap, forced evaporative cooling in the crossed Quasi-Electrostatic trap was done by simultaneously reducing the trap depth of both the single beam traps by reducing the trapping beam intensities using the accousto-optic modulators. The optimized evaporative cooling was obtained using a non-linear evaporation ramp given by the formula: \[ U(t) = U_0 (1 + t/\tau)^{-\beta} \] where \( \tau = 0.3 \) sec and \( \beta = 1.2 \). The evaporative cooling was done for different ramping times and then the atoms were held in the dipole trap for 20 msecs before releasing the dipole trap for detection of the atoms. The atomic cloud, in free expansion after the evaporative cooling, was detected using the absorption imaging technique after an expansion time of 2.5 seconds.

The image of the thermal cloud, after an evaporation ramp for 200 msecs at a final power of 3.5 W in each of the beams and mean trap frequency of 545 Hz, is shown in Fig 7(a). Fig. 7(b) shows an absorption image after an evaporation ramp for 400 msecs to a final power of 2.4 W and mean trap frequency of 450 Hz. After evaporative cooling for 600 msecs to a final power of 1.5 W in the crossed dipole trap with a mean trap frequency of 360 Hz, appearance of a significantly denser central region was observed in the absorption image as shown in Fig. 7(c) indicating the BEC transition. The atom number in the condensate is about \( 10^5 \) as estimated from the time-of-flight measurements and the temperature is between 500 nK to 300 nK as estimated from the Time-of-flight absorption images (Unlike in the case of TOF signals on a photodiode as used in Fig. 5 and Fig. 6., the absorption images on the CCD camera can be used to estimate temperatures down to about 100 nK. The absorption imaging technique was implemented after the data in Fig. 5 and Fig. 6 were obtained.) The time for the transition is comparable to those observed in tightly confining magnetic traps based on atom chips and micro-wires.

The atom number and the size estimated from the absorption images shown in Fig. 7 indicates a phase-space density exceeding unity. The peak atom number density of the atoms after 600 msecs of evaporation is estimated to be \( 1.4 \times 10^{14} \) atoms/cm\(^3\). This combined with the temperature of 400 nK gives a phase space density of 3.6. Hence there is an increase in phase-space density by a factor of 360 after 600 msecs of forced evaporation as compared to the initial conditions in the crossed dipole trap. This was accompanied by a loss of atoms by a factor of 500. It seems possible to optimize the evaporation further.

Thermal cloud at 300 nK will expand to diameter of 50 microns in 2.5 ms after which the absorption image is taken. This added to the resolution function of 35 microns will give 85 microns as the width of a thermal cloud, and another 20 microns of expansion occurs due to the absorption of resonant photons during 1 msec of probe pulsing (random walk) which expands the thermal cloud to a width of about 100 microns, whereas we see at most 35 microns for the width of the central spot. This implies that the dense central spot cannot be a thermal cloud at 400 - 300 nK. The rapid evaporative cooling of atoms in the crossed dipole trap to BEC transition within 600 msecs can be attributed to the high initial elastic collision rate between atoms in the trap.

7. Conclusion and outlook

In this article we have reported the preliminary results of evaporative cooling in both single beam and crossed beam Quasi-Electrostatic trap formed by using CO\(_2\) laser with wavelength 10.6 μm. Evidence of Bose-Einstein condensation was observed after evaporative cooling in the crossed trap configuration. Our experimental set-up for \(^{87}\)Rb BEC in which the focussing lenses are mounted outside a standard steel vacuum chamber, while using a moderate power CO\(_2\) laser, is much simpler than other such all-optical BEC experiments \([7, 18]\). One of the beams can be retroreflected to produce a one-dimensional optical lattice. The technical simplicity of
**Figure 7.** (colour online) Bose-Einstein condensation in a crossed Quasi-electrostatic trap. Absorption images of atomic cloud after evaporation in the crossed dipole trap after a non-linear evaporation ramping recorded after an expansion time of 2.5 msecs. (a) Thermal cloud before BEC transition after an evaporation ramp of 200 msecs to a final power of 3.5 W in each of the trapping beams (b) After evaporative ramp of 400 msecs to a final power of 2.4 W (c) Bose-Einstein condensate after evaporative cooling for 800 msecs to a final power of 1.5 W. Field of view is 300 $\mu$m.

Our experimental set-up combined with its advantages of exceptionally high atom number and density in the MOT enabled a very high initial atom number and a high evaporative cooling speed in the dipole trap, making it a convenient and versatile set-up for experiments with ultracold atoms and spinor condensates.

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