Expansion of laser cooled atomic clouds in a near-resonant laser field

S Pradhan and B N Jagatap

Laser & Plasma Technology Division, Bhabha Atomic Research Centre, Mumbai-400 085, India

bnj@barc.gov.in

Abstract. Expansion of a cold cloud of cesium atoms trapped in a magneto-optical trap is studied by switching off a pair of counter propagating trapping beams. This corresponds to 1-D expansion of the cold cloud in presence of near resonant laser beams that are orthogonal to the expansion direction. Fluorescence imaging of the expanding cloud shows that the dynamics of expansion is complex and includes three distinctive temporal features- initial contraction followed by ballistic expansion and eventually sputtering of the cloud to leave a core that exhibits damped expansion. These are respectively related to the reduction in the repulsive radiation trapping force, initial temperature of the cold cloud and the stochastic heating arising from the random nature of the photon absorption and emission processes.

1. Introduction
Studied on spatio-temporal expansion of a cloud of cooled and trapped atoms in a magneto-optical trap (MOT) are of considerable interest for characterizing the state of the cold cloud. Usually such studies are carried out on cold clouds that are allowed to expand in vacuum after switching off the trapping laser beams. The cloud expansion, in such a case, is completely determined by the internal energy of the cloud and the gravity, and as a consequence it provides a measure of the temperature ($T$) of the laser-cooled atoms [1,2]. The objective of this paper is to report experimental observations on an entirely new situation where a cold cloud of atoms is balanced against gravity and expanding in presence of a near-resonant photon field. Dynamics of this expansion is expected to be complex and interesting since the photon field can alter the slow motion of the atoms by absorption and emission processes, analogous to the cold collisions that show significant dependence on these radiative processes [3,4]. By suitably configuring the trapping laser fields of a MOT, we have achieved an idealized 1-D expansion of cold clouds of cesium atom in presence of an orthogonal 2-D laser field. Experimental results show that the expansion behaviour deviates considerably from the usual ballistic result and in a way they provide a fresh insight into the issue of the motion of atoms in near-resonant radiation field.

2. Experimental set-up
The experimental set-up used in this work is shown schematically in figure 1. The basic apparatus in this set-up is a MOT that captures, cools and confines Cs atoms directly from a room temperature atomic source [5,6]. Two external cavity tunable diode lasers (ECDL), whose frequencies are stabilized using saturated absorption spectroscopy set-up (SAS) on the $6s_{1/2}F=4 \rightarrow 6p_{3/2}F'=5$ cooling
transition (ECDL1) and $6s_{1/2} F=3 \rightarrow 6p_{3/2} F'=4$ repumping transition (ECDL2), are used in a standard six-beam $\sigma_+ - \sigma_-$ configuration. Each cooling beam has diameter ~8 mm, intensity $I \sim 14 \text{ mWcm}^{-2}$ and detuning $\delta \sim -3 \Gamma$, where $\Gamma$ is the natural line width. The hyperfine repumping beams individually have a diameter of ~8 mm and intensity of ~10 mWcm$^{-2}$. The axial ($z$ axis, along the symmetry axis of the coils) and radial (x-y plane) magnetic field gradients, produced by two current carrying coils, are ~20 and ~10 Gcm$^{-1}$ respectively. The trap parameters are optimized to obtain maximum number of trapped atoms in the MOT. The size of the cloud of cold atoms is measured using a CCD device. The observed profiles are Gaussian in three dimensions with rms sizes ($\omega_x, \omega_y, \omega_z$) ranging from 0.2 to 0.6 mm. The steady state number of trapped atoms ($N$) is obtained by measuring fluorescence intensity ($I_f$) of the cold cloud using a pre-calibrated light collection and detection system. For measurement of $T$ of the cloud, release and recapture (R&R) method [1] is implemented using amplitude modulation (AM1) of the main cooling beam (ECDL1).

![Figure 1](image)

Figure 1. Schematics of the experimental set up. ECDL1-cooling diode laser, ECDL2- repumping diode laser, SAS- saturation absorption spectroscopy, PC- computer with data acquisition and locking unit, OSC- oscilloscope, BS- beam splitter, M- mirror, L- lens, Q- quarter wave plate, AM1 and AM2- amplitude modulator for R&R method and 1D expansion respectively, S- slit, PD- photo detector, CCD- charge coupled device, MC- magnetic coils, CS- cesium reservoir, UHV- ultra high vacuum pumping station.

The experimental scheme for studying expansion dynamics in laser field is as follows: The cold cloud of cesium atoms trapped at the center of the MOT is allowed to expand in $x$-direction by switching off ($t=0$) the trapping laser beams along $\pm x$ direction while keeping the other beams along $\pm y$ and $\pm z$ directions intact. This is achieved by amplitude modulation (AM2) of the $\pm x$ trapping beams to generate dark and bright intervals of lengths $t_D \sim 40$ ms and $t_B \sim 3$ s respectively. The length of the bright interval is sufficiently large for the cloud to grow and attain the steady state. Of interest in the present study is the dynamics in the dark interval where the cold cloud expands along $\pm x$ direction in presence of two orthogonal pairs of trapping beams. During expansion the laser beams along the $z$-axis balance the cloud against the gravity. In effect we achieve an idealized 1-D expansion of the cloud devoid of the effect of gravity and in presence of an orthogonal 2-D laser field. The very presence of trapping beams along $\pm y$ and $\pm z$ directions helps to illuminate the cold cloud and yield fluorescence for spatio-temporal imaging of the expanding cloud using a CCD. The expansion of the
cold cloud is followed starting from $t=0$ (switch off) to $t=t_D = 40$ ms at every $\Delta t=0.5$ ms time interval. The cloud images thus obtained are analyzed to obtain the changes in the rms radii $\omega_x$ and $\omega_z$. While the expansion dynamics is studied for cold clouds of different $N$ and $T$, we report here a few specific interesting cases.

3. Results and Discussions

Time evolution of the spatial profiles of a typical cold cloud of atoms, as it expands in the experimental configuration discussed above, is shown in figure 2 for a few discrete time steps.

Figure 2. Fluorescence images of a cold cloud of atoms after $\pm x$ pair of beams of a Cs MOT are switched off. Frame (a) is for steady state of the cloud. Frame (b) is immediately after switching off ($t=0$) the $\pm x$ pair of beams. Frames (c)-(l) are images for a few discrete times as indicated on every frame.
Figure 2a corresponds to the fluorescence image of the cloud in the steady state of the MOT. The cloud is ellipsoidal in shape with $\omega_x = 0.5 \text{ mm}$ and $\omega_z = 0.29 \text{ mm}$. Figures 2b-l show various stages of evolution of the cloud and in all these the center of mass of the cloud does not show any downward drift owing to the presence of trapping beams along $z$-direction which cancel the effect of gravity. The image of the cloud immediately after switching off ($t=0$) the pair of trapping beams in $x$-direction is shown in figure 2b. Here the cloud size is observed to contract to give $\omega_x = 0.45 \text{ mm}$ and $\omega_z = 0.22 \text{ mm}$. The fluorescence images of figures 2c-e for $0 < t \leq 4 \text{ ms}$ correspond to expansion of the cold cloud along $x$-direction. In these figures we observe that the cloud size along $z$-direction is hardly changed owing to the trapping beams along $z$-direction. The expansion in the time scale $0 < t < 4 \text{ ms}$ is thus an idealized 1-D expansion of the cold cloud in presence of the orthogonal pair of laser beams. This 1-D expansion continues further in figures 2f and 2g for $t=5$ and $6 \text{ ms}$ respectively, but along with expansion a number of small bunches of cold atoms start to move away from the main cloud. As time progresses the expulsion of atoms becomes a dominant process, as may be seen from figures 2h-k for the time interval $9 \text{ ms} \leq t \leq 17 \text{ ms}$. The sputtering of atoms is more or less isotropic although the confining force along the $\pm y$ and $\pm z$ directions is still in place. It leaves behind a core of cold atoms, which appears to be expanding very little. Ultimately at long enough times ($t=25 \text{ ms}$) the cloud appears to explode violently as observed in the image of figure 2l. Figure 2 is representative of expansion behaviour of a cold cloud of atoms in a 2-D configuration of laser fields. Experiments on cold clouds obtained under different experimental conditions, however, suggest that the detailed features are dependent on $N$ and $T$.

![Figure 3](image.png)

**Figure 3.** Time variation of $\omega_x$ (■) and $\omega_z$ (○) of an expanding cold cloud after ±x trapping beams are switched off ($t=0$). The rms sizes for $t < 0$ correspond to the cloud in the steady state. The solid curve is a plot of $\omega_x(t)$ for 1-D free expansion of a cloud of $T= 800 \mu \text{K}$.

More insight into the dynamics of expansion may be obtained by considering the variation of $\omega_x$ and $\omega_z$ for $0 \leq t < t_0$ obtained from the analysis of the fluorescence images. This is illustrated in figure 3 for a cloud with $N=1.4 \times 10^6$ and $T=800\pm150 \mu \text{K}$ as measured by R&R method. We have considered here a cloud of somewhat higher temperature since this case helps to decipher the essential features underlying the expansion rather easily. Note in figure 3 that both $\omega_x$ and $\omega_z$ show a dip at $t=0$, which corresponds to the contraction of the cloud. For $t < 5 \text{ ms}$, the cold cloud expands along $x$-direction.
keeping its size along z-direction intact. Beyond t ~ 5 ms the rate of change of $\omega_z$ starts to decrease and $\omega_z$ shows tendency to increase. Referring to figure 2 we see that for t ≥ 5 ms, atoms are expelled from the cloud to leave behind a small core. The sizes $\omega_x$ and $\omega_z$ plotted in figure 3 for t ≥ 5 ms correspond to those of the central core. The cloud size for 5 ≤ t < 10 ms is therefore determined by the balance between the process of expansion and the process of expulsion of atoms. Beyond t > 10 ms, the process of sputtering becomes the dominant process, which results in severe uncertainties in the measurement of the size of the cloud. From figures 2 and 3 we observe that the cold cloud evolves with three distinctive features: contraction at t=0, expansion for 0 < t < 5 ms and sputtering of the cloud for t > 5 ms, which ultimately results in a violent explosion-like behaviour.

We attribute the initial contraction of the cloud to the decrease in the radiation trapping force [7] once one pair of the trapping beams is switched off. The radiation trapping force, which is repulsive in character, arises from the absorption of re-emitted photons and its magnitude is proportional to the total intensity of the trapping beams (~ 6$I$) and $N$. The steady state size of the cold cloud in a MOT (figure 2a) is determined by the balance between the trapping force and the repulsive radiation trapping force; the later leads to expansion of the cold cloud and the effect is seen in limiting the density of cold atoms [7]. When one pair of trapping beams is switched off the magnitude of the repulsive force decreases, which results in contraction in size of the cold cloud (figure 2b). Note here that the photon emission process being isotropic the cloud size decreases uniformly in all directions although only one pair of beams (±x) is switched off. Experiments conducted on clouds of different $N$ show that the relative contraction of a given cloud at t=0 is directly proportional to $N$. This observation provides a supporting evidence for the role of the radiation trapping force in the initial evolution of the cold cloud.

In the time domain 0 ≤ t < 5 ms, the cold cloud expands along x-direction with negligible effect on $\omega_x$. In order to test whether the 1-D expansion in this time regime has a ballistic character, we fit the data $\omega_x$ vs t to the well known equation $\omega_x^2(t) = \omega_x^2(0) + (k_BT/M)t^2$ [2,8] where $k_B$ is the Boltzmann constant, $M$ is the mass of the cesium atom and $T$ is the temperature of the cloud. In figure 2 we have included a curve that represents free expansion of a cold cloud with $T=800$ $\mu$K (as measured by R&R method). It may be seen that $\omega_x(t)$ follows this curve very closely for 0 ≤ t < 5 ms. We thus conclude that for t < 5 ms the cloud essentially expands in ballistic manner.

The mechanism responsible for expulsion of atoms from the cloud is stochastic heating [9] caused by the absorption and emission of photons due to the orthogonal laser beams. In our experimental configuration the ±y and ±z laser beams provide a 2-D damping force on a cloud that is expanding along ±x direction. This damping force reduces the average velocity of the atoms and does not permit expansion of the cloud in y- and z- directions, at least initially (cf. figure 3). However, the fluctuations in this 2-D force produces heating of the cloud since every absorption and emission cycle represents a random walk of the momentum of the atom. After a given number of cycles the mean square momentum of the atom grows which results in increase in the kinetic energy, $(dE/dt) = D_p/M$ where $D_p$ is the momentum diffusion constant [9]. These heated atoms leave the cloud isotropically as is evident from figure 2. For t > 5 ms the rate of expulsion of atoms dominates over the rate of expansion and as a result the size of the core appears to stay unchanged. The onset of stochastic heating is also evident from the behaviour of $\omega_x(t)$, which shows tendency to increase for t > 5 ms. For sufficiently large times the stochastic heating becomes too large to result in a violent explosion of the cold cloud.

4. Conclusion
This paper addresses the question of expansion of a laser cooled atomic cloud that is balanced against gravity and expanding in presence of a near resonant laser field. This presents a new situation where the laser field modifies the slow motion of atoms by the radiative processes in close analogy with cold collision processes. The problem is studied experimentally by allowing 1-D expansion of a cold cloud of Cs atoms in presence of 2-D configuration of near resonant beams that are orthogonal to the expansion direction. This is achieved by temporally modulating a pair of counter propagating trapping
beams of a MOT and following the evolution of the cloud in the spatial and temporal domain. Experimental results show that expansion behaviour is characterized by three distinct processes that occur in different time domains, and the mechanisms responsible for these processes are of fundamental interest in the studies of laser cooling and trapping. Contraction of the cloud at \( t=0 \) clearly demonstrates the existence of the radiative trapping force in a MOT. Ballistic expansion in the intermediate time scale (0 < \( t < 5 \) ms) is of interest for measurement of the temperature of the cold cloud. Third time scale (\( t > 5 \) ms) corresponds to the stochastic heating of the cold cloud, which results in sputtering of the cloud and eventual violent explosion at long times (\( t \sim 25 \) ms). The experiments reported here offer an excellent opportunity to quantify radiative trapping force in a MOT, temperature of the cold cloud and the momentum diffusion constant of atoms in a near resonant laser field. Details of these investigations will be reported elsewhere.

References
[1] Chu S, Hollberg L, Bjorkholm J E, Cable A and Ashkin A 1985 Phys. Rev. Lett. 55 48
[2] Vorozcovs A, Weel M, Beattie S, Cauchi S and Kumarakrishnan A 2005 J. Opt. Soc. Am. B 22 943 and references therein
[3] Wallace C D, Sanchez-Villicana V, Dinneen T P and Gould P L 1995 Phys. Rev. Lett. 74 1087
[4] Walhout M, Stert U, Orzel C, Hoogerland M and Rolston S L 1995 Phys. Rev. Lett. 74 506
[5] Monroe C, Swann W, Robinson H and Wieman C 1990 Phys. Rev. Lett. 65 1571
[6] Pradhan S, Gaur S J, Manohar K G and Jagatap B N 2005 Phys. Rev. A 72 053407
[7] Sesko D W, Walker T G and Wieman C E 1991 J. Opt. Soc. Am. B 8 946
[8] Overstreet K R, Zabawa P, Tallant J, Schwettmann A and Shaffer J P 2005 Optic Express 13 9672
[9] Lett P D, Phillips W D, Rolston S L, Tanner C E, Watta R N and Westbrook C I 1989 J. Opt. Soc. Am. B 6 2084