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High sensitivity probe absorption technique for time-of-flight measurements on cold atoms

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Abstract. We report on a phase-sensitive probe absorption technique with high sensitivity, capable of detecting a few hundred ultra-cold atoms in flight in an observation time of a few milliseconds. The large signal-to-noise ratio achieved is sufficient for reliable measurements on low intensity beams of cold atoms. We demonstrate the high sensitivity and figure of merit of the simple method by measuring the time-of-flight of atoms moving upwards from a magneto-optical trap released in the gravitational field.

Keywords. Laser cooling; magneto-optical trap; time-of-flight; phase-sensitive detection; absorption measurement.

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1. Introduction

Detection of a small number of cold atoms in flight is of importance in experiments in atom optics, atom interferometry and in precision measurements using atomic beams and atomic fountains. Due to the tremendous progress in laser cooling and trapping of atoms in the past two decades, it is now routinely possible to obtain about 10^8 cold atoms with a temperature of a few microKelvin [1]. New generation experiments have produced collimated beams of cold atoms with fluxes of 10^9–10^{12} atoms/s with velocities in the range of 1–50 m/s [2–5]. For many experiments in atom optics and with atomic fountains, as well as for determining the temperature and velocity characteristics of cold atoms, detection techniques based on fluorescence or absorption are used. Usually the temperature of the atomic cloud is inferred from the velocity distribution, obtained from the time-of-flight (TOF) signal of a ballistically expanding cloud. TOF signal can be observed by collecting the fluorescence on to a photomultiplier tube or a high sensitivity photodiode [6,7]. Absorption imaging using a high sensitivity CCD camera gives the size of the expanding cloud and hence the velocity distribution of the atomic cloud can be determined. However, getting the TOF signal of the expanding cloud by the probe absorption method after it is released from a standard magneto-optical trap (MOT) at about 100 μK is difficult when the number of atoms in the cloud is less than a million or so. This is because the change in the probe power due to the absorption by a small number of atoms interacting with the probe beam, during the short time of passage of the atoms through the probe, is not significantly larger than the laser intensity fluctuations. For example, in a free fall TOF experiment on cold atoms from a vapor loaded MOT, there are typically less than 10^6 atoms in a thin probe beam, 1 cm below the trap, for a duration of about 2–3 ms at the peak of the absorption signal. This corresponds to only 0.1% absorption from the probe beam that usually has an intensity much less than the saturation intensity. But the absorption technique has the desirable advantage that the perturbation on the atoms is relatively insignificant in an approximately balanced beam due to the small power used. It is possible to get the TOF signal with reasonable signal-to-noise ratio (S/N) by keeping the probe close to the MOT [8]. Then the number of atoms interacting with the probe is larger due to the lesser expansion of the cloud in the shorter duration of free fall through the probe. Also, the time of interaction is increased and a better signal can be obtained. The characteristics of the TOF signal with the finite size of the cloud, and the accurate determination of the temperature when the probe is kept close to the cloud have been discussed in ref. [8]. The absorption signal thus detected by a photodiode is mostly dominated by the laser intensity fluctuations and the S/N is of the order of unity for a MOT of 10^6 atoms detected 1 cm below the MOT center.

There are many situations in atom optics experiments and in the experiments using cold atomic beams or atoms in fountain geometry where the instantaneous number of atoms interacting with the probe beam is less than 10^6. For example, even in the case of a relatively intense, collimated cold atomic beam with 10^{10} atoms/s with an average velocity of 30 m/s, as in the low velocity intense source (LVIS) [2], the peak signal in a 1 mm thick resonant probe beam corresponds to the absorption by 3×10^5 atoms. In atomic fountains and in atom optics experiments this could be an order of magnitude smaller, since there is additional velocity or state selection.

The ultimate absorption detection limit of a single atom with good S/N has been demonstrated as far back as in 1987, in the case of a single mercury ion in a Paul trap, with an integration time of several tens of seconds [9]. Detection of single atoms in a MOT within 10 ms is possible by detecting the resonant fluorescence from the atoms using elaborate optics as implemented recently to detect single atoms in an optical dipole trap [10]. Recently there has been remarkable developments in detecting single atoms passing through a small cavity by absorption detection [11,12]. In this case, the short observation time is compensated by the high probability of absorption in the high finesse cavity. Our discussion in this paper pertains to a regime where the number of atoms are at least a few thousands, but the available observation time is small, of the order of a few milliseconds. Then a simple absorption technique can still be used with good S/N by reducing the noise bandwidth by phase-sensitive detection around the resonance peak. While the phase-sensitive detection of the fluorescence signal is being used in many laboratories, we focus in this paper on the absorption detection of a small number of atoms with sensitivity enhanced by the modulation–demodulation scheme.

We have detected peak signal corresponding to less than 10^3 atoms in the probe with significant improvement in the S/N, by modulating the probe laser frequency with time period much shorter than the time spent by moving atoms in the probe and then detecting the signal with phase-sensitive demodulation. By using a lock-in amplifier with a photodiode and a low noise amplifier, we could improve the S/N by a factor exceeding 20. In this article, we describe the detection of the TOF signal of rubidium atomic clouds released from a MOT. The temperature was determined from the observed TOF signal. The technique is sensitive enough to detect those *atoms that fly upward from the MOT* even up to a height of 1 cm, clearly demonstrating its efficacy for atomic fountain experiments. This has enabled us to detect as small as a few 100 atoms in the probe beam within an observation time of less than 10 ms. The product of the integration time and the number of atoms normalized to the same S/N is better than the ultimate absorption limit obtained for the single ion earlier. (This advantage arises from the fact that the S/N improves only as the square root of the observation time, which exceeded 10 s for the single ion.) This product can be taken as a figure of merit of the detection technique, and the results reported in this paper represent one of the best figure of merit achieved in absorption detection. The simple method is now routinely used in our atom optics experiments on the reflection of atoms from magnetic thin films [13]. The sensitivity could be improved further for continuous atomic beams, with longer integration times.

2. Experimental details

In our experiment, ^{85}Rb atoms were trapped in a MOT formed in a SS octagonal chamber equipped with glass view ports and evacuated to 5×10^{-10} Torr. A commercial rubidium getter was used as the source. The MOT was loaded at a pressure less than 1×10^{-9} Torr for about 10 s to obtain the cold atomic cloud with 5×10^6 to 1×10^7 atoms. A quadrupole field of gradient 6 G/cm was generated by two anti-Helmholtz coils fitted close to the vacuum chamber. The stray magnetic field in the absence of the quadrupole field was canceled using three pairs of Helmholtz coils.

Two external cavity diode lasers (Toptica DL100) working at 780 nm were used for the MOT. The linewidth of the lasers are of the order of 1 MHz. The cooling laser was locked at 13 MHz below the cooling transition $5S_{1/2}$ $F_g = 3 \longrightarrow 5P_{3/2}$ $F_e = 4$. The re-pump laser was locked to the $5S_{1/2}$ $F_g = 2 \longrightarrow 5P_{3/2}$ $F_e = 3$ transition. The cooling and re-pump beams were expanded to a Gaussian width of 10 mm. The power in each cooling beam was about 5 mW.

The schematic of the experimental set-up for the detection of the time-of-flight (TOF) signal is shown in figure 1. The probe was derived from the cooling laser. By using an acousto-optic modulator (AOM) the frequency of the probe was brought on resonance to the $5S_{1/2}$ $F_g = 3 \longrightarrow 5P_{3/2}F_e = 4$ transition. The probe beam was expanded to 15 cm $\times$ 0.5 mm of Gaussian width using a cylindrical lens. A rectangular slit of 20 mm $\times$ 1 mm was used after the expander. The probe was retro-reflected and sent to a photodetector by using a quarter wave plate and a polarizing cube beam splitter. The photodetector was a Hamamatsu photodiode

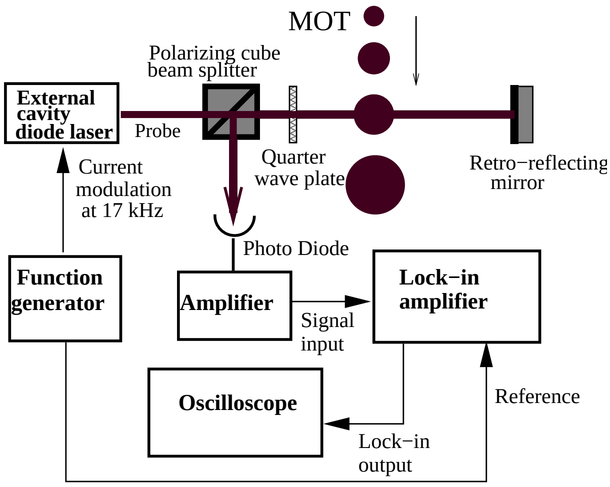

Figure 1. Schematic of the experimental set-up. The probe beam is 20 mm wide, which is more than the cloud size and 1 mm thick in the direction of gravity.

(S2386-44K) with an active area of 3.6 mm × 3.6 mm and photosensitivity of 0.5 A/W at 780 nm. The maximum dark current is 20 pA. The photodiode amplifier (PDA100 from Toptica) used in the experiment has a current-to-voltage converter followed by an optional high pass filter and a variable attenuator and one more stage of amplification with a variable gain up to 1×10^7. We use 2–10 μW power for the probe without saturating the detector. The photodiode signal was detected using a commercial lock-in amplifier. For the reference to the lock-in amplifier, the laser frequency was modulated by modulating the current to the laser at 17 kHz, which is limited by the frequency response of the electronics used in our laser system. The laser frequency modulation depth (about 2–4 MHz P-P) was optimized to get the best S/N. The same current modulation was used to do the frequency modulation spectroscopy for locking the laser frequency at the center of the appropriate transition line.

3. Experimental results

In one set of experiments, the probe was kept approximately 12 mm below the atomic cloud in the MOT. The probe power was 2 μW. The TOF signals of the atomic cloud released from the MOT is shown in figure 2.

In another set of experiments, the cooling beam frequency was red-detuned by 55 MHz from the cooling line after loading the MOT and after switching off the magnetic fields, and the power was reduced to about 1 mW per beam using an AOM to further cool the atoms in the optical molasses for 15 ms [7]. The observed TOF signal is shown in figure 3. The signal shown in the inset was obtained in a conventional absorption TOF measurement, without the phase-sensitive detection, after passing through a low pass filter of 10 kHz. The S/N is an order of magnitude better in the phase-sensitive technique.

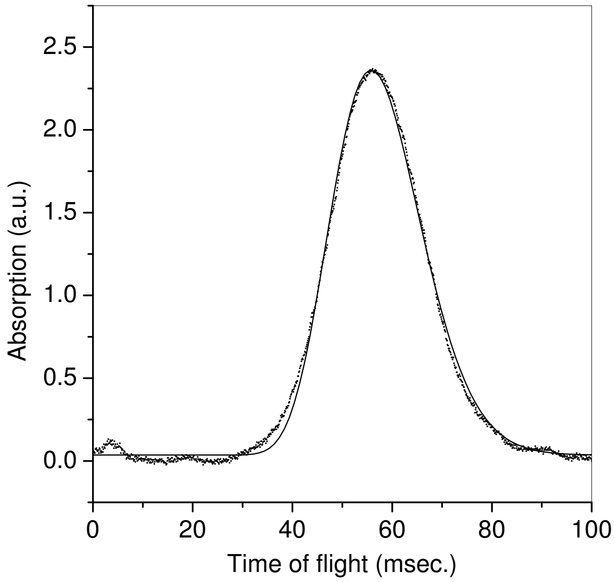

Figure 2. TOF signal of the atomic cloud containing a few million atoms released from the MOT after 12 mm of free fall. The probe power was 2 μW. Dotted line is the TOF signal observed by the phase-sensitive probe absorption technique, which is averaged over five data. Solid line is the fitted curve using the expression given in eq. (5). The values for the fitting parameters are $a_0 = 0.04$, $P_1 = 0.012$, $\sigma_v^2 = 0.0097$ (m/s)^2 and $t_0 = 0.057$ s.

The shape of the time-dependent absorption TOF signal for the case of a Gaussian profile of the atomic cloud and the probe beam is given in ref. [8]

$$N(t) = \frac{P_0}{2\pi\sqrt{(\sigma_t^2 + \sigma_{Ix}^2)(\sigma_t^2 + \sigma_{Iy}^2)}} \exp\left[-\left(\frac{g\left(t_0^2 - t^2\right)}{2\sqrt{2}\sqrt{\sigma_t^2 + \sigma_{Ix}^2}}\right)^2\right], \qquad (1)$$

where z is the probe beam propagation direction and x is the gravity direction, t_0 is the mean time-of-flight of the atoms. The probe beam is kept below the MOT center at a distance of $\frac{1}{2}gt_0^2$, and it has a Gaussian intensity distribution in x–y plane. P_0 is the power of the probe beam, σ_{Ix} and σ_{Iy} are the Gaussian beam radii ($1/e^2$) in x- and y-axis respectively. $\sigma_t = \sqrt{\sigma_0^2 + \sigma_v^2 t^2}$ is the Gaussian radius of the ballistically expanded cloud at time t, where σ_0 and σ_v are the Gaussian radii of the size and velocity distribution of the atomic cloud respectively. σ_v is related to the temperature (T) of the atoms by the formula

$$T = \frac{M}{k_{\rm B}}\sigma_v^2, \qquad (2)$$

where M is the mass of rubidium and $k_{\rm B}$ is Boltzmann's constant. In our experiment, the probe beam has a Gaussian radius of 15 cm in the y-direction and hence $\sigma_{Iy} \gg \sigma_t$. So eq. (1) is simplified to

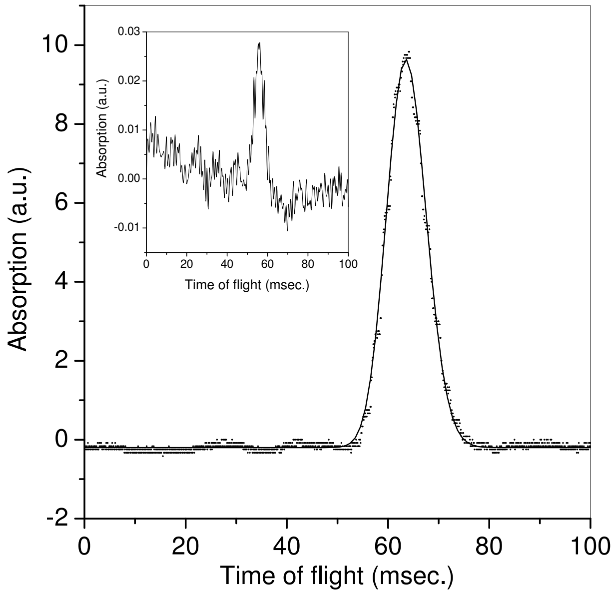

Figure 3. TOF signal of the atomic cloud containing a few million atoms released after cooling in the optical molasses. The probe beam of power 2 μW was kept 12 mm below the MOT center. Dotted line is the TOF signal observed by the phase-sensitive probe absorption technique. Solid line is the fitted curve using the expression given in eq. (5). The values of the fitting parameters are $a_0 = -0.2$, $P_1 = 0.02$, $\sigma_v^2 = 0.00097$ (m/s)^2 and $t_0 = 0.064$ s. Conventional TOF signal using a low pass filter of 10 kHz without phase-sensitive detection is shown in the inset. A small delay of the TOF peak is observed in the case of phase-sensitive detection, which is due to the signal passing through a low pass filter of the lock-in amplifier.

$$N(t) = \frac{P_0}{2\pi\sigma_{Iy}\sqrt{(\sigma_t^2 + \sigma_{Ix}^2)}} \exp\left[-\left(\frac{g\left(t_0^2 - t^2\right)}{2\sqrt{2}\sqrt{\sigma_t^2 + \sigma_{Ix}^2}}\right)^2\right]. \tag{3}$$

The absorption signal also depends on the absorption probability $P(\omega_{\mathrm{L}})$ at the probe beam frequency (ω_{L}), which has a Lorentzian profile.

In the case of phase-sensitive detection using laser frequency modulation, the first harmonic output of the lock-in amplifier is proportional to the first derivative of the absorption profile with respect to the laser frequency. If the laser frequency is locked at the peak of the transition line, the first harmonic output of the lock-in amplifier becomes zero. However, the second harmonic output of the lock-in amplifier is

$$S(t) = a_0 + g_1 \frac{\mathrm{d}^2 P(\omega_{\mathrm{L}})}{\mathrm{d}\omega_{\mathrm{L}}^2} N(t), \tag{4}$$

where g_1 is the gain of the photodiode amplifier and the lock-in amplifier. a_0 is the DC offset. Putting the expression for $N(t)$ of eq. (3), the above equation can be written as

$$S(t) = a_0 + \frac{P_1}{\sqrt{(\sigma_t^2 + \sigma_{Ix}^2)}} \exp\left[-\left(\frac{g\left(t_0^2 - t^2\right)}{2\sqrt{2}\sqrt{\sigma_t^2 + \sigma_{Ix}^2}}\right)^2\right], \tag{5}$$

where $P_1 = \frac{P_0 g_1}{2\pi\sigma_{Iy}} \frac{\mathrm{d}^2 P(\omega_\mathrm{L})}{\mathrm{d}\omega_\mathrm{L}^2}$ is a proportionality constant. The second derivative of the Lorentzian has a maximum value at the peak, and hence, the second harmonic output of the lock-in amplifier gives a maximum signal when the probe frequency is at the center of the transition line. The TOF signals were observed by detecting the second harmonic output of the lock-in amplifier. To determine the temperature, the TOF signals are fitted to eq. (5). a_0, P_1, t_0 and σ_v are taken as the fitting parameters and the temperature is calculated using eq. (2). The size of the cloud (σ_0) is 0.75 mm which is determined from the fluorescence image on a CCD camera. The temperature of the atoms released from the MOT is 81 $\pm$ 5.3 μK which is determined from the TOF signal shown in figure 2. The temperature of the atoms released after cooling in the optical molasses is 12.2 ± 0.6 μK which is determined from the TOF signal shown in figure 3. A small amount of stray light (less than 1 nW) scattered from the glass windows due to the presence of the MOT beams falls on the photodetector. So, when the MOT beams are turned off, a small change in the intensity is detected, which causes a spurious peak appearing in the time range of 0–5 ms in the TOF signal observed in figure 2 and also in figure 4. However, it is not appreciable in figure 3, because the intensity of the MOT beams was reduced for the molasses cooling before turning it off and the changes in the stray light are not visible in the plot in comparison with the much larger absorption signal.

To test the sensitivity of our detection technique, we kept the probe about 5 mm above the cloud to detect those small number of atoms which have their velocity upward initially. A Monte Carlo simulation was done to find the number of atoms in the probe. For the simulation, we assumed an isotropic atomic cloud with a Gaussian spatial distribution. The cloud size was taken as 0.75 mm. The TOF signal from the Monte Carlo simulation fits well with the observed TOF signal at a cloud temperature of 75 μK. The probe was taken as a flat beam of width 1 mm in the direction of gravity and infinity in the other two directions. The total number of atoms in the cloud was taken as 5 million, which was determined approximately from the fluorescence signal detected by a photodetector. The TOF signal from the Monte Carlo simulation and the experimental TOF signal are shown in figure 4.

From figure 4, it is quite evident that the peak of the signal corresponds to a few thousand atoms. The S/N is about 15 in this case and it is clear that one can detect as small as a few hundred atoms using this technique. The sensitivity of the technique was also cross-checked by detecting the atoms dropped from a faint MOT containing about 6000 atoms and keeping the probe beam 12 mm below the MOT center. The TOF signal was observed with a S/N of about 5.

For continuous beam sources, the integration of the modulated signal can be done for a longer time and much better detection sensitivities can be achieved in principle. We expect that the detection of a few tens of atoms instantaneously interacting with a probe beam will become possible with this technique, with integration time of the order of a second.

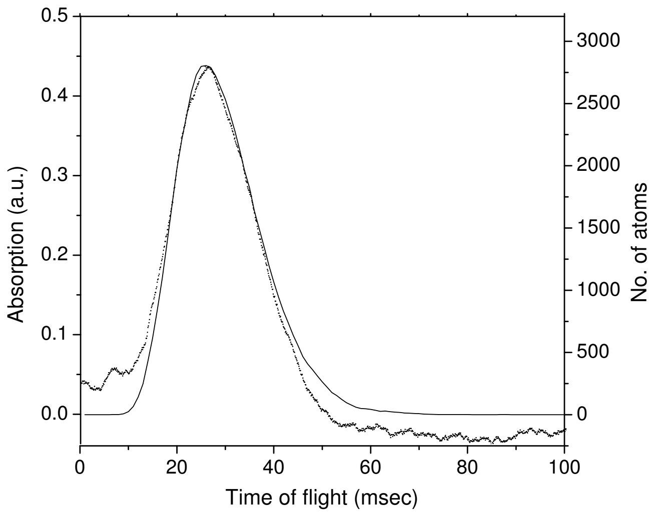

Figure 4. TOF signal of the atoms released from a MOT observed by keeping the probe beam 5 mm above the cloud. Dotted line is the TOF signal observed by the phase-sensitive probe absorption technique and it is averaged over 20 data. The probe power was 5 μW. Solid line is the TOF signal obtained from the Monte Carlo simulation for a flat probe beam kept 5 mm above the MOT center.

4. Conclusion

A phase-sensitive probe absorption technique that improves significantly the sensitivity of detection of a small number of atoms in time-of-flight or in low intensity beams of cold atoms is reported. By using a lock-in amplifier with a photodiode and a low noise amplifier, the S/N of the TOF signal has been improved enough to detect a few hundred atoms in an observation time of about 1 ms. The product of the available observation time and the S/N is among the best reported for absorption detection. This technique is very useful in atom optics experiments (e.g. observation of atoms bouncing from surfaces) and in experiments that study the atom–surface interactions [13–15] and quantum reflection [16], where the perturbation due to the radiation pressure needs to be minimized and a small number of atoms needs to be reliably detected. It can also be used efficiently for characterizing cold atomic beams.

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References

[1] H J Metcalf and P Van Der Straten, *Laser cooling and trapping* (Springer, New York, 1999) and references therein

[2] Z T Lu, K L Corwin, M J Renn, M H Anderson, E A Cornell and C E Wieman, *Phys. Rev. Lett.* **77**, 3331 (1996)

[3] K Dieckmann, R J C Spreeuw, M Weidemuller and J T M Walrnaven, *Phys. Rev.* **A58**, 3891 (1998)

[4] T Lahaye, J M Vogels, K Gunter, Z Wang, J Dalibard and D Guery-Odelin, *Phys. Rev. Lett.* **93**, 093003 (2004)

[5] S Chaudhuri, S Roy and C S Unnikrishnan, TIFR Preprint, available at www.tifr.res.in/∼filab

[6] P D Lett, W D Phillips, S L Rolston, C E Tanner, R N Watts and C I Westbrook, *J. Opt. Soc. Am.* **B6**, 2085 (1989)

[7] C Salomon, J Dalibard, W D Phillips, A Clairon and S Guellati, *Europhys. Lett.* **12**, 683 (1990)

[8] T M Brzozowski, M Maczynska, M Zawada, J Zachorowski and W Gawlik, *J. Opt. B: Quantum Semiclass. Opt.* **4**, 62 (2002)

[9] D J Wineland, W M Itano and J C Bergquist, *Opt. Lett.* **12**, 389 (1987)

[10] W Alt, D Schrader, S Kuhr, M Müller, V Gomer and D Meschede, *Phys. Rev.* **A67**, 033403 (2003)

[11] A Boca, R Miller, K M Birnbaum, A D Boozer, J McKeever and H J Kimble, *Phys. Rev. Lett.* **93**, 233603 (2004)

[12] M Münstermann, T Fischer, P W H Pinkse and G Rempe, *Opt. Commun.* **159**, 63 (1999)

[13] A K Mohapatra and C S Unnikrishnan, *Europhys. Lett.* **73**, 839 (2006)

[14] C I Sukenik, M G Boshier, D Cho, V Sandoghdar and E A Hinds, *Phys. Rev. Lett.* **70**, 560 (1993)

[15] A Landragin, Y Courtios, G Labeyrie, N Vansteenkite, C I Westbrook and A Aspect, *Phys. Rev. Lett.* **77**, 1464 (1996)

[16] F Shimizu, *Phys. Rev. Lett.* **86**, 987 (2001)