

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

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Abstract

We report on a 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 in this phase sensitive technique is sufficient for reliable measurements on low intensity atomic beams of cold atoms. We illustrate the high sensitivity and figure of merit of the simple method in measurement of time-of-flight of atoms moving upwards from a magneto-optical trap released in the gravitational field.

Key words: Laser cooling, Magneto-Optical Trap, time of flight, Phase sensitive detection, absorption measurement

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1 Introduction

Detection of small number of cold atoms in flight is of importance in experiments in atom optics, atom interferometry and in precision measurements on 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 few millions of cold atoms with temperature of few micro kelvin [1]. New generation experiments have obtained collimated

beams of cold atoms with fluxes of $10^9 - 10^{12}$ atoms/s with velocities in the range of 1 m/s – 50 m/s [2, 3, 4]. For many experiments in atom optics and 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 cloud is inferred from the velocity distribution and is obtained from the time of flight (TOF) signal of a ballistically expanded cloud. TOF signal can be observed by collecting the fluorescence on to a PMT or a high sensitive photo diode [5, 6]. Also absorption imaging using a high sensitive CCD camera gives the size of the expanded cloud and hence the velocity distribution of the cloud can be determined. However getting the TOF signal of the expanded cloud after releasing from a standard magneto-optical trap at about 100 μ K by probe absorption method is difficult when the number of atoms in the cloud is less than a million or so because of the small absorption of probe due to the small number of atoms interacting with the probe beam during the short time of passage of the atoms through the probe. For example, in a free fall experiment determined by gravity on cold atoms from a MOT, there are typically less than 10^6 atoms in the 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 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 S/N ratio by keeping the probe close to the cloud [7]. 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 has been discussed in reference [7]. The absorption signal thus detected by a photo diode is mostly dominated by the laser intensity fluctuation and the (S/N) is order of unity for a MOT of 10^6 atoms detected 1 cm below the cloud.

There are situations in atom optics experiments and in 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/sec 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 resonance 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 are additional velocity or state selection.

The ultimate absorption detection limit of a single atom with good S/N ratio has been demonstrated as far back as in 1987, in case of a single mercury ion in a Paul trap, with an integration time of several tens of seconds [8]. Detection of single atom in a MOT within 10 msec is possible by detecting the resonant fluorescence from the atom and is recently demonstrated to detect single atom in optical dipole trap [9]. Recently there has been remarkable developments in detecting single atom passing through small cavities by absorption detection [10, 11]. In this case the small observation time is compensated by the high probability of absorption in the high finesse cavity. Our discussion in this paper pertains to regime where the number of atoms are at least a few thousands, but the available observation time is small, of the order of milliseconds. Then a simple absorption technique can still be used with good S/N ratio by reducing the noise bandwidth by phase sensitive detection around the resonance peak. The absorption technique has the added advantage in some experimental situations that the atoms are not perturbed much due to unbalanced radiation pressure since the probe beam has intensity much smaller than the saturation intensity. 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 signal to noise ratio, by modulating the probe laser frequency and then detecting the signal with phase sensitive demodulation. By using a lock in amplifier with a photo diode and low noise amplifier, we could improve the signal to noise ratio by a factor exceeding 20. In this article we describe the detection of TOF signal of Rubidium atomic cloud released from a Magneto-Optical Trap (MOT). The temperature was determined from the observed TOF signal. The technique is sensitive enough to detect those *atoms that fly upward from a MOT* even at a height of 1 cm, clearly demonstrating its efficacy for atomic fountain experiments. This has enabled detection of as small as 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 ratio, is better than the ultimate absorption limit obtained for the single ion earlier (This

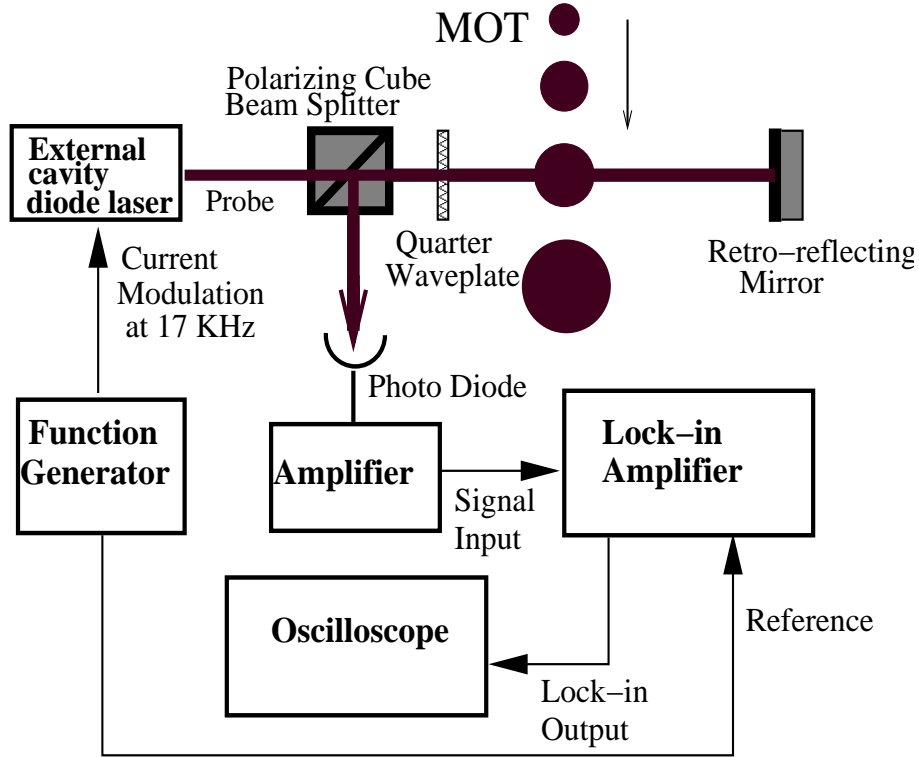


Figure 1: Schematic of the experimental set up. The probe beam is 20 mm wide, which is more the cloud size and 1 mm thick in gravity direction.

advantage arises from the fact that the S/N improves only as the square root of observation time, which exceeded 10 seconds 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 represents 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. 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. Our MOT was formed in a SS octagonal chamber equipped with glass view ports and evacuated to

a vacuum of 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 seconds to obtain cold atomic cloud with 5×10^6 to 1×10^7 atoms. A quadrupole field of gradient 6 G/cm was generated by two air cooled anti-Helmholtz coils fitted close to the vacuum chamber. The stray magnetic field, in the absence of quadrupole field was canceled using 3 pairs of Helmholtz coils.

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

The schematic of the experimental set up for the detection of time of flight (TOF) signal is shown in the figure 1. The probe was derived from the cooling laser. By using AOM the frequency of probe was brought on resonance to $5S_{1/2} F_g = 3 \longrightarrow 5P_{3/2} F_e = 4$ and expanded to $15 \text{ cm} \times 0.5 \text{ mm}$ of Gaussian width using cylindrical lens. A rectangular slit of $20 \text{ mm} \times 1 \text{ mm}$ was used after the expander. The probe was retro reflected and sent to a photo detector by using a quarter wave plate and a polarizing cube beam splitter. The photo detector was a Hamamatsu photo diode (S2386-44K) with an active area of $3.6 \text{ mm} \times 3.6 \text{ mm}$ which has photo sensitivity of 0.5 A/W at 780 nm. The maximum dark current is 20 pA. A low noise photo diode amplifier (PDA100 from Toptica Photonics AG) was used. The photo diode amplifier has current to voltage converter followed by an optional high pass filter and a variable attenuator and one more stage of amplifier with a variable gain upto 1×10^7 . We use $2 \mu\text{W}$ to $10 \mu\text{W}$ power for the probe without saturating the detector. The photo diode 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 electronics used in our laser system. The laser frequency modulation depth (about 2 – 4 MHz PP) was optimized to get the best S/N ratio. It has been observed that the laser intensity changes by 0.1% of it's intensity due to small modulation of current. However the intensity modulation includes a dc shift in the signal, which doesn't affect the shape of the signal. The same current modulation was used to do the FM spectroscopy for locking the laser frequency at the

center of the appropriate transition line.

3 Experimental Results

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

In another set of experiment, the cooling beam frequency was detuned to 55 MHz from the cooling line after loading the MOT and switching off the magnetic fields, and the intensity was reduced to about 1 mW using an acousto optic modulator to further cool the atoms in an optical molasses for 15 msec [6]. The observed TOF signal is shown in the figure 3. The signal shown in the inset was obtained in a conventional absorption TOF measurement, without the phase sensitive detection, but passed through a low pass filter of 10 KHz. The S/N ratio is an order of magnitude better in the phase sensitive technique. There is an overall delay in the signal from the lock-in amplifier due to the low pass filter at the output, but this is known for the specific settings of parameters, and can be corrected for.

The shape of the absorption TOF signal for the case of a Gaussian profile of the atomic cloud and the probe beam is given in the reference [7]

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

Here z is the probe beam propagation direction and x is the gravity direction. The probe beam is kept below the MOT at a distance of $\frac{1}{2}gt_0^2$, which 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 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. σ_0 is the Gaussian radius of the trapped cloud. The Gaussian radius σ_v of the velocity distribution is associated with the temperature T of the cloud by the formula

$$T = \frac{M}{K_B} \sigma_v^2 \quad (2)$$

In our experiment, the probe beam has a Gaussian radius of 15 cm in y -

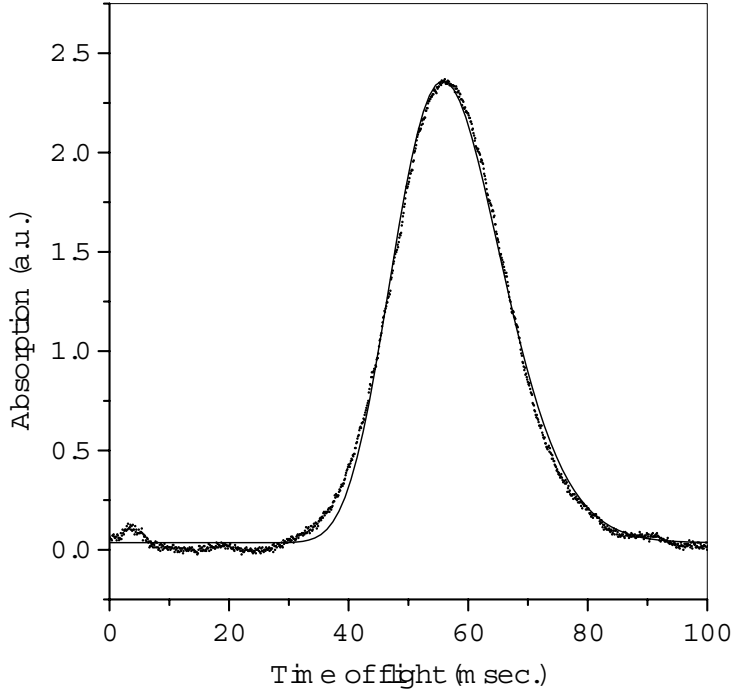


Figure 2: TOF signal of the atomic cloud containing few million atoms released from the MOT. The probe power was $2 \mu\text{W}$ and kept 12 mm below the cloud. Dotted line is the TOF signal observed by phase sensitive probe absorption technique, which is averaged over 5 data. Solid line is the fitted curve using the expression given in the equation (5). The values for the fitting parameters are $a_0 = 0.03589$, $P_1 = 0.01147$, $\sigma_v^2 = 0.00968$ and $t_0 = 0.057$ sec. The discrepancy in the fitting is due to the approximation in the cloud size and probe beam profile

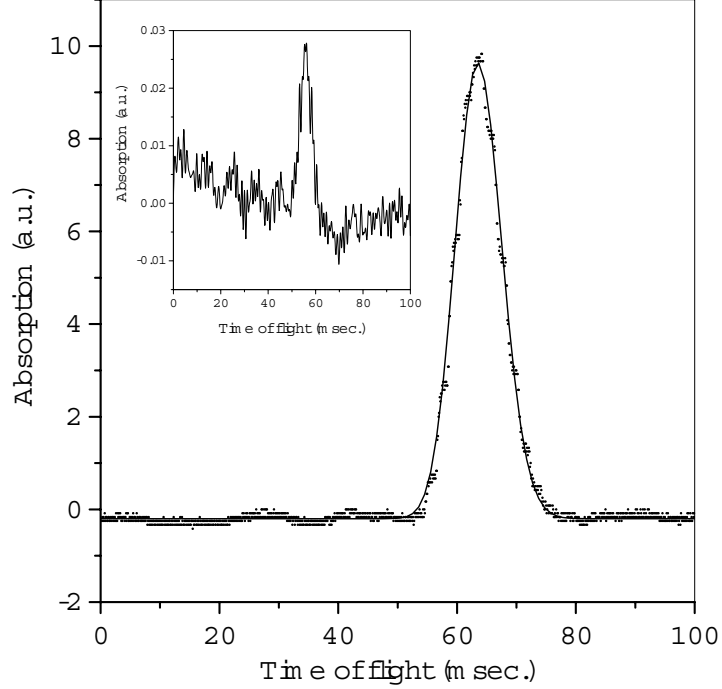


Figure 3: TOF signal of the atomic cloud containing few million atoms released after cooling in an optical molasses. The probe power was $2 \mu\text{W}$ and kept 12 mm below the cloud. Dotted line is the TOF signal observed by phase sensitive probe absorption technique. Solid line is the fitted curve using the expression given in the equation (5). The values for the fitting parameters are $a_0 = -0.2011$, $P_1 = 0.02$, $\sigma_v^2 = 0.000974$ and $t_0 = 0.064$ sec. Conventional TOF signal using a low pass filter of 10 KHz without phase sensitive detection is shown in the the inset. The decaying background is due to the presence of a low frequency noise (few Hz).

direction and hence $\sigma_{Iy} \gg \sigma_t$. So the equation (1) is simplified to

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

The absorption signal also depends on the absorption probability $P(\omega_L)$ 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 lock-in output 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 of the lock-in output becomes zero. However the second harmonic of the lock-in output is

$$S(t) = a_0 + g_1 \frac{d^2 P(\omega_L)}{d\omega_L^2} N(t) \quad (4)$$

Where g_1 is the gain of the photo diode amplifier and lock-in amplifier. a_0 is the dc offset. Putting the expression for $N(t)$ of equation (3), the above equation can be written as

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

Where $\left(P_1 = \frac{P_0 g_1}{2\pi\sigma_{Iy}} \frac{d^2 P(\omega_L)}{d\omega_L^2} \right)$ is a proportionality constant. The second derivative of the Lorentzian has a maximum value at the peak, hence the second harmonic lock-in output gives a maximum signal for the probe frequency at the center of the transition line. So in the experiment TOF signals were observed by detecting the second harmonic of lock-in output. To determine the temperature, TOF signals are fitted to the equation (5). a_0 , P_1 , t_0 and σ_v are taken as the fitting parameter and temperature is calculated using equation(2). The size of the cloud (σ_0) is 0.75 mm which is determined from the fluorescence image by a CCD camera. The temperature of our MOT is $81 \pm 5.3 \mu\text{K}$ which is determined from the TOF signal shown in the figure 2. The temperature of the cloud released after cooling in molasses is $12.2 \pm 0.57 \mu\text{K}$ which is determined from the TOF signal shown in figure 3. A small amount of stray light (less than 1 nWatt) scattered from the glass windows due to presence of the MOT beams falls on the photo detector, which couldn't

be avoided in our experimental configuration. So when the MOT beams are turned off a small change in intensity is detected, which causes a spurious peak appeared in time range of 0 – 5 msec in TOF signal observed in figure 2 and also observed in figure 4. However it is not appreciable in the figure 3, because the intensity of the MOT beams were reduced for the molasses cooling before turning it off and the changes in stray light is 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 velocity is upward initially. Monte Carlo simulation was done to find the number of atoms in the probe. For the simulation we assumed the isotropic cloud of initial Gaussian spatial distribution. The cloud size was taken to be 1 mm. The TOF signal from the Monte Carlo simulation fits well with the observed TOF signal at a cloud temperature of $75 \mu\text{K}$. The probe was taken as a flat beam of width 1 mm in the direction of gravity and infinity in 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 photo detector. The TOF signal from the Monte Carlo simulation and the experimental TOF signal are shown in the figure 4.

From the figure it is quite evident that the peak of the signal corresponds to a few thousand atoms. The signal to noise ratio 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 keeping the probe beam 12 mm below a faint MOT with small number of atoms. Atoms were dropped from a very weak MOT containing about 6000 atoms and the TOF signal was observed with a signal to noise ratio 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. If the laser intensity fluctuations are controlled by using high stability power supplies, we expect that detection of a few atoms in a beam will become possible with this technique, with integration times of less than 10 seconds.

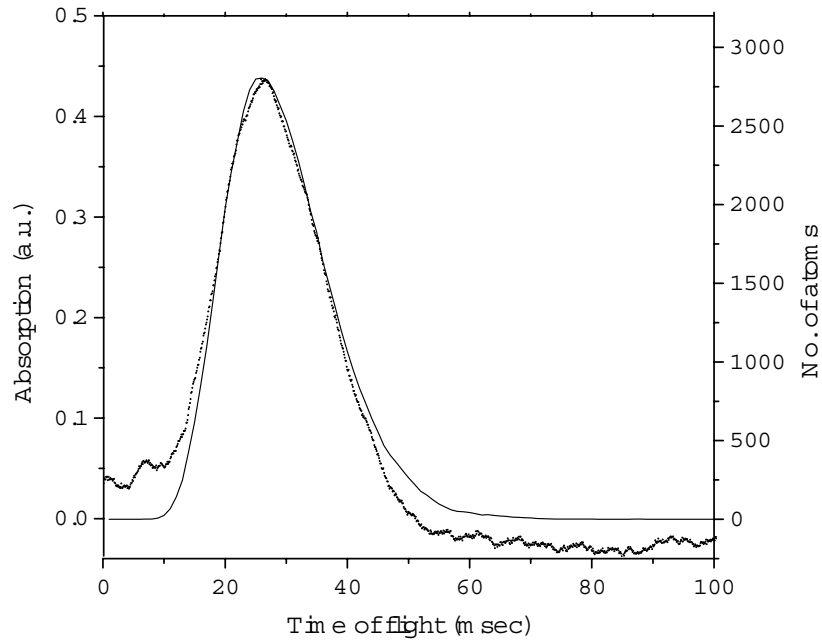


Figure 4: TOF signal of the atoms released from a MOT observed by keeping the probe 5 mm above the cloud. Dotted line is the TOF signal observed by phase sensitive probe absorption technique and is averaged over 20 data. The probe power was $5 \mu\text{W}$. Solid line is the TOF signal observed from the Monte Carlo simulation for a flat probe beam kept 5 mm above the MOT of temperature $75 \mu\text{K}$.

4 Conclusion

A phase sensitive probe absorption technique that improves significantly the sensitivity of detection of 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 photo diode and low noise amplifier the S/N of the TOF signal of cold atom clouds has been improved enough to detect few hundreds atoms in an observation time of 1 ms. The product of the available observation time and the S/N ratio 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 atom-surface interactions [12, 13] and quantum reflection [14] where perturbation due to 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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