Temperature measurement of the cold cloud of atoms

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The various techniques of measuring the temperature of a cloud of atoms in a magneto-optic trap are outlined. The relative merits of the different methods are discussed.

THE measurement of the temperature of the cold atoms in optical molasses is a crucial task. In fact, it was the measurement of a temperature much lower than expected[1] that spurred hectic activity in the theory of laser cooling, leading to the formulation of the theory of polarization gradient cooling[2].

Unlike most conventional temperature measurements, the measurement of the temperature of a cold cloud is a contactless technique. Here temperature is a statistical concept, and is based on the Maxwell–Boltmann velocity distribution. An ideal gas consists of atoms in random motion, moving in straight lines until they collide with themselves or with the walls of the container. The atoms do not all have the same velocity, but a distribution of velocities, given by the Maxwell probability distribution.

$$P(v) = n(m/2\pi kT)^{3/2} \exp(-mv^2/2kT). \qquad (1)$$

Here v is the speed of the atom, m the mass, k the Boltzmann constant and T the temperature. In an ideal gas, the Maxwell distribution of velocity is attained due to 'thermalization' or frequent collisions among the atoms. In a laser-cooled gas, however, since the density of atoms is quite low (~ $10^9/cm^3$), collisions between atoms are infrequent. Thermalization is achieved by a random walk in a viscous force. The atoms move in straight lines, in the intersection of the three pairs of mutually perpendicular trap beams. Due to the absorption of photons and re-emission in random directions, the recoil momenta give rise to a random walk in the viscous medium formed by the confining beams. (An exception is the Bose–Einsten condensate, where atoms have a very narrow distribution of velocities, ideally a delta peak centred at $v = 0$).

The measurement of temperature of the cold cloud consists of measuring the velocity distribution of the atoms in the cloud, and determining the value of T in the above equation that gives the best fit to the experimental data.

There are essentially five methods of determining the velocity distribution, each with its own merits and demerits.

The decay method

A cold cloud is formed at the centre of the six confining beams. The trap has to be loaded periodically as the atoms perform a random walk in the viscous fluid in the trap region and diffuse out at a rate given by eq. (2).

$$\bar{n}(t) = 6n_0 \sum((1/v^2) \exp(-D\pi^2v^2t/R^2))/\pi^2, \qquad (2)$$

where n_0 is the initial number of atoms, t the time, R the radius of the trap, D the diffusion constant. The number n as a function of time is estimated by measuring the intensity of the fluorescence signal as a function of time, which is typically as shown in Figure 1. The value of D is extracted by fitting the curve to eq. (2). Using the expression $D = KT/\alpha$, the temperature T is determined.

A shortcoming of this method is that it overestimates the T, because the drift velocity due to beam imbalance, intensity hotspots, etc. are ignored.

Release and recapture

This is a ballistic measurement technique. The molasses are loaded and with the trapping beams on, the loading is shut off. The molasses then begin to decay. The trapping beams are then blocked for a time T_{off}, typically a few milliseconds. With no confining beam, the atoms move ballistically and some of them leave the trap volume. The trap beams are then unblocked, causing the remaining atoms to fluoresce. The intensity of the fluorescence signal just prior to blocking of the trap beams, and just on unblocking the trap beams gives an estimate of the number of atoms that have remained in the trap region. A release and recapture measurement would give an intensity profile as shown in Figure 2. A Maxwell velocity distribution is assumed, along with an initial spatial distribution. The fraction of atoms remaining in the trap region is measured as a function of T_{off}. The T that gives the best fit is assumed to be the temperature of the cloud.

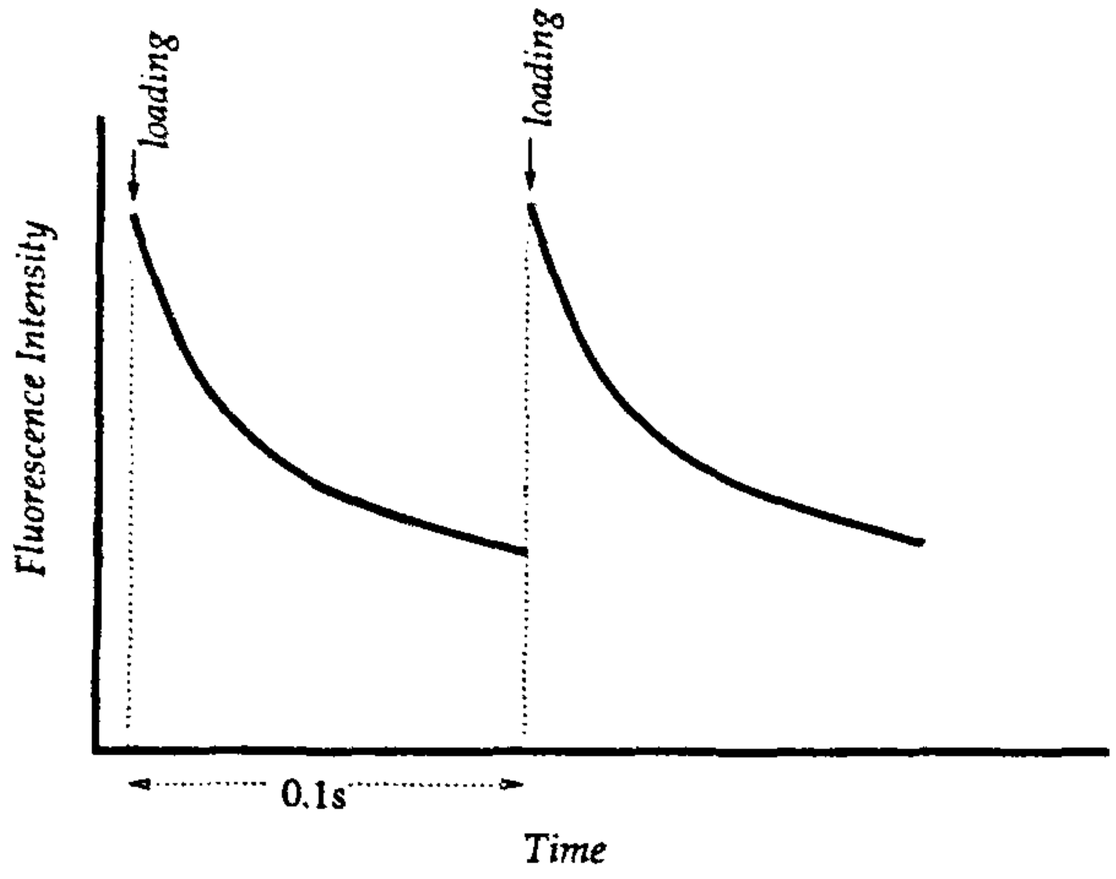

Figure 1. The fluorescence intensity as a function of time in a trap. The dotted line indicates the time at which the loading is stopped.

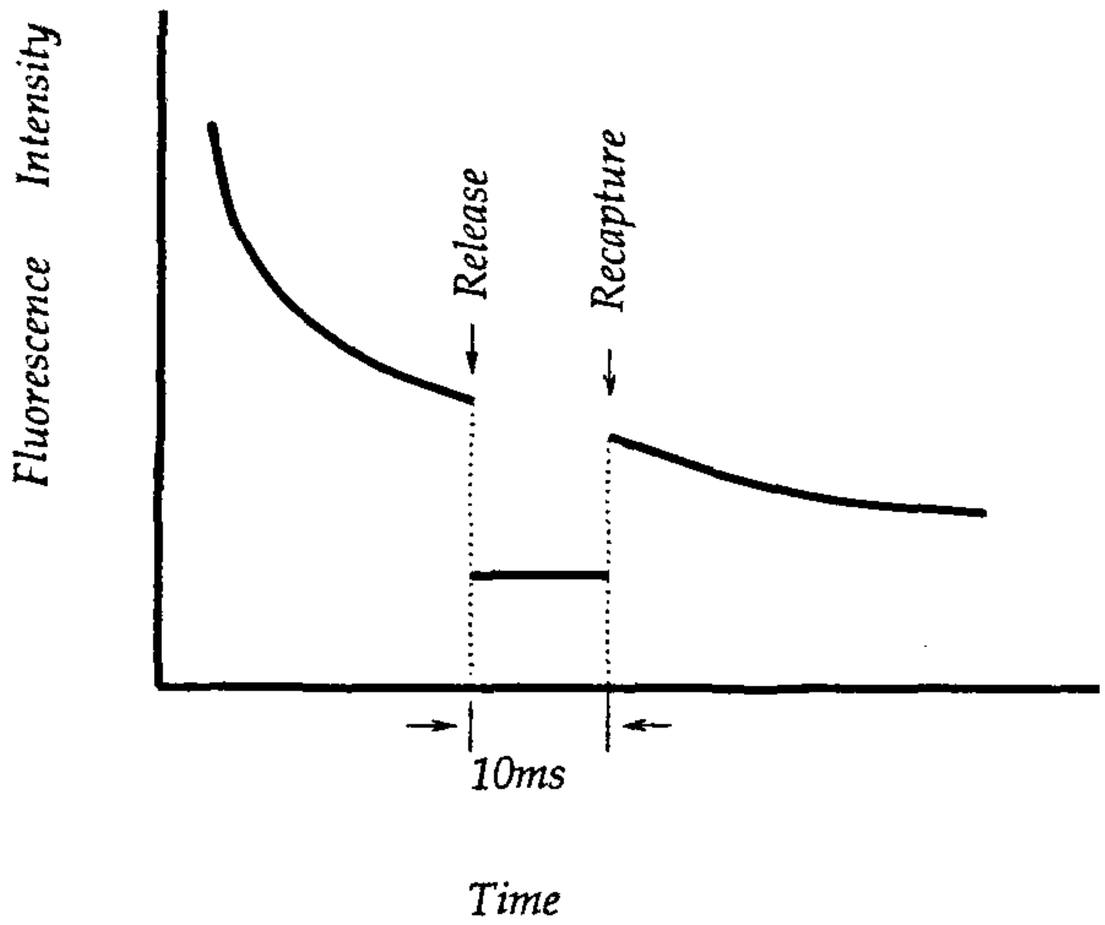

Figure 2. The fluorescence intensity as a function of time in a trap. The dotted line at the left indicates the time at which the trap beams are switched off (release), while the one at the right indicates the time at which the trap beams are switched on once again (recapture).

This method gives errors proportional to the temperature. Further, it requires that the initial spatial distribution of the atoms be known.

Time of flight

In this method the trapping beams are switched off once a cold cloud is formed. The cloud then falls downward under the action of gravity. The atoms have a distribution of velocity, in all directions. Thus, while all atoms feel a downward acceleration, the atoms move in directions that are determined by their instantaneous velocity at the time of release. Atoms moving in the upward direction move with a decreasing velocity upwards and after reaching a certain height (determined by their initial velocity and the deceleration due to gravity), begin their descent. Atoms moving sideways follow a parabolic path (Figure 3).

A probe beam passes horizontally a few centimeters below the trap region. As the atoms fall within the probe beam, they scatter the probe light. The scattered light is collected by a lens and focused onto a PMT. The intensity of probe-induced fluorescence as a function of time gives an indication of the number of atoms reaching the probe as a function of time. This is compared with the expected fluorescence signal assuming Maxwellian velocity distributions at different temperatures, and the best fit is accepted.

The main sources of error in the measurement of temperature by this method are due to the following:

- Incorrect measurement of molasses-probe separation. An error of 0.5 mm in the separation results in an error of 6 μK at a temperature of 100 μK.
- The probe causes heating that expels the atoms. While in the direction of the probe the atoms experience a retarding force, no such force is experienced in the transverse directions, and the atoms may be expelled from the probe region before they have scattered many photons to contribute to the fluorescence signal.
- Incorrect assumption of the probe profile gives rise to errors in the measured temperature.

It is desirable to have a weak probe (0.5 mW), for too high an intensity of the probe causes the atoms to be expelled from the beam. The error in the temperature determined by this technique is almost independent of temperature.

Fountain method

A releated method is the fountain method[1]. Here too the atoms are released by switching off the trap beams. The

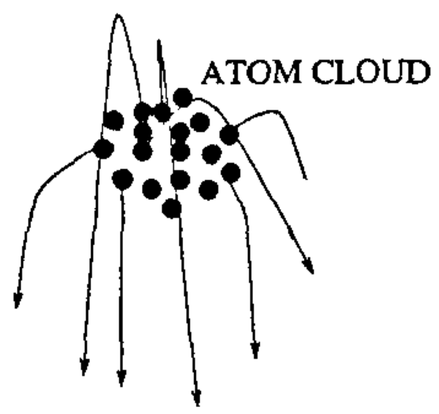

Figure 3. A schematic diagram of the time-of-flight technique. The atoms follow different trajectories, depending on their instantaneous velocities at the time of their release. The probe beam passes below the trap region.

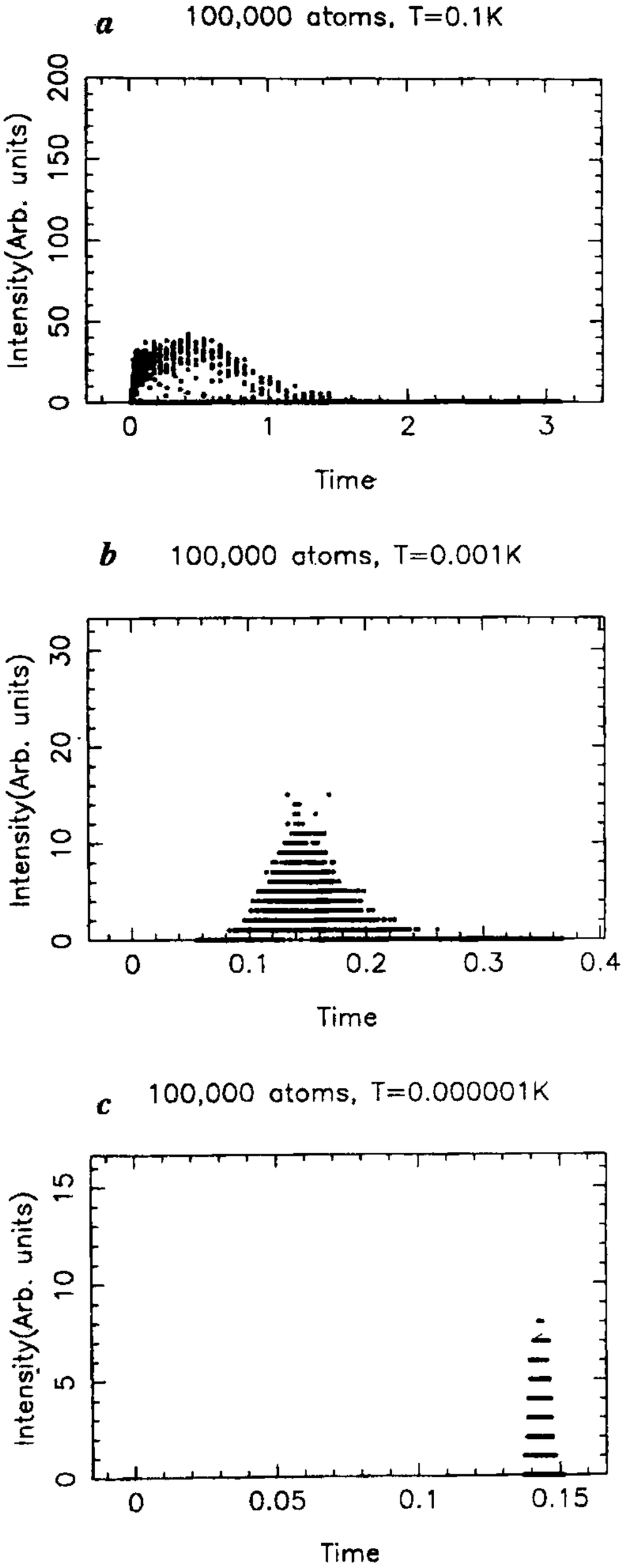

Figure 4. Results of simulation of the fluorescence intensities from a cloud of 100,000 atoms, for temperatures (*a*) 0.1 K (*b*) 1 mK (*c*) 1 μK. The probe is assumed to be 10 cm below the trap region.

probe in this case is passed above the cloud. The number of atoms reaching the probe over a given period of time is measured as the integrated fluorescence intensity. This gives a sampling of the velocity distribution with atoms having an upward velocity above a certain value (determined by the height of the probe). As in earlier methods, the temperature is deduced assuming a Maxwell distribution of velocities.

Shower method

This is another variant of the time of flight technique, with the probes placed below the cloud, at different horizontal displacements. The time integrated fluorescence signal is measured, and the temperature is determined assuming a Maxwell–Boltzmann velocity distribution. This method is sensitive to the horizontal component of velocity too.

While in the time of flight method the time variation of the fluorescence signal is measured, in the fountain and shower methods, the time integrated signal is recorded. Thus, errors arising out of incorrect knowledge of the molasses-probe separation, or the spatial distribution of atoms in the cloud are avoided. The last three methods discussed above are sensitive to different components of velocities. In contrast, the release and recapture, and the decay method are sensitive to all velocity components.

In our laboratory, we propose to use the time-of-flight technique. With minor modifications, this can be configured to the shower or fountain technique. While the magneto-optic trap is nearly complete, the temperature measuring system is being set up. We have developed computer programs which can fit the measured intensity time profile to that expected from assumed Maxwell distribution at various temperatures, to extract the temperature. Some simulated time-of-flight signals, obtained using this code, are given in Figure 4.

1. Lett, P. D., Watts, R. N., Westbrook, C. I., Phillips, W. D., Gould, P. L. and Metcalf, H. J., *Phys Rev. Lett.*, 1988, **61**, 169.
2. Dalibard *et al.*, *J. Opt. Soc. Am.*, Nov. 1989, Special issue on laser cooling.

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