Some Investigations of Laser Cooled Atoms

by

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Certificate:

This is to certify that the thesis entitled "Some Investigations of Laser Cooled Atoms" submitted by Uday Kumar Khan for the award of the degree of DOCTOR OF PHILOSOPHY of Jawaharlal Nehru University is his original work. This has not been published or submitted to any other University for any other Degree or Diploma.

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Declaration:

I hereby declare that the work reported in this thesis is entirely original. This thesis is composed independently by me at Raman Research Institute, Bangalore, under the supervision of Dr. Hema Ramachandran. I further declare that the subject matter presented in this thesis has not previously formed the basis for the award of any degree, diploma, membership, associateship, fellowship or any other similar title of any university or institution.

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Contents

Preface

Atoms can be cooled to temperatures of a few tens to a few hundreds of micro Kelvin by three pairs of counter-propagating beams of resonant laser light. Such cold atoms can also be trapped in a magneto-optical trap. Several interesting properties exhibited by such cold atoms have been studied in the literature.

A program for setting up laser cooling of atoms was undertaken in the Raman Research Institute in 1998 and a cold cloud of Rubidium atoms was produced and trapped successfully. This thesis reports some new results of our studies on such a cold cloud of Rubidium atoms.

Chapter I of the thesis gives a brief survey of techniques for laser cooling and trapping of atoms. The survey deals with Doppler and Sub-Doppler cooling mechanisms, and gives a brief description of the time of flight technique for measuring the temperature of the cold atoms. Magnetic, optical and magneto-optical traps can be used to trap these cold atoms to increase their density. While a brief mention is made of the first two types of traps, the magneto-optical trap is considered in some detail as it turns out to be the workhorse for trapping of the cold atoms. This brief survey is not intended to be comprehensive. It presents the relevant material necessary for understanding the work described in subsequent chapters.

Chapter II starts with a discussion of the hyperfine level scheme of the energy levels of the two isotopes of Rubidium, namely these with mass numbers 85 and 87. All our experiments are performed on ^{85}Rb, which is the most abundant isotope. The transition used in the cooling is the one in which an electron is raised from the $5S_{1/2}$ to the $5P_{3/2}$ atomic energy level in this atom. The wavelength of this transition is ~ 780 nm. Relatively inexpensive laser diodes giving an output of about 100 mW and tunable over a wavelength range of about 10 nm are available and have been used as the excitation source. Since the emission of such diodes has a width of a few GHz and the laser operates in multi-mode, it is necessary to reduce the width of the laser radiation to a few MHz and make it operate in a single mode. This is done by introducing a grating stabilized external cavity. The operation of the external cavity diode laser (ECDL) is described. The wavelength of such an ECDL depends on the temperature and the current through the diode. Circuits are described to control the temperature to within 10 mK and the current to within 10 μA of the set value. Several such ECDLs were home built for our use. For laser cooling it is necessary to have two laser beams, one called the cooling beam and the other called the repumper beam. The frequency of the former will have to be locked to within a few MHz of the cooling transition (F = 3 $->$ F′ = 4) and the latter to the repumping transition (F=2 $->$ F′ = 3) in ^{85}Rb. To distinguish the hyperfine lines, which are a few tens to a few hundred MHz in separation from the Doppler background, which is 2 GHz in width, the method of saturation absorption spectroscopy is used. This method is described and the principle of locking the laser is discussed. The locking circuit to our ECDL was also built in the laboratory.

The cold cloud is formed in a vacuum chamber made of stainless steel with a large number of ports for the ingress and egress of the laser beams and for viewing the cloud. The chamber design is described. The chamber is evacuated to a pressure of 1×10^{-9} mbar using a turbomolecular pump and an ion pump. The optical arrangement to produce three retro-reflected beams travelling in mutually orthogonal directions is achieved with the help of beam splitters and mirrors. Circular polarization of the light is achieved through the use of quarter wave plates. The magnetic field gradient is produced at the center of the overlapping region of the three beams in the vacuum chamber is produced by two identical coils in the anti-Helmholz configuration placed along one of the beams. This arrangement produces zero field at the center point with the field gradient increasing linearly as one moves away from the point. The repumper beam was also aligned to travel along the cooling beams. With this arrangement we were able to get a cold cloud of Rb atoms. These matters are discussed in this chapter.

With this arrangement we performed the following experiment. Keeping the repumper beam on the repumper transition the detuning of the cooling beam was ramped from the blue to the red side of the transition at different ramp rates. We expected the cloud to contain the largest number of atoms at a certain value of the detuning. So we expect the fluorescence from the cloud to reach a peak value at a given detuning to the red of the transition whether the detuning is being ramped up or ramped down. But we found that the fluorescence peaks at different detunings during the ramp up and ramp up. More interestingly the intensity I_{up} of the peak during ramp up is more than the intensity I_{dn} of the peak during ramp down. The ratio $\rho = I_{dn}/I_{up}$ varied in a systematic fashion with the period of the ramp, its value increasing from a small value as the ramp period is increased and tending to a value unity at very large ramp period. These observations were understood on the basis of a one-dimensional model. Cloud formation is a dynamical process involving two phenomena: atoms are captured in the trap at a rate, which is dependent, among others factors, on the detuning of the cooling beam. The rate R_L of loading depends as the fourth power of the capture velocity V_c, which is the maximum entrance velocity of an atom at a given detuning, which can be captured. This can be worked out by a numerical simulation by invoking the Doppler damping force on the atom whose dependence on the detuning is known. There are warm Rb atoms in the background and atoms will get sufficient energy to leave the trap due to collisions between the cold and warm atoms. The escape velocity depends on the force constant in the trap. The decay of atoms take place with a characteristic time τ which can be written as τ_0 f(δ_c/Γ), where f is a function of the ratio of the cooling beam detuning to the natural line width Γ of the excited state and τ_0 is parameter which depends on the magnetic field gradient and the magnetic moment of the atom in the ground state. This function is also known from the expression for the restoring force constant in a magneto-optic trap. Both the loading rate and the lifetime are substituted in the rate equation to determine the growth and decay of atoms in the cloud as the detuning is ramped up and down. The fluorescent intensity can be obtained by multiplying the number of atoms with the rate for spontaneous transition from the excited state, which is a steeply varying function of the detuning. This model could explain qualitatively the experimental results on the dependence of the position of the peaks and their full widths at half maxima on the detuning. More importantly these experiments showed that the asymmetry parameter ρ is sensitive only to the normalized period of ramp T/τ_0 and is relatively insensitive to other parameters such as the intensity of the incident beams, the radius of the beams and the magnetic field gradient. With a choice of τ_0 of 1.25 s, the experimental results fell on the theoretically calculated curve. This gave a lifetime τ of 0.7 seconds at a detuning of -1/2Γ, which is consistent with the expected lifetime at a pressure of 1×10^{-9} mbar. So we propose a new method for the determination of the lifetime of the atoms in the trap which is more convenient than the conventional method and also has the advantage of being non-destructive. These results are discussed in Chapter 3.

It is necessary to measure the temperature of the cold cloud. The time of flight method described in Chapter I, though accurate, is a destructive method. We used a method proposed by Kohns et al. In this method the cold cloud of atoms is bounced about the center of the trap by a periodic magnetic field produced by an oscillating current through a pair of Helmholz coils. The fluorescence from the bouncing cloud of atoms is detected by a femtowatt detector and processed by a lock in amplifier. This gives the phase of the displacement of the cloud as a function of the frequency of the oscillating magnetic field. The variation of the phase as a function of frequency can be fitted to the expression from a forced damped linear harmonic oscillator to obtain the resonant frequency of the atom ω_{trap} in the trap and the damping constant. From the natural frequency the force constant κ of the trap is obtained. Fitting the profile of the fluorescent intensity of the cloud as a function of position to a Gaussian the radius of the trap can be estimated. From the equipartition theorem the temperature of the cold cloud is estimated from knowledge of the force constant and radius. The cloud temperature was estimated at 200 μK with a possible error of about 20 μK. These results are discussed in Chapter IV.

The following experiment was then performed on ^{85}Rb in a molasses, and in the cloud in the MOT. The cooling laser beam was kept at a fixed red detuned value and the frequency of the repumper beam was then ramped over the full width of its hyperfine transition F = 2 to F′. We expected the fluorescent intensity to be a maximum when the repumper was in resonance with F = 2 to F′ = 3 transition. Surprisingly we observed two peaks symmetrically situated about the repumper-detuning zero. As the detuning of the cooling beam was increased more towards the red, these peaks split into two each and their spacing increased. Another surprising observation was that for a given magnitude of the cooling laser detuning irrespective of whether it was towards the red or blue of the cooling transition we observed four peaks at the same positions. This indicated that the phenomenon is not connected with the low temperature of cold atoms. One would get the same results whatever the temperature of the atoms. The peaks occurred for repumper detunings $\delta_r = \delta_c$ and $\pm(\delta_c + 63$ MHz). A more interesting feature is that the fluorescence peaks had a width of 30 MHz while the Doppler width at room temperature is of the order of 2 GHz. As the detuning of the cooling laser beam was increased beyond 100 MHz many more peaks could be seen in the fluorescence. These results were understood on a one dimensional model in which an atom moves in one dimension in the presence of two retroreflected beams one a cooling beam and one a repumper beam. At a certain detuning δ_c an atom moving with a critical velocity $v_c = |\delta_c|/\mathrm{k}$, where k is the wave vector of the cooling laser beam, will see the photons from one of the cooling laser beams in exact resonance with the transition F = 3 to F′ = 4 and so will be excited with the maximum probability. If the repumper detuning is different from $|\delta_c|$, then the same atom will not see the repumper beam in resonance with the transition F = 2 to F′ = 3 and so the repumper will not be effective in pumping the atoms from the level F = 2 to the level F = 3. The number of atoms in level 3 will decrease and correspondingly the intensity of the fluorescence from F′ = 4 to F = 3 will be less. On the other hand when the repumper detuning satisfies the condition $\delta_r = \delta_c$ one or the other of the repumper beams will be exactly in resonance with the transition F = 2 to F′=3. This repumper beam becomes extremely effective in repumping atoms from F = 2 to F = 3 and in a few microseconds will transfer almost 90% of the atoms to the level 3. The atoms reside in the molasses region for a much longer time and so the fluorescence intensity will show a maximum value. The width of the fluorescence intensity arises from a narrow range of velocities around v_c for which values the build up of population will still be large. Since there is a second hyperfine excited level

F′ = 2, we will again get a maximum in fluorescence intensity when the repumper comes into resonance with this transition which will occur when $\delta_r = \pm(\delta c + 63$ MHz) where 63 MHz corresponds the energy level difference between the F′ = 3 and F′ = 2 excited states. A numerical one-dimensional calculation of this model gives results in accordance with expectations. We have also explained the occurrence of more lines as the cooling laser detuning is increased to large values. These are new results, which are described in Chapter V.

In Chapter VI a four level density matrix calculation is done to account for the results in Chapter V. We consider the inverted N system consisting of levels F′ = 4, F = 3, F′ = 3 (or 2) and F = 2. The elements of the density matrix are written in terms of the Rabi frequencies of the cooling and repumper beams. The cooling beam connects F = 2 to the two excited levels F′ = 4 and F′ = 3 (or 2). The Rabi frequencies for the two transitions will however be different for the cooling beam because of the difference in the matrix elements of the dipole moments for the two transitions. Using a rotating wave approximation the time evolution of the density matrix elements is written. Since the matrix is of order 4x4 there are 16 elements of the density matrix. However the condition that $\sum_j \rho_{ij} = 1$, there are fifteen independent elements of the density matrix.

The steady state solutions of these fifteen elements are obtained for a given velocity v of the atom. The detuning of the cooling and repumper beams for this atom will be augmented by the Doppler shift. The element ρ_{jj} (summed over all values of the velocity of the atoms after weighting them with the one dimensional Maxwellian distribution of velocities) gives the steady state population in the level j and the element $\rho_{ij}(i \neq j)$ gives the coherence betwen levels i & j. The imaginary part of $\rho_{23'}$ is a measure of the effectiveness of the repumper beam in repumping the atoms from level 2 to level 3′. The calculation of the populations in the states 2,3,4′ and 3′ fully substantiate the model proposed in the previous chapter to account for the sharp peaks obtained in fluorescence. These results are described in Chapter VI.

The work described in chapters 5 and 6 have appeared in print; the following are the references :

1. Observation of narrow fluorescence from doubly driven four-level atoms at room temperature
   U.K. Khan, J. Sebastian, N. Kamaraju, A. Narayanan, R. Srinivasan and H. Ramachandran, Europhysics Letters, **67**, 35-41 (2004).

2. Fluorescence from doubly driven four-level atoms: A density matrix approach
   A. Narayanan, R. Srinivasan, U.K. Khan, A. Vudayagiri, and H. Ramachandran, European Physical Journal D, **31**, 107 (2004).

The work described in chapters 3 and 4 will be communicated for publication shortly.