Precision control of magneto-optically cooled rubidium atoms

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ABSTRACT

Research interest in designing sources of cold atoms has significantly increased during the past ten years with the development of suitable laser sources for magneto-optical trapping and the further mastering of evaporative cooling in order to achieve Bose-Einstein condensation. The magneto-optical trap is now viewed as a standard research facility worldwide and has opened up many new exciting research directions in atomic physics. One area of interest is that of combining spherical microcavities with cold atomic sources in order to achieve efficient photon exchange between the cavity and atom for further understandings of cavity quantum electrodynamics. This could eventually lead to atom entanglement via photon exchange which would have implications for quantum logic design. However, initial attempts to achieve such interactions have been hindered by inadequate control and manipulation of the cold atom source. Here, we present work on designing and building an ultra-stable source of magneto-optically cooled rubidium atoms with a temperature in the tens of μK range. We discuss the different cooling mechanisms involved in the process and present a suitable experimental arrangement including details on the ultra-high vacuum chamber, the laser systems being used and the source of rubidium vapour. Finally, we discuss some future direction for the research including the diffraction of atoms from gratings and micron-sized objects and the parameter control of the cloud of atoms.

Keywords: Magneto-optical trapping, rubidium, diffraction, control, laser stabilisation

1. INTRODUCTION

During the past fifteen years interest in magneto-optical trapping of neutral atoms has exploded due to the range of fundamental studies and applications that can be performed. The realisation of a cold atom source has, by now, become a standard tool in numerous research laboratories and the magneto-optical trap is even being used as a demonstration tool in many advanced undergraduate programmes due to the ready availability of the required trapping components (lasers, optics, etc.) for alkali atoms. The subsequent achievement of a new state of matter, the Bose-Einstein condensate,[1-3] in 1995 relied heavily on the principles behind magneto-optical trapping and resulted in a whole new avenue of exploration for scientists leading to such striking outcomes as the realisation of atom lasers,[4] the Mott insulator states for neutral atoms,[5] Tonks-Girardeau gas[6] and the study of Feshbach resonances.[7] The last two cases have even enabled researchers to tune between atomic and molecular condensates. Apart from the many fundamental tests of quantum mechanics that have been performed, the progress has also opened many new perspectives in precision metrology, ultra-sensitive sensors and the engineering of quantum states for quantum information processing and quantum computing. The additional interest in controlling and manipulating internal and external degrees of freedom of cold atoms in order to achieve reliable and reproducible quantum engineering has also led to significant theoretical and experimental developments in these areas. If quantum engineered technologies are ever to be as indispensable as classically engineered technologies it is imperative that a quantum control theory be developed that is applicable to the dynamics of the quantum systems and that can predict the stability of such systems.

The control of cold atoms can be viewed in the following way. Quantum or coherent control of a system allows the use of quantum interference between multiple excitation pathways in order to cancel coupling to unwanted, non-radiative channels thereby reducing decoherence to negligible levels. A common technique for achieving this is in using far-off resonant laser (dipole) traps and this has been discussed in detail by Jessen *et al.*[8] In order to develop a full theoretical description applicable to quantum feedback control it is necessary to expand classical feedback theory and apply it to a quantum system while, at the same time, quantum measurements must be studied in a manner suitable for control theory. An example of a system under quantum feedback control is that of a single atom in an ultra low-loss optical cavity.[9,10] By

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continuous measurement of the atomic motion and the use of a real-time feedback signal one can optimize the cooling of the atom to the ground state of the mechanical potential of several photons in the cavity. This is achieved by constantly adjusting the intensity of a driving laser that balances the slow leak rate of photons from the cavity, thereby removing kinetic energy from the atom's centre-of-mass motion. Quantum control theory could also be expanded beyond feedback control in order to develop a number of possible control strategies including, for example, feedforward or predictive control or a combination of such standard control strategies. The engineering requirement would depend on the nature of the system being controlled and the level of information that can be extracted from the system.

The manipulation of atoms can be achieved by making use of the manner in which atoms couple to the external environment e.g. coupling of the magnetic moment to magnetic fields, coupling of mass to gravitational and inertial fields etc. This manipulation is frequently achieved through the design and realisation of atom optical elements relying on one or other of the available coupling regimes e.g. waveguides, mirrors, diffraction gratings, beamsplitters etc. can be fabricated using either light or magnetic fields. Some of the progress made in these areas has been discussed in a recent review edited by Berman[11] and there is still much interest in developing novel manipulation schemes for atoms based on the aforementioned regimes. In this paper we will first review the principle behind magneto-optical trapping with particular emphasis placed on neutral rubidium atoms. We will concentrate our discussions on ^{87}Rb but it is worth noting that the same techniques apply to ^{85}Rb. We will then describe a typical experimental set-up for trapping cold atoms as used in our laboratory and, finally, we will consider a number of feasible directions that we aim to explore e.g. diffraction of atoms from a wire array and precision control of cold atoms to study decoherence effects.

2. REVIEW OF MAGNETO-OPTICAL TRAPPING

The development of sources for cold atoms has prompted significant research into the control and manipulation of these atoms over the past two decades. In particular, the ready availability of cold atoms has provided researchers with opportunities for studying quantum behaviour and has led to wide-ranging outcomes including the achievement of Bose-Einstein condensation in alkali atoms, higher precision atomic clocks and candidates for the generation of quantum logic gates. Laser cooling of atoms is, by today, the most successful cooling method and it was first proposed by Hänsch and Schawlow[12] in 1975. A comprehensive review of laser cooling and trapping techniques for atoms is given by Metcalf and van der Straten.[13] The most commonly used cold atom source is the magneto-optical trap[14] (MOT) and a brief review of the cooling mechanisms involved and the principles behind this technique is presented here.

2.1 Temperature in laser cooling experiments

In laser cooling, there are three characteristic temperatures that define the final temperature attainable using various optical cooling techniques. In order to reach temperatures low enough to achieve Bose-Einstein condensation, however, an additional cooling mechanism - evaporative cooling - would have to be considered. The discussion here is limited to a cold sample of alkali atoms, rather than a condensate. When discussing the "temperature" of cold atoms it is important to recognise that this is not equivalent to temperature in the usual thermodynamical sense since the atoms are not in thermal equilibrium with the environment. Therefore, when we use the term temperature to describe a sample of cold atoms, we are referring to the average kinetic energy (in one dimension) of the atomic sample, $\overline{E} = k_B T / 2$, where k_B is the Boltzmann constant.

The first temperature to consider is related to the kinetic energy of the atoms and is determined from the relationship $k_B T_v = M v^2$, where v is the mean velocity of the atoms and M is the atomic mass. If one considers a lower velocity limit of 1 m/s for atoms to absorb light due to the presence of the Doppler shift, the corresponding temperature is several mK.

The next limit on temperature arises from the natural width, γ, of atomic transitions and is often called the Doppler limit for cooling. This temperature is given by $k_B T_D = \hbar \gamma / 2$, where $2\pi\hbar$ is Planck's constant. Typical Doppler-limited temperatures are several hundred μK.

The final temperature to be considered is that associated with the photon recoil of an atom. This recoil limit temperature is given by $k_B T_r = \hbar^2 k^2 / M$ and is typically a few μK, corresponding to a recoil velocity of ~1 cm/s.

Note that the temperatures achievable via laser cooling are far lower than those reached by any previous methods of cooling. In order to put this into context, ultra-cryogenic cooling methods are generally operating in the tens of mK range whereas cold atoms are routinely cooled to μK and sometimes even nK regions.

2.2 Radiative force on atoms

There are many recognised ways for successfully slowing and cooling a beam of atoms. The MOT makes use of the radiative force on atoms arising from multiple photon absorptions and emissions of laser light that is on or near resonance with an atomic transition and work in this area was pioneered by Ashkin[15] in 1978. Each photon, of frequency f, absorbed by an atom transfers a momentum of hf/c to the atom, where c is the speed of light. The atom absorbs this light energy and is excited. The momentum transfer results in the atom recoiling from the light with an equivalent momentum. The opposite holds true when the atom emits a photon. Each absorption/emission cycle results in an atomic recoil velocity given by $v_r = hf/cM \cong$ few cm/s. While this velocity change is clearly small compared to the mean thermal velocity of the atoms (e.g. 170 m/s for rubidium at room temperature), a standard laser is capable of providing sufficient energy for up to 10^7 photon absorptions per second. Therefore, the total resultant momentum transfer can slow an atom down from room temperature to velocities of the order of cm/s in about 1 ms.

2.3 Optical Molasses

In a MOT the combination of laser beams and magnetic fields results in a slowing and trapping of atoms into a well-defined region in space. Three pairs of counterpropagating laser beams are used and these intersect at the trap region, which is typically a few mm^3 in volume. The movement of the atoms at the intersection region is strongly restricted in all three dimensions due to the radiative forces from the six intersecting laser beams. If the atoms were at rest, the net force due to the radiative forces from each pair of counterpropagating beams would be zero, since the contribution from one beam would cancel with the other. However, in reality the atoms are not at rest but moving constantly (albeit slowly) in the trapping region. Due to the Doppler effect, if an atom is moving towards a laser beam the frequency of the light, as seen by the atom, is increased by an amount equal to $\Delta f = vf/c$. In order to compensate for this Doppler shift, the frequency of the laser beams is detuned slightly below resonance. As a result of the detuning, atoms moving towards the laser have a higher probability of absorbing a photon since these transitions remain on resonance with the atomic transition. Equivalently, atoms moving away from the laser have a lower absorption probability. Therefore atoms interact more strongly with lasers travelling in opposition to the atoms and the overall effect is a net transfer of momentum that opposes the atomic motion. The slowing force is proportional to the atomic velocity when the velocity is low enough. This leads to a viscous damping of the atomic motion and results in atomic confinement in the trapping region. The effect is termed "optical molasses" due to the analogy to viscous forces.[16] Note that the laser detuning must be constantly adjusted to allow for changes in Δf as the atoms slow down.

2.4 Sub-Doppler cooling

In 1987, experimentalists at NIST[17] reported on cooling a gas of sodium atoms to 43 μK, well below the supposed Doppler cooling limit of 240 μK. Two groups subsequently developed theories for sub-Doppler cooling[18,19] based on including the atomic sublevels in the modelling of the system. It was shown that optical pumping of atoms between the different magnetic sublevels can provide an additional cooling mechanism that allows sub-Doppler temperatures to be reached. This mechanism originates from the polarisation gradient experienced by an atom as it moves through a pair of orthogonally polarised, counterpropagating beams and the non-adiabatic response of the atom to the changing light field along its passage. In the initial work by Lett *et al*[17] the linear polarisation of each beam pair was orthogonal to that of the other two pairs. Nowadays, the standard beam arrangement consists of three σ^+/σ^- pairs of beams as proposed by Dalibard and Cohen-Tannoudji.[18] The resulting electric field of the standing wave is of constant magnitude with linear polarisation along the beam path. However, the direction of polarisation rotates through 2π over each optical wavelength.

If we consider an atom at rest, the ground state magnetic orientation resulting from optical pumping distributes the atoms over the ground state sublevels, with maximum population in the sublevel aligned along the local direction of the polarised light. Thus, the magnetic orientation is determined from the population distribution and the excited state population follows that of the ground state adiabatically. For moving atoms, however, the situation differs if the light field varies in space, as is the case for sub-Doppler cooling. The cooling of an atom arises when it moves through a beam region where the quantisation axis is rotating. The atom must be optically pumped in order to follow this rotation.

The cooling relies on an imbalance in the atomic state populations that results from the time delay for a moving atom to follow the field direction compared to the adiabatic passage achieved by stationary atoms. In sub-Doppler cooling, the minimum atom temperature that can be reached is limited by the recoil energy of the atoms and corresponds to 180 nK for ^{87}Rb.

2.5 The magneto-optical trap

The first trapping of neutral atoms using magnetic forces was described by Migdall *et al.*[20] In this case, trapping was achieved using the interaction between the atomic magnetic moment and the magnetic field. By combining elements of magnetic and optical trapping the MOT was developed and first demonstrated in 1987 by Chu and co-workers.[14] Trapping and cooling of the atoms can be achieved through a combination of inhomogeneous magnetic fields and optical pumping processes and radiative pressures within the system. The MOT has proven to be an extremely versatile laboratory tool and its popularity stems from its robust nature, its relative low cost and the reasonable ease with which it can be constructed. The magnetic field gradients needed (~3 G/cm) are well within the limits attainable by standard Helmholtz coils operating at reasonable currents (e.g. 200 turns with 1 Amp) and the light fields are relatively flexible with regard to beam imbalance and polarisation. For alkali atoms, commercial diode lasers provide suitable intensities and wavelengths and reduce the complexity and cost even further. The addition of the anti-Helmholtz coils to the set-up provides a spherical, quadrupole magnetic field, arranged so that the zero of the field is at the trap centre. The field increases approximately linearly as one extends outwards from the zero region, along the symmetry axis of the coils. The magnetic field Zeeman shifts the atomic sublevels and increases the absorption probability for atoms moving towards the centre of the trap. Temperatures in the μK range are routinely achieved using magneto-optical trapping.

In order to understand what is happening, let us consider a simplified system in one dimension. We will assume that the excited state has three Zeeman hyperfine levels, $M_e = 0, \pm 1$. Fig. 1 shows an energy level representation of the trapping processes within the MOT.

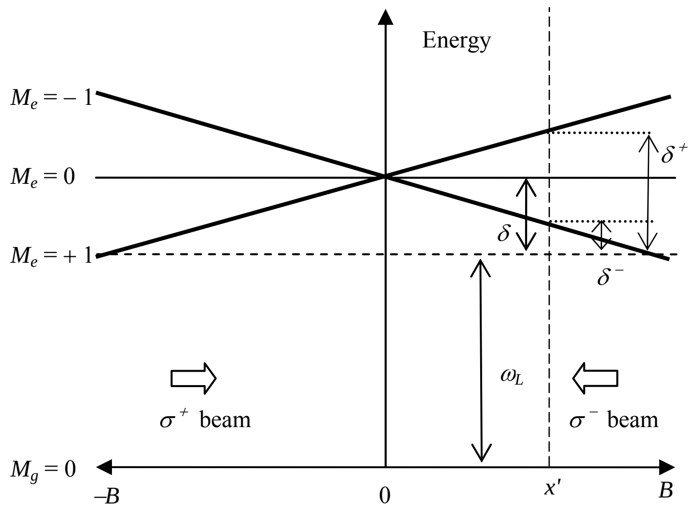

Figure 1: One dimensional model of the MOT. The full length, horizontal dashed line represents the laser frequency as seen by an atom at rest in the trap centre.

Two orthogonally polarised, counterpropagating beams intersect at the point where the *B*-field from the anti-Helmholtz coils is zero. This is the trapping zone for the atoms. The laser beams are detuned below the ground to excited state atomic resonance by an amount δ. Due to the presence of the magnetic field, the atomic hyperfine energies vary according to an atom's position along the symmetry axis of the anti-Helmholtz coils, x. When the atom is in the negative *B*-field region of the MOT, the $M_e = +1$ energy levels have a higher probability of photon absorption due to the detuning being reduced in this region. This arises because here the energy levels are shifted downwards due to the Zeeman shift. Similarly for positive *B*-fields, the excitation to the $M_e = -1$ level is closer to resonance than the $M_e = +1$ level. If the

beam polarisations are now chosen so that σ^+ light is coming from the left and σ^- from the right, atoms moving towards positive *B*-fields (e.g. at position *x'*) will absorb more σ^- light than σ^+. This is due to the Doppler shift of the detuning, δ, so that it reduces to δ^- for atoms moving towards the beam and increases to δ^+ for atoms moving away from the beam. In Fig. 1, atoms at position *x'* and in the $M_e = -1$ level are therefore in resonance with the σ^- beam. These atoms are then pushed back towards the centre of the trap (i.e. to zero *B*-field region). For atoms moving towards negative *B*-field, the probability of experiencing a photon kick is higher for the σ^+ beam than the σ^- beam and these atoms are also pushed back towards the centre. The overall effect is that atoms moving in both directions are preferentially kicked towards the centre of the trap. Both cooling and trapping of the atoms is achieved through this scheme.

3. EXPERIMENTAL SET-UP

The experimental set-up being used is similar to the standard MOT arrangement described elsewhere[21] and a schematic representation is shown in Fig. 2. The anti-Helmholtz coils for the magnetic trapping are ideally separated by a distance equal to the radius of one coil, which is about 14 cm. The coils are connected in series to ensure that the current flowing through each coil is equal in magnitude, though opposite in direction. Additionally, three pairs of Helmholtz coils are arranged around the trapping region, each orthogonal to the other two, in order to cancel the earth's magnetic field at the trapping region. Note that, for the sake of clarity, these coils are not shown in Fig. 2.

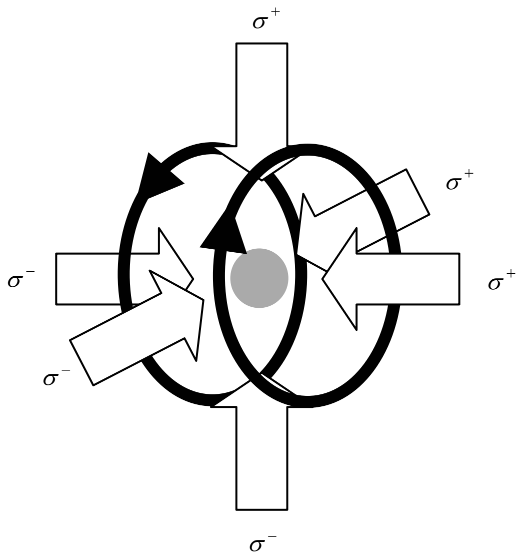

Figure 2: Schematic representation of the MOT. Three laser beams are retro-reflected and have circular polarisations as shown. Two coils, in anti-Helmholtz configuration, provide a *B*-field with zero magnitude in the trapping region.

3.1 Rubidium trapping and cooling

The two naturally occurring isotopes of rubidium are ^{85}Rb and ^{87}Rb with abundances of 72% and 28% respectively. Some important parameters associated with cooling and trapping the ^{87}Rb isotope are presented in Table 1. These include the value of the wavelength (in vacuum) for the cooling transition at 780.23 nm, the saturated absorption value of 1.6 mW/cm^2 and the recoil velocity of 0.59 cm/s. Three pairs of circularly polarised, counterpropagating laser beams are used for the main trapping and cooling beams, full details of which are given below. An energy level diagram showing the trapping and hyperfine pumping transitions for ^{87}Rb is given in Fig. 3. For rubidium, about one in every one thousand excitations causes the atom to decay to the lower, hyperfine ground state and, hence, it falls out of resonance with the trapping laser. A repumping laser tuned to F = 1 → F' = 1 & 2 crossover is superimposed onto one of the trapping beams to ensure repopulation of the upper, hyperfine ground state. A similar arrangement can be used for trapping ^{85}Rb.

Property	Value
Cooling transition	$5S_{1/2}$, F = 2 → $5P_{3/2}$, F' = 3
Nuclear spin	3/2
Wavelength in vacuum	780.23 nm
Mass	1.44×10^{-25} kg
Lifetime of upper state	27 ns
Natural linewidth	5.9 MHz
Absorption cross-section	291×10^{-15} m^2
Saturation intensity	1.6 mW/cm^2
Recoil temperature	180 nK
Recoil velocity	0.59 cm/s
Ground hyperfine splitting	6834.68 MHz

Table 1: Relevant properties of ^{87}Rb for laser cooling and trapping.

The trapping beams are derived from a single laser in an extended cavity configuration and a free-running diode laser is used for the repumping beam. Two SAES rubidium getters are spot-welded onto the pins of an electrical feed-through and a current of several Amps is passed through the getters in order to provide the rubidium vapour for the MOT. There is sufficient rubidium in the chamber when the fluorescence from the background vapour is observable in the path of the trapping beams. Each getter consists of several milligrams of rubidium contained in a small oven. These getters can be operated separately in order to prolong their lifetime or together if more rubidium is required.

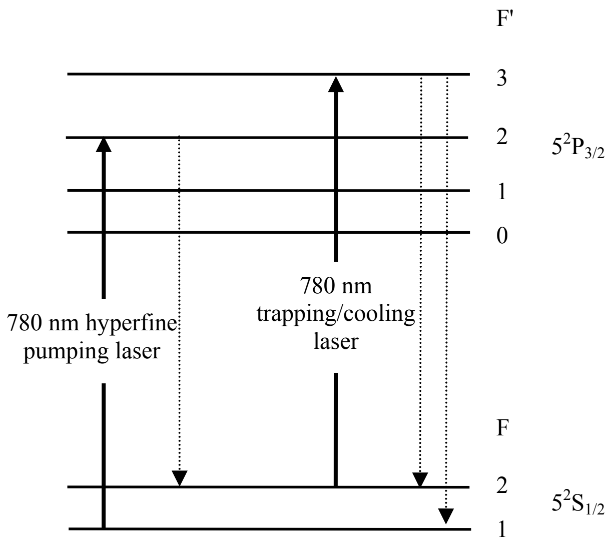

Figure 3: ^{87}Rb energy level diagram showing the trapping and hyperfine transitions and the decay channels of interest.

3.2 Vacuum chamber

A pressure of ~10^{-8} Torr is obtainable in the vacuum chamber using a 55 litre/s Varian Starcell ion pump and this is further reduced to ~3×10^{-9} Torr by baking the chamber for up to 48 hours at about 150°C. Initial pump down is achieved using a rotary pump, which is then isolated from the main chamber via a manual angle valve once pressure is low enough for the ion pump to take over. The pressure in the main chamber is measured using a combined pirani and ionisation gauge. Currently, the main chamber consists of a 6-way DN63CF cross with a glass bottle attached to one of

the arms. The beam intersection (i.e. trapping) region lies within the glass bottle. This will eventually be replaced by a custom-built stainless steel chamber, designed to allow optimum optical access. The switch from the glass bottle to the metal chamber will facilitate the installation of macroscopic elements (e.g. atom mirrors, sphere arrays etc) into the chamber.

3.3 Laser systems and frequency stabilisation

The cooling, trapping and repumping of the atomic ensemble is provided by two separate lasers. An extended cavity diode laser (Sacher Tiger ECDL at 780 nm) provides the necessary optical power at the cooling transition frequency (c.f. Fig. 3). This laser can supply up to 600 mW of output power with a 100 kHz linewidth in a single transverse mode. Optical pumping into the lower, hyperfine ground state is compensated for by illuminating the atomic ensemble using light from a wavelength selected, free-running laser (Sanyo DL-7140-201W at 780.1 nm in air). The repumping laser has a linewidth on the order of the natural width of a strong transition in rubidium (5-6 MHz) and an output power in the region of tens of mW is achievable after optical isolation and appropriate beam conditioning. Thus, both lasers can be tuned to any frequency point in the Rb D_2 line and frequency stabilised with respect to sub-Doppler saturated absorption responses.

The stabilisation set-ups are very similar to each other and the set-up for the main cooling laser is shown in Fig. 4. It is based on saturation absorption spectroscopy in a room temperature cell.

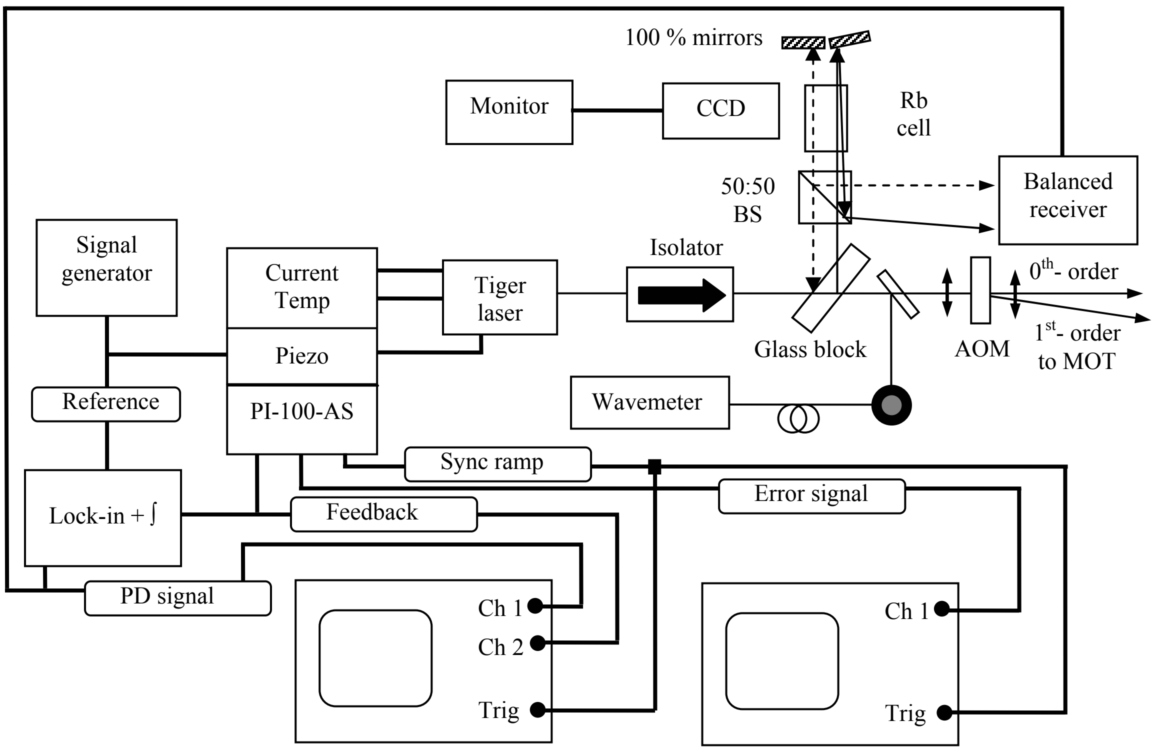

Figure 4: Laser stabilisation set-up. The dashed line represents the probe beam that provides the Doppler-broadened signal containing the saturated absorption features. The full line represents the probe beam that provides only the linear, Doppler-broadened signal with no features evident. The signals are subtracted from each other in order to obtain only the features of interest. PD: Photo diode, BS: Beamsplitter, AOM: Acousto-optical modulator.

After passing through an Isowave 40-dB large-aperture optical isolator two weak (~4%) pick off beams are taken via a thick glass block placed in the path of the main laser beam. These two *probe* beams then pass through a 50:50 beamsplitter (BS). Half of the laser power is lost at the beamsplitter, whilst the other half passes through a rubidium vapour cell. We use a 50 mm long pyrex cell with optical quality windows at each end, supplied by TOPTICA

Photonics. After passing through the cell the two beams are reflected back towards the beamsplitter. These beams are then deflected onto the two photodiodes of a Sacher balanced-receiver.

One of the probe beams is reflected back on itself and gives rise to a profile similar to that shown in Fig. 5(a). This is a standard saturated absorption profile showing the Doppler-broadened linear profile with a dip in the absorption at an atomic resonance of frequency f_o. The second probe beam is reflected back at a small angle (~5^o) and so there is no overlapping of beams within the vapour cell. The absorption profile measured with this probe beam is depicted in Fig. 5(b). This is a simple Doppler-broadened linear profile. The balanced-receiver performs the subtraction of the two probe beam signals to yield a Doppler-free narrow absorption feature (c.f. Fig. 5(c)). This is the well-known[22] technique of Doppler-free saturated absorption spectroscopy. We use it to resolve and ultimately lock the lasers to the peaks of interest in the rubidium hyperfine spectrum.

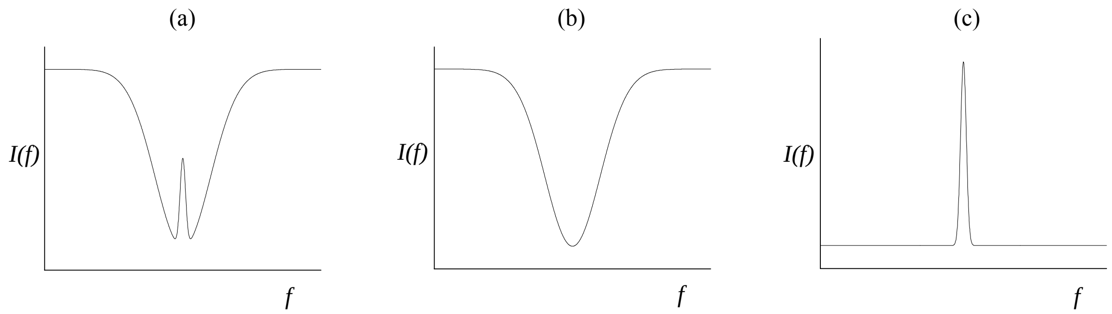

Figure 5: Transmitted intensity, *I(f)*, versus frequency, *f*. (a) Linear, Doppler-broadened absorption profile with narrow, non-linear feature evident; (b) Doppler-broadened profile; (c) Difference of profiles (a) and (b) revealing the narrow absorption feature.

A high-contrast crossover saturated absorption peak is used as an error signal for frequency stabilisation of the cooling laser, after lock-in detection and integration. For ^{87}Rb and the $5S_{1/2} \rightarrow 5P_{3/2}$ transition, this represents the F = 2 → F' = 3 and F = 2 → F' = 2 crossover peak located 133 MHz below the cooling transition. For ^{85}Rb and the $5S_{1/2} \rightarrow 5P_{3/2}$ line this would represent the F = 3 → F' = 4 and F = 3 → F' = 2 peak located 92 MHz below the cooling transition. In both cases, the stabilised laser frequency can be shifted on resonance by passing the beam through an acousto-optical modulator (AOM) that operates in the band from 87 MHz to 133 MHz, ensuring that it lies in the vicinity of the cooling transition. The power of the laser is computer controlled by modulating the acoustic wave power to the AOM and the frequency shift is controlled by a voltage control oscillator (VCO). After magnification of the beam diameter to ~16 mm it is split into three, equal intensity, retro-reflected beams that intersect in the MOT region after passing through polarisation optics.

The operation of a magneto-optical trap is far more tolerant to the frequency of the repumping light, which is tuned to the F = 1 → F' = 1 & 2 transition. Thus, a simple DC-level stabilisation is implemented in our set-up to locate the frequency of the free-running laser in the centre of the lower, ground state hyperfine line (i.e. F = 1 for ^{87}Rb). Repumping light is injected into only one of the three crossed beam pairs of the MOT by overlapping it at a beamsplitter.

A time-of-flight (TOF) measurement to determine the temperature of the cold atomic ensemble is provided by beam-splitting a small fraction from the repumping beam. This narrow, probe beam propagates in the horizontal direction about 10 mm below the atom cloud position. As the atoms are released from the trap (by either switching off the lasers and the magnetic fields or by blocking the repumping beam at the intersection of the trap), they fall under gravity, pass through the probe beam and absorb light. The cloud also undergoes a thermal expansion while falling the 10 mm. The temperature of the atoms can be determined from the width and distribution of the TOF measurement arising from the absorption signal.

4. FUTURE WORK

There are a number of directions to follow once the source of cold atoms is optimised. Particular areas of interest include control of the trap parameters through real-time feedback and other classical control strategies, quantum control of the cold atoms and manipulation of the atoms using light and/or magnetic fields.

4.1 Diffraction of atoms from magnetic gratings

It has been shown previously that magnetic structures, fabricated from permanent magnets, magnetic films or current carrying wires, can all be used to manipulate atoms. Demonstration experiments include the reflection of cold atoms from current carrying wires and magneto-optical film[23] and the guiding of atoms by the field produced from a pair of entwined solenoids.[24] The principle behind these experiments results from the interaction between an atom with a magnetic dipole moment, $\boldsymbol{\mu}$, and an inhomogeneous magnetic field, $\boldsymbol{B}$. In the presence of the field the atom experiences an interaction potential given by:

$$U = -\boldsymbol{\mu}.\boldsymbol{B} \ . \tag{1}$$

The atomic energy levels are split into Zeeman sublevels with energy varying according to the sublevel and the magnitude of the field, B. The energy of each level is determined using

$$E = m_F \mu_B g_L B \ , \tag{2}$$

where m_F is the magnetic quantum number, μ_B is the Bohr magneton and g_L is the Landé factor. The values of m_F are related to the total angular moment of the atom, F, by $-F \leq m_F \leq F$.

The magnetic field, therefore, exerts a force on the atom, $\boldsymbol{F}_{grad}$ which is given by

$$\boldsymbol{F}_{grad} = -m_f \mu_B g_L \nabla B \ . \tag{3}$$

Hence, atoms with $E > 0$, arising from the correct sign of m_F, will be repulsed by the magnetic field. This effect has been used to demonstrate magnetic mirrors[25] and guides[24] and can also be used to design magnetic gratings for atoms from a periodic potential. Diffraction gratings for atoms have been previously demonstrated using light fields[26] and atoms have also been manipulated by adding a periodic bias field to a permanent magnet field.[27] However, we are particularly interested in diffraction from a current carrying wire array, which has advantages over the permanent magnets primarily due to the fact that the magnetic field can be switched on and off as required and its intensity can easily be varied by adjusting the applied current. Some work has already been done on this area[28] and we plan on pursuing this topic by developing a full analysis of the atomic manipulation and deriving appropriate expressions for the separation of the individual diffraction peaks. It has been shown previously that this is highly dependent on the modulation frequency of the periodic potential,[28,29] which would allow us to diffract the atoms at large angles of incidence. In addition to the work on the diffraction grating we plan on investigating the diffraction of atoms by a spherical object with diameter ~80 microns.

4.2 Control of a cold atom source

We aim to study fully the coherence loss mechanisms that arise when cold atoms are approached to a "hot" surface. Of particular interest to us is when this surface consists of a microcavity e.g. a fluoride glass microsphere. This would enable us to study the possibility of photon exchange. In order to fully understand the processes involved a thorough investigation must be made of the forces that result, depending on the angle of incidence of the atoms. In recent years, interest in the coherent control of atoms has increased due to the knowledge that can be acquired and applied in quantum information techniques. In these experiments, the coherence of the laser is ideally transferred to the quantum systems therefore allowing one to control the quantum state. A good introductory review on the subject is provided by Habib *et al.*[30] The difficulty primarily lies in obtaining "real-time" information on the natural time scales involved for atomic decoherence. In addition to studying quantum control, we are also planning on incorporating differing classical control strategies in order to stabilise the cloud of cold atoms. Parameters that can be controlled include the trap intensity (via

monitoring of the rubidium vapour within the trap and adjustments on the current through the getters) and trap position (via the cancellation fields and introducing variations in these to fine-tune any position perturbations from external fields).

5. CONCLUSION

We have presented a review of the various cooling mechanisms used in order to obtain a sample of cold, rubidium atoms in the μK region using magneto-optical trapping. Sub-Doppler cooling can be achieved by making use of the polarisation of the laser fields and the variation in the quantisation direction as the atom moves through a laser beam. The MOT experimental set-up has been presented, including details on the vacuum system, the rubidium source and the frequency stabilisation of the cooling and repumping lasers. We have also considered briefly the effect of external magnetic fields on atoms and have shown that these fields can be used to manipulate the atoms and generate simple atom optics elements such as diffraction gratings, guides and mirrors. Finally, we discussed the general directions being followed in cold atom studies within our research group, including the design of a diffraction grating and the stabilisation of the parameters associated with a cloud of cold, rubidium atoms.

ACKNOWLEDGEMENTS

The authors thank Stephen Collins and Gerard Rasmussen for technical support. This work is supported by Science Foundation Ireland project number 02/IN1/I28. MM acknowledges financial support from the Council of Directors for the Institutes of Technology - Strand 1 project number PRDSP/04/CK06. KD is grateful for financial support from the Cork Institute of Technology Postgraduate Scholarship Fund.

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