LOADING OF A FAR OFF RESONANCE DIPOLE
FORCE TRAP FOR STABLE ^{39}K

by

Erika Prime

M.Phys., University of Manchester, 2002

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

The Faculty of Graduate Studies

(Physics)

THE UNIVERSITY OF BRITISH COLUMBIA

August 2005

© Erika Prime, 2005

Abstract

The TRIumf Neutral Atom Trap (TRINAT) group is performing precision measurements to test the standard model of the weak interaction. Nuclear β decay asymmetry experiments are carried out on radioactively decaying potassium isotopes, trapped in a Magneto Optical Trap (MOT). In order to accurately test whether parity is fully violated, atoms of well defined polarisation are required. A useful tool which can achieve a high level of polarisation is a Circularly polarized Far Off Resonance dipole Force Trap (CFORT). This work is the first step in its development; building the necessary components in order to successfully load stable ^{39}K into a linearly polarised FORT from a MOT, where the atoms are pre-cooled to a temperature of a few hundred μK . The FORT consists of 700mW of light from a Titanium Sapphire ring laser, linearly polarized and focused with a 200mm achromatic lens to a waist of $35\mu\text{m}$. The light is detuned between 1 and 20nm from the D_1 transition and this gives rise to trap depths in the region of a few millikelvin. A characterisation of the FORT loading efficiency and lifetime as a function of FORT beam detuning, power and ellipticity are studied.

Contents

Abstract	ii
Contents	iii
List of Tables	vi
List of Figures	vii
Acknowledgements	x
1 Introduction	1
2 The Physics of Neutral Atom Traps	9
2.1 The Physics of a Magneto Optical Trap (MOT)	9
2.1.1 Pre-cooling the Atoms	9
2.1.2 The Damping Force	10
2.1.3 The Restoring Force	11
2.1.4 The Repumping Light	14
2.2 The Physics of a Far Off Resonance dipole force Trap (FORT)	17
2.2.1 Induced Dipole Moments	17
2.2.2 Light Shifts	17
2.2.3 A Potential Gradient and Dipole Force	18

2.2.4	Linearly versus Circularly polarized FORT (CFORT)	21
3	The Magneto Optical Trap (MOT)	26
3.1	The Experimental Setup and Optimisation of the MOT	26
3.1.1	The MOT Beams	26
3.1.2	The Trapping Chamber and Source of Potassium	29
3.1.3	The Magnetic Field	29
3.1.4	Optimisation of the MOT Parameters	30
3.1.5	The Scan Procedure	31
3.1.6	Results of Optimisation	32
3.2	The Characterisation of the MOT	36
3.2.1	Measuring the Temperature of the MOT Cloud	36
3.2.2	Method One: Release and Recapture	36
3.2.3	Method Two: Free Expansion	39
3.2.4	Results of Temperature Characterisation	41
3.2.5	Measuring the Lifetime of the MOT	47
4	The Far Off Resonance dipole force Trap (FORT)	50
4.1	The Experimental Setup of the FORT	50
4.1.1	Characterising the FORT Beam	50
4.1.2	The Resulting Trap Depth	54
4.2	FORT Loading and Diagnostics	58
4.2.1	The Alignment of the FORT and the MOT	58
4.2.2	The Sequence for Loading the FORT from the MOT	59
4.2.3	Scattered Light Background	62
4.2.4	Triggering	62

4.2.5	The Initial Signal	63
4.2.6	The Warmer MOT Cloud	66
4.3	The Characterisation of the FORT: Loading and Loss Rates . .	68
4.3.1	Measuring the FORT Collection Efficiency	68
4.3.2	FORT Collection Efficiency as a Function of Wavelength	69
4.3.3	FORT Collection Efficiency as a Function of Power . .	72
4.3.4	FORT Collection Efficiency as a Function of Ellipticity	74
4.3.5	The Loading Curve	77
4.3.6	A FORT Lifetime Model	79
4.3.7	Measuring the FORT Lifetime	85
4.3.8	The FORT Lifetime as a Function of Wavelength . . .	85
4.3.9	The FORT Lifetime as a Function of Power	89
4.3.10	The FORT Lifetime as a Function of Ellipticity	90
4.3.11	Ground State Dipole Force Fluctuation Heating	92
5	Summary, Conclusions and Future Work	98
	Bibliography	105
A	An External Probe Beam	110
A.1	Probe Beam Applications	110
A.1.1	Detecting the FORT Atoms	110
A.1.2	Measuring the AC Stark Shift	111
A.1.3	Potential Applications for the Probe Beam	113
A.2	Probe Beam Setup	113
A.3	Probe Beam Characterisation	115

List of Tables

3.1	Summary of the MOT optimisation results.	35
3.2	Summary of the MOT temperature measurement results. . . .	41
4.1	Fit results for the characterisation of the FORT beam.	54
A.1	Fit results for the characterisation of the probe beam.	116

List of Figures

2.1	Zeeman splittings for a $J_g = 0$ to $J_e = 1$ atomic transition. . .	13
2.2	Form of the spherical quadrupole field.	14
2.3	Anti-Helmholtz coil and six laser beam configuration.	14
2.4	Hyperfine structure of ^{39}K with MOT light frequencies.	15
2.5	AC Stark shifts for a red-detuned laser field.	18
2.6	The FORT trapping potential.	19
2.7	Hyperfine structure of ^{39}K with FORT light frequencies. . . .	21
2.8	FORT potential as function of m_f sublevel.	25
3.1	MOT beam setup.	27
3.2	Photograph of the MOT setup.	30
3.3	Optimum MOT beam frequencies.	33
3.4	Fits of the number of atoms in the MOT as a function of MOT-off time.	42
3.5	Fits of the MOT cloud diameter as a function of MOT-off time.	44
3.6	Gaussian fits of the MOT cloud profile.	45
3.7	CCD picture of the $408\mu K$ MOT cloud during the cooling stage.	46
3.8	Fit of the number of atoms building in the MOT cloud as a function of time.	47

3.9	MOT lifetime and relative MOT fluorescence as a function of dispenser current.	49
4.1	MBR beam profile.	53
4.2	Varying spotsize of the MBR output.	53
4.3	FORT trap depth as a function of FORT wavelength.	56
4.4	FORT trap depth as a function of detuning from the D_1 transition, before and after the MBR.	57
4.5	MOT-FORT setup.	58
4.6	Time diagram of the duty cycle.	60
4.7	First signal from atoms in the FORT.	63
4.8	FORT signal as a function of MOT cloud position.	65
4.9	Scans of the trapping light frequency during the cooling and the loading stages.	67
4.10	FORT collection efficiency as a function of detuning from the D_1 transition.	70
4.11	FORT collection efficiency as a function of power.	73
4.12	FORT collection efficiency as a function of ellipticity.	75
4.13	FORT trap depth as a function of ellipticity.	76
4.14	Percentage of MOT atoms collected in the FORT as a function of loading time.	78
4.15	Fluorescence signal from atoms in the FORT as a function of MOT-off time.	83
4.16	Decaying fluorescence signal from atoms in the FORT as a function of MOT-off time as predicted by the FORT scattering theory.	84

4.17	FORT lifetime as a function of detuning from the D_1 transition.	87
4.18	FORT lifetime as a function of red-detuning from the D_1 transition for potassium dispenser current of 3.5 and 4A.	89
4.19	FORT lifetime as a function of power.	90
4.20	FORT lifetime as a function of ellipticity.	91
4.21	Fit of the FORT decay rate as a function of ellipticity.	95
4.22	Transition probabilities between the various hyperfine levels of ^{39}K	96
A.1	Probe beam profile.	115
A.2	Varying spotsize of the probe beam.	116
A.3	Varying spotsize of the probe and FORT beams.	117

Acknowledgements

I would like to take a moment to express my gratitude and thank those people without whom I would not have been able to achieve this work.

Dr. John Behr, my supervisor, for his limitless time and for continually pushing me to achieve and not give up.

Dr. Mathew Pearson, TRINAT's Post.Doc., for his constant reassurance, fruitful discussions and practical expertise.

Owen Cherry, a Co-op. student, for reassembling the off-line setup, where my project began.

Tam Nhan, also a Co-op. student, for performing the camera F-stop calibration measurements.

The rest of the TRINAT group, which has changed some what during the course of my M.Sc., for listening and discussing my progress.

My friends in the lab including Joe Vaz for rides and dinners, Matt Smith for tackling the UBC system first, Thomas Cocolios for keeping me smiling,

Jens Dilling and Jens Lasson for supportive chats and the racquetball crew for the weekly relaxation.

My UBC Office mates for getting me through the courses.

Tony Walters, the Graduate Secretary, for his humour, a shoulder to cry on and reminding me of reality.

Prof. Rob Kiefel and Prof. Kirk Madison for carefully reading my thesis and giving their thoughtful input.

My friends outside the lab including my roommates, the Belgium Luge Team and the Fringe regulars for listening and encouragement.

Jen Braun for being understanding, supportive, making me value myself and for being a constant source of motivation.

And finally my family for always being proud and telling me I could do it.

Thank you to NSERC for the funding and TRIUMF for the facilities.

Chapter 1

Introduction

Manipulation of matter with light is not a recent concept. The idea of cooling and trapping atoms with lasers has been around for over twenty five years. In 1975 Hänsch and Schawlow introduced the idea of laser cooling based on the resonant scattering of photons[1]. It was suggested that the kinetic energy of moving atoms could be reduced by the mechanical action of near resonant laser radiation. Due to the conservation of momentum, there is a net change in an atom's velocity during the photon absorption and emission cycle. The Doppler effect makes the radiation pressure on a free atom velocity dependent because a moving atom sees the frequency of the laser light shifted. Counter-propagating photons are still resonant with a moving atom if this shift is compensated for by detuning the light below the atomic absorption line. Atoms are therefore slowed and thus cooled. For more than just a unidirectional force, a gas of atoms is illuminated from all directions by six laser beams along each of the six cartesian coordinate directions.

Stopping an atom requires the scattering of many photons. The invention of narrow linewidth, tunable lasers, which have high spectral brightness improved the rates of absorption and fluorescence. The resulting substantial decelerating force made three dimensional Doppler cooling experimentally achievable. This so called "optical molasses" was first demonstrated with sodium atoms by Chu et al. in 1985[2]. Sodium is an alkali atom. Alka-

lis in general have simple and convenient energy level structures for laser cooling because cooling transitions have wavelengths in the visible to near infrared region. Continuous-wave lasers with sufficient power exist at these frequencies.

There is a limit to the amount an atomic sample's average kinetic energy is reduced by this laser cooling method due an inherent spread of velocities produced by the recoiling photon. For a sample with a well defined velocity distribution a lowest attainable temperature, the Doppler cooling limit[3], can be assigned. This is the energy associated with the natural width of the resonant atomic transition used for cooling and is on the order of $100\mu K$ for alkali atoms.

An optical molasses is only a dissipative manipulation as it only provides a viscous damping force opposing the atoms motion. Atoms are free to diffuse around and therefore spatial confinement is absent. A Magneto Optical Trap (MOT) provides simultaneous dissipation and confinement. Circularly polarized light is used for the optical molasses beams and a spherical quadrupole magnetic field is added, such that when an atom moves away from the origin, its atomic energy levels get Zeeman shifted into resonance with a beam, which pushes it back. A MOT was first demonstrated experimentally by Raab et al. in 1987 again with sodium atoms[4]. 10^7 atoms were collected in a less than a 0.5mm diameter region.

It is possible to collect atoms directly from a room temperature vapour using a MOT because there are enough atoms in the tail of the thermal Maxwell-Boltzmann distribution[3] which have velocities lower than the capture velocity of the MOT. Re-thermalisation upon "bouncing" off the trap-

ping chamber walls keeps the low energy tail filled. MOT trap depths are on the order of a few K. These traps are very robust and hence have today become a basic building block for many atomic physics experiments.

The presence of near resonant light limits the MOT cloud density due to re-scattering of photons and excited state collisions. Typically MOT densities are around 10^{11} atoms/cm³[5]. A higher phase space can be achieved leading to the quantum degenerate regime by use of other cooling techniques, e.g. evaporative cooling, which leads to a Bose Einstein Condensate[6], or by transferring cold MOT atoms in to a more conservative trap. A Far Off Resonance dipole force Trap (FORT)[7] is such a passive trap. Far off resonance implies detunings from atomic resonance of tens of nanometers, which is on the order of 10^6 linewidths. For such large detunings, the photon scattering rate becomes so low that there are relatively few optical excitations. An effectively conservative potential results, which leads to negligible photon recoil heating[3] and consequently long confinement times with no additional cooling necessary, as long as other heating mechanisms do not dominate. A 65nm red-detuned rubidium dipole force trap resulted in peak photon scattering rates of typically 400Hz and therefore recoil heating trap lifetimes as long as 40s[8]. With additional cooling mechanisms such as Sisyphus cooling, densities as high as 10^{13} atoms/cm³ have been achieved within the FORT environment[5].

This different method of optically trapping neutral atoms was first proposed in 1978 by Ashkin[9]. The trap consists of a single focused Gaussian laser beam, with the light typically detuned a few nanometers below the atomic resonance. The dipole force results from the interaction between an

induced atomic electric dipole moment and an electric field. This force is proportional to and points in the direction of the intensity gradient. Stability is achieved because the dipole force dominates over the destabilising influence of the scattering force for detunings well below resonance and for strongly focussed beams. It was first demonstrated by Chu et al. in 1986 and was in fact the first ever observation of optically trapped neutral atoms[7]. Five hundred sodium atoms were confined in a volume of $10^3 \mu m^3$.

The atoms were first cooled below $10^{-3} K$ in optical molasses and then captured by a dipole force optical trap. This pre-cooling is crucial when trapping atoms from a room temperature vapour because experimentally achievable FORT trap depths are shallow, on the order of milliKelvin.

The first FORTs were loaded by alternating the FORT and optical molasses, which cools atoms into the trap[8]. It was thought that switching the trapping forces on and off in this way would avoid any interference with the MOT damping process due to the optical Stark shift of the atomic resonance caused by the FORT beam. However, later the FORT and MOT clouds were overlapped continuously and the loading improved. More than 10^6 atoms resulted[10].

The need for laser cooled and trapped atoms has been a motivation for the development of the many schemes for preparing cold, dense samples of atoms. Stable neutral atom traps have diverse applications from atom optics to exploring the quantum degenerate regime or performing precision measurements such as high resolution spectroscopy and frequency standards[11].

The precision measurements performed by the TRIumf Neutral Atom Trap (TRINAT) group, like many other experiments requiring a sample of

trapped atoms, make use of the specific advantages and disadvantages of the various possible trapping and cooling mechanisms, which were successfully realised experimentally in the 80s and 90s.

TRINAT traps radioactive potassium using a two MOT setup[12]. A proton beam from the TRIUMF main cyclotron bombards a heated target, alkalis diffuse out of the target and are surface ionised and extracted as an ion beam. The beam is mass separated in a high resolution mass separator and is then electrostatically transported to the laser lab. The ion beam is stopped, neutralised and collimated into the primary MOT's vapour cell[13]. The primary MOT is supplied with ^{36}K (*half-life* = 342ms), ^{37}K (*half-life* = 1.226s) and $^{38}\text{K}^m$ (*half-life* = 0.925s) from the online Isotope Separator and Accelerator Facility (ISAC). These isotopes have been trapped and with these atomic samples, TRINAT has performed symmetry tests of the standard model, similar in concept to the original β - *decay* experiments of Wu et al.[14].

β - *decay*[15] is a process through which unstable atoms can become more stable. During a β^+ - *decay*, a proton in an atom's nucleus turns into a neutron, a positron and a neutrino. The positron(β particle) and neutrino (ν) fly away from the nucleus, which now has one less proton than it started with and hence has become another element. β - *decay* is determined by the weak interaction[15] and the standard model[15] predicts values for the various parameters which describe this interaction. Measurement of these β - *decay* observables and comparison with theory determines the validity of the standard model in this regime.

It is possible to determine the angular distribution of the β particles emit-

ted from many decays by detecting these particles with a combined silicon strip and plastic scintillator detector. The recoiling nuclei, which are now ions, are detected using an electric field to collect them on to a Micro Channel Plate. If these ions are detected in coincidence with the β particles the neutrino angular distribution can be determined. These angular distributions are dependent on the $\beta - \text{decay}$ observables and $\beta - \nu$ correlation measurements have been used by TRINAT to set limits on the scalar interaction[16].

In many cases these angular distributions also depend on the nuclear polarization. Therefore in order to extract the observable of interest, it is necessary to have parent nuclei with well defined nuclear polarization because errors in the knowledge of this polarization will propagate through to the error on the determined observable¹. In addition applying the parity operator[15] to the system of a *beta - decaying* nucleus can be simulated by simply flipping the spin of the decaying nucleus. Comparing the determined observables in the two cases will result in a test of parity violation. $\beta - \text{decay}$ spin asymmetry experiments have been used by TRINAT to be sensitive to the presence of right handed currents in the weak interaction[17]. However, in order to accurately detect such a small asymmetry a precision measurement with a high level of sensitivity is required.

Trapped samples of ^{37}K were optically pumped to achieve 97 ± 1 percent atomic and nuclear polarization. This method relies on the fact that the atomic and nuclear spins are coupled. Repeated absorptions of circularly polarized light add angular momentum to the atom and pump the system

¹E.g., the TRINAT experiments measure the angular distribution of neutrino's with respect to the nuclear spin, $\omega(\theta) = 1 + B_\nu P \cos \theta$, where P is the nuclear vector polarisation and B_ν is the quantity of interest.

to the fully stretched sublevel. Complete polarization can be achieved, but realizable levels of polarization are limited by the quality of the circular polarization of the optical pumping light. Changing the helicity of the light results in the necessary spin flip.

The nuclear polarization is determined by fitting the expressions for the angular distributions to the data with the beta decay observables taking on the values determined by the standard model. It is also determined independently by monitoring the atomic fluorescence with a CCD camera. Fully polarized atoms cannot absorb any more circularly polarized light, so the degree to which the fluorescence extinguishes provides a probe of the polarization.

If a trapped sample is 100 percent polarised then it has a well defined nuclear spin axis and isotropic $\beta - decays$ will result only from untrapped, unpolarised background atoms. In the case of non perfect polarization some of the $\beta - decays$ from within the trapped sample will also contribute to the isotropic distribution, but if the level of polarisation is well known then it is possible to correct for this contribution. Therefore in order to improve the spin asymmetry experiments performed by TRINAT an atomic sample with not just a high level of polarisation, but very well defined polarisation is required.

TRINAT needs an atom trap for collecting a large number of radioactive neutral potassium atoms with the following specific characteristics. It is necessary to have a tightly confined, well localised cloud in a largely perturbation free environment. The trapping potential should be deep and heating processes should be limited such that atoms remain in the trap for as long

as possible or at least on a timescale on the order of their lifetimes, which is approximately 1s. Finally, as mentioned, a high level of well defined spin polarisation is essential. It is this last point which is not satisfied by a MOT, an external optical pumping beam is necessary for spin polarisation. Using a double MOT setup, atoms are initially trapped in a high pressure cell and are then transferred to a lower pressure cell. This allows the atoms to accumulate with essentially no background vapour. If the atoms are then transferred into a FORT, all of the above required features are present. A Circularly polarised FORT (CFORT) offers energy splittings dependent on the internal spin states of an atom and this allows for confinement of just one magnetic sublevel, if the right CFORT frequency is chosen. Also the limited spontaneous photon scattering rates cannot rapidly destroy the ground state atomic polarisation. Transitions between non degenerate magnetic sublevels may allow one to drive additional sub-Doppler cooling schemes. Also a FORT does not require any magnetic fields to function so the presence of background fields is further limited.

TRINAT also has a second MOT setup, the off-line MOT, which is independent of the ISAC beam. The off-line MOT has its own source of naturally abundant, stable potassium and can therefore be used outside of TRINAT's allotted beam time. The goal of this setup is to develop a CFORT for stable ^{39}K which will eventually be implemented on-line with radioactive isotopes.

Whist the key concepts have been briefly mentioned here, a full treatment of the theory can be found in chapter 2.

Chapter 2

The Physics of Neutral Atom Traps

2.1 The Physics of a Magneto Optical Trap (MOT)

2.1.1 Pre-cooling the Atoms

In a typical FORT the laser light is detuned from resonance on the order of 10^6 linewidths. The resulting conservative potential is nearly non-dissipative and consequently does not cool atoms. In order to load a FORT with a depth of a few milliKelvin from a room temperature vapour, atoms must be pre-cooled in a MOT. Once atoms are trapped, further cooling within the FORT environment is also needed to counteract possible heating effects that would boil atoms out of the trap.

MOTs are a widely used standard source of cold, neutral atoms. Atoms are cooled by means of Doppler cooling to temperatures of less than 1mK. The Doppler limit[3] is given by

$$T_D = \frac{\hbar\gamma}{2K_B} \quad (2.1)$$

where γ is the natural linewidth of the cooling transition and $K_B (= 1.38066 \times 10^{-23} J/K)$ is the Boltzmann constant. It results in a value of $146\mu K$ for ^{39}K and is similarly a few hundred μK for other alkalis. It is possible to go below

this limit and approach temperatures close to the recoil limit, but special sub-Doppler cooling techniques, such as polarisation gradient cooling[11], are required. The recoil limit[3] is defined as the temperature associated with the gain in kinetic energy by emission of one photon and is given by

$$T_{rec} = \frac{\hbar^2 K^2}{MK_B}, \quad (2.2)$$

where $\hbar k$ is the recoil momentum obtained by an atom of mass M . This expression results in a value of $0.81\mu K$ for ^{39}K . It is possible to reach lower temperatures and achieve smaller recoil heating rates with heavier alkalis because they have lower recoil temperatures. This puts potassium at a disadvantage compared to other elements previously trapped in FORTs, such as rubidium and cesium, which have $T_{rec} = 0.37\mu K$ and $0.198\mu K$ respectively. However a larger problem for achieving low temperatures in potassium is the small hyperfine structure. It makes sub-Doppler cooling mechanisms difficult, as they are based on optical pumping between ground state Zeeman sublevels.

2.1.2 The Damping Force

Radiation pressure is due to the conservation of momentum during the absorption and then emission of light. When an atom absorbs a photon, it is excited to a higher energy state and recoils in the direction of the incoming light, consequently changing its velocity by an amount $\frac{\hbar k}{M}$. When the atom returns to the ground state by spontaneous emission, it recoils again, this time in the direction opposite to that of the emitted photon. Spontaneous emission is a random process with a symmetric distribution when averaged

over many cycles, or over a large sample of atoms. Thus it does not contribute to a net change in velocity.

Atoms within a vapour are moving. In order for counter-propagating light to be resonant with these atoms the light must be detuned below the atomic resonance in order to compensate for the resultant Doppler shift. An atom then sees light that it is moving towards, Doppler shifted closer to resonance and light that it moves away from, Doppler shifted away from resonance. Therefore atoms predominantly scatter photons from the forward direction and they slow down. This is a velocity dependent effect and as the atoms slow, the Doppler shift changes and tunes the laser out of resonance with these atoms. Therefore a laser beam of fixed frequency will interact only with a fixed velocity class of atoms.

Atoms illuminated in all dimensions will see an effective viscous damping force everywhere opposing their motion. However, this optical molasses is not yet a trap because atoms are free to diffuse around and escape from the interaction region. In order to confine the atoms a spatially-dependent trapping force is required.

2.1.3 The Restoring Force

A MOT uses a combination of magnetic and optical fields to create a position dependent force, pointed towards the centre of the trap[11]. The permanent magnetic dipole moment of an atom interacts with a magnetic field and causes the atomic energy levels to shift by means of the Zeeman effect[18]. If a $J_g = 0$ to $J_e = 1$ atomic transition is considered, three Zeeman components are produced for the excited state. For an inhomogeneous magnetic field,

which increases in strength as you go away from the origin, the magnitude of the Zeeman splitting between these components also increases with distance from the origin. This is shown in figure 2.1.

Consider a point, z' , on the positive z -axis where the magnetic field is of the form $B(z) = bz$. The effect is to shift the $m_e = +1$ sublevel of the excited state up and the $m_e = -1$ sublevel of the excited state down. In order to utilize the radiative selection rules, the six counter-propagating laser beams of the molasses are set up such that they have opposite circular polarisations. With circularly polarised light, it is possible to drive $\Delta m = \pm 1$ transitions. If a laser beam propagating in the positive z direction has σ^+ polarization and a beam in the negative z direction has σ^- polarisation, then an atom with a positive z coordinate, such as at z' , sees the σ^- beam Zeeman shifted closer to resonance. It will preferentially absorb such a σ^- photon and will be pushed back to $z = 0$. A similar effect is produced on the other side of the origin, on the negative z axis, and the atom consequently experiences an effective restoring force. If an atom moves away from the origin it is Zeeman shifted into resonance with a beam which pushes it back.

Figure 2.1: The Zeeman splittings as a function of distance along the z axis from the centre of the MOT for a $J_g = 0$ to $J_e = 1$ atomic transition, along with the effective detunings and the polarisation of the counter-propagating laser beams.

The necessary inhomogeneous magnetic field is provided by a pair of Anti-Helmholtz coils. These are two coaxial coils separated by 1.2 times their radius with currents running through them in opposite directions. Such a configuration produces a spherical quadrupole field, that has a local minimum at the origin where the centre of the trap forms. The form of the spherical quadrupole field is shown in figure 2.2 and a diagram of the Anti-Helmholtz coils and six laser beam configuration is shown in figure 2.3.

Figure 2.2: The form of the spherical quadrupole field.

Figure 2.3: The Anti-Helmholtz coil and six laser beam configuration.

2.1.4 The Repumping Light

MOT's have been produced for many alkalis, however the trapping of potassium isotopes was demonstrated considerably later than the other alkali-metal atoms due to a major difference. The interaction between the magnetic field produced at the nucleus by an electron, which includes spin and orbital angular momentum, with the magnetic dipole moment of the nucleus results in the hyperfine structure[18] within an atom. The nuclear magnetic moments of potassium isotopes are comparatively quite small, leading to correspondingly small hyperfine splittings of optical transitions. There-

fore a slightly different approach to trapping was necessary. The hyperfine structure for the isotope of interest, ^{39}K , is shown in figure 2.4. The D_1 , ($4S_{1/2} \rightarrow 4P_{1/2}$), and the D_2 , ($4S_{1/2} \rightarrow 4P_{3/2}$), transitions are shown.

Figure 2.4: The hyperfine structure of ^{39}K with the relevant MOT light frequencies.

The laser trapping frequency is red-detuned with respect to the $4S_{1/2}$ $F_g = 2$ to $4P_{3/2}$ $F_e = 3$ transition, the analogous D_2 transition used for trapping other alkalis in MOTs. However in ^{39}K the excited state splitting between the $P_{3/2}$ $F_e = 3$ and $F_e = 2$ states is only 21 MHz compared to the natural linewidth of 6.09 MHz. Typically the MOT light detuning is larger

than the whole hyperfine structure of the excited state and in addition the high laser powers used result in power broadening. This results in unresolved excited state hyperfine structure, so the trapping field can excite many of the Zeeman sublevels within the excited state manifold and consequently the spectral isolation needed for trapping is reduced.

The initially closed trapping transition, where spontaneous decay returns the atom to the same initial level, provides the largest frictional force and is now no longer isolated. Through spontaneous decay of the $F_e = 2$ excited state, there is strong optical pumping of the atoms to the other $4S_{1/2} F_g = 1$ hyperfine ground state and this state is too far from the trapping resonance to allow further excitation. It is necessary to combat this effect in order to keep the trapping process going.

This is achieved by introducing a small amount of light differing in frequency from the trapping light by the ground state hyperfine splitting ($= 462 MHz$). This beam excites from the lower $F_g = 1$ hyperfine ground state, bringing the atoms back to the trapping cycle. This is called repumping light. Repumping light is needed for trapping all alkalis, however in potassium the power in this beam is comparable to that of the trapping light beam and also it contributes to the trapping effect.

^{39}K and ^{41}K are stable bosons and were trapped first[19]. Since then ^{40}K , a weakly radioactive fermion ($half-life = 1.28 \times 10^9 years$)[20] and the radioactive isotopes, $^{38}K^m$ ($half-life = 0.925s$), ^{37}K ($half-life = 1.226s$) and ^{36}K ($half-life = 0.36s$), produced using an online isotope separator, have also been trapped in a MOT[21].

2.2 The Physics of a Far Off Resonance dipole force Trap (FORT)

2.2.1 Induced Dipole Moments

A FORT is a purely optical trap. The key to its operation is the dipole force, which arises from the interaction of an atomic electric dipole moment, $\vec{d}$, with an electric field, $\vec{E}$. The Hamiltonian[3] is given by

$$H = -\vec{d} \cdot \vec{E}. \quad (2.3)$$

However, neutral atoms do not have permanent electric dipole moments. Consequently, in order to trap using the electrical interaction, dipole moments must be induced[22]. An atom in an oscillating electric field can be thought of as a forced oscillator[23]. The electric field with which the electric dipole moment will interact actually provides the driving field which induces the dipole moment. The sign of the interaction is dependent on the detuning of the field with respect to the atomic resonance transition. When the driving field frequency is below resonance, red-detuned, the atom's induced dipole moment is in phase with the driving field. Alternatively when the frequency is above resonance, blue detuned, it is completely out of phase with the field.

2.2.2 Light Shifts

This interaction between the induced electric dipole moment and the electric field results in a perturbation on the energy levels within the atom. The resulting energy shift is called the AC Stark shift[3]. If a two level atom is considered, a red-detuned electric field would result in lowering the energy

of the ground state, E_g , and raising the energy of the excited state, E_e . This effect, of the two energy levels repelling each other, is shown in figure 2.5. For a blue-detuned electric field the opposite is true, resulting in a positive ground state energy shift. As the name suggests the trapping electric field is far off resonance, consequently there are relatively few optical excitations and atoms spend a great deal of time in the ground state. Therefore, it is the light shifted ground state which is the relevant potential for the motion of atoms.

Figure 2.5: The energy levels of a two level atom in the case of zero electric field and also in the presence of a red-detuned electric field, where AC Stark shifts result.

2.2.3 A Potential Gradient and Dipole Force

If a spatially inhomogeneous electric field is used, the resulting interaction and associated energy level shift will also vary in space. The interaction is directly proportional to the magnitude of the electric field. Therefore, the negative energy shift for the ground state produced by a red-detuned electric

field would be greatest in the regions of highest field strength. If the electric field is produced by a laser beam which is tightly focussed, a potential well is created for the ground state atoms in the region of the beam focus. Atoms “roll” into this potential well and are effectively attracted towards the focus. It is this potential gradient which results in the dipole force, an effective restoring force pointing towards the centre of the beam focus. An illustration of the trapping potential is shown in figure 2.6[11]. A blue-detuned laser field would result in a potential barrier and hence a repulsive force pointing away from the focus region.

Figure 2.6: An illustration of the FORT trapping potential resulting from a focussed laser beam, where z and r are the longitudinal and radial coordinates respectively, z_0 is the Rayleigh range and ω_0 is the beam waist. The spot size, which is the radius of the laser beam, increases by $\sqrt{2}$ over this Rayleigh range.

An expression for the FORT potential[24] at the beam focus for an alkali atom can be written as

$$U_0 = \frac{\hbar\gamma I_0}{24I_s} \left[\left(\frac{1}{\delta_{1/2}} + \frac{2}{\delta_{3/2}} \right) - g_f m_f \sqrt{1 - \epsilon^2} \left(\frac{1}{\delta_{1/2}} - \frac{1}{\delta_{3/2}} \right) \right], \quad (2.4)$$

where γ is the natural linewidth of the relevant optical transition, which is the spontaneous decay rate for the excited state of the atom. In ^{39}K $\gamma D_1 = 6.08 MHz$ and $\gamma D_2 = 6.16 MHz$. $I_0 (= \frac{2P}{\pi\omega_0^2})$ is the laser beam intensity in terms of the total beam power, P , and the beam waist, ω_0 , which is the beam radius at the focus of a gaussian beam. $I_s (= \frac{2\pi^2\hbar c\gamma}{3\lambda^3})$ is the saturation intensity for the relevant optical transition and is given in terms of the laser wavelength, λ . The detunings $\delta_{1/2}$ and $\delta_{3/2}$ are in units of γ and are the difference between the laser frequency and the D_1 and D_2 transition frequencies respectively. ϵ is the ellipticity or polarisation of the laser field. ϵ can have values from 0, circularly polarised light, to +1, linearly polarised light. A full definition of ϵ is given by equation 4.3. m_f is the Zeeman sub-level of the atom and $g_f (= [F(F+1) + (S(S+1) - (I(I+1))]/[F(F+1)])$ is in terms of the electron spin, S , the nuclear spin, I and the hyperfine state, $|\vec{F}\rangle = |\vec{I}\rangle + |\vec{J}\rangle$, where the total angular momentum is $|\vec{J}\rangle = |\vec{L}\rangle + |\vec{S}\rangle$ is in terms of the orbital angular momentum, $\vec{L}$.

The hyperfine structure for ^{39}K , is again shown in figure 2.7 and all the magnetic sublevels within each hyperfine state are included.

Figure 2.7: The hyperfine structure of ^{39}K with relevant FORT beam detunings.

2.2.4 Linearly versus Circularly polarized FORT (CFORT)

If a perfectly linearly polarised laser field is used, $\epsilon = 1$, the second term in equation 2.4 is eliminated. The expression is no longer dependent on m_f and all the internal spin states of the alkali atom in the ground electronic state have degenerate energy. This is not the case for $\epsilon \leq 1$. An elliptically polarised laser field acts as a fictitious magnetic field producing an “optical”

Zeeman effect[25] and the degeneracy of the Zeeman sublevels is lifted.

The FORT trapping potential, in a form which includes the Gaussian shape of the laser beam profile, is given by

$$U(r, z) = U_0 \frac{\exp[-2r^2/\omega(z)^2]}{1 + (z/z_0)^2}, \quad (2.5)$$

where r and z are the radial and longitudinal position from the centre of the beam focus, U_0 is given by equation 2.4 and $\omega(z) \left(= \omega_0 \sqrt{1 + (z/z_0)^2} \right)$ is the beam radius in terms of the Rayleigh range, z_0 . Plots of the potential at the beam focus in terms of radial cross-section of the beam for various m_f sublevels of the $F_g = 2$ hyperfine ground state are shown in figure 2.8 for two cases of FORT laser detuning; when the FORT laser is to the red of both the D_1 and the D_2 transitions and when the FORT laser lies in between these two transitions.

In order to achieve a fully polarised atom, confinement to just one magnetic sublevel is necessary. The non-degeneracy of the internal spin states due to the circularly polarised laser field makes this possible. As shown in figure 2.7, initially the FORT laser is red detuned with respect to both the D_1 and the D_2 transitions. At such a FORT laser frequency, for a given helicity of circularly polarised light, the FORT light tends to optically pump atoms into one of the fully stretched $m_f = 2$ sublevels of the $F = 2$ ground state. At this FORT frequency, this is shallowest potential. It can be confirmed that the atoms are only in this particular sublevel by performing a trick, which involves switching the frequency of the laser light. With the sign of the circular polarisation fixed, when the FORT laser frequency lies in between the D_1 and D_2 transitions (but not too close to the D_2), the sign

of the second term in equation 2.4 changes. The FORT light still tends to optically pump atoms into the same fully stretched $m_f = 2$ sublevel of the $F = 2$ ground state, but at this FORT laser frequency this is now the deepest potential, from which atoms are not readily lost. It is clearly shown in figure 2.8 how the depth of the FORT potential for the various m_f sublevels of the $F = 2$ ground state changes with the detuning of the FORT beam with respect to the D_1 transition. With the new FORT detuning, the laser is now to the blue of the D_1 transition and the resulting positive energy shift for the D_1 ground state sublevels consequently means that atoms are repelled from these ground states. This is except for the fully stretched $m_f = 2$ sublevel in the $F = 2$ ground state because with a perfectly circularly polarised laser field, this state has zero coupling to the D_1 excited states. This fully stretched sublevel still couples to the D_2 excited states and the D_2 ground state energy shift is still negative as the FORT light is still to the red of the D_2 transition. Atoms are thus attracted to this one internal spin state only. This idea was first put forward by the group of C. E. Wieman at JILA[26].

Achieving perfectly circularly polarised light is difficult. Less than perfect helicity limits the level of polarisation that can be achieved with the optical pumping method. It is therefore, important to consider exactly how this would limit the function of a CFORT. When the FORT is to the red of the D_1 transition it is necessary to wait for CFORT photon scattering to spin polarise the sample sufficiently through optical pumping. The quality of the circularly polarised light will determine what percentage of the population will end up in the fully stretched sublevel. When the laser wavelength is jumped to the blue across the D_1 transition, only those atoms in the maximally spin

polarised state are trapped. If the helicity of the light is less than perfect then this fully stretched state will still be weakly coupled to the D_1 excited states. Whilst loss will occur from the remaining atoms in the fully stretched sublevel, limiting the trap lifetime, the polarisation of the sample will be unaffected.

(a) FORT detuning=3nm to the red of the D_1 transition. (b) FORT detuning=1nm to the blue of the D_1 transition.

Figure 2.8: The FORT potential at the beam focus as a function of radial distance from the centre of the beam for the various different m_f sublevels of the $F = 2$ hyperfine ground state, where the FORT beam is to the red of the D_1 transition in (a) and in between the D_1 and D_2 transitions in (b). This is for perfectly circularly polarised light, $\epsilon = 1$.

Chapter 3

The Magneto Optical Trap (MOT)

3.1 The Experimental Setup and Optimisation of the MOT

3.1.1 The MOT Beams

The MOT beams are produced by a Coherent 899-21, a commercial CW Titanium Sapphire ring laser. It has a typical power output of 1.1W, at a wavelength $\approx 767nm$, the D_2 transition in ^{39}K . Unfortunately, this is in the region of an Oxygen molecular resonance and results in a loss of power unless the laser cavity is purged with nitrogen[19]. The pump source is provided by an Argon Ion laser, operating at multi-lines visible and at 14.5W full power. Stability of the MOT is achieved by frequency locking the laser light. The 899 is externally frequency locked to a potassium cell using saturation spectroscopy[27]. One cavity mode can be selected and a single frequency can be chosen by tuning the intra-cavity optics such as the bi-refrigent filter and the thin and thick etalons. The MOT beam setup is shown in figure 3.1.

Figure 3.1: The MOT beam setup.

The laser light is split in two and each of these beams is passed through an acousto-optical modulator (AOM)¹, in order to provide the trapping and repumping light at the necessary frequencies. The trapping light is detuned with respect to the $D_2F_g = 2$ to $F_e = 3$ transition and the repumping light is detuned with respect to the $D_2F_g = 1$ to $F_e = 2$ transition as shown in figure 2.4. DAC voltages are supplied to the AOMs, in order to remotely control their modulation and RF inputs. The AOMs are set up in a double pass

¹An AOM is a Bragg diffraction device that can be used to control the power, frequency or spatial direction of a laser beam with an electrical drive signal. It is based on the acousto-optic effect, i.e., the modification of the refractive index by the oscillating mechanical pressure of a sound wave. A piezoelectric transducer is used to excite a radio-frequency sound wave inside a transparent crystal. Light can then be diffracted at the periodic refractive index grating generated by the sound wave. The scattered beam has a slightly modified optical frequency (increased or decreased by the frequency of the sound wave) and a slightly different direction. The frequency and direction of the scattered beam can be controlled via the frequency of the sound wave, while the acoustic power allows the control of the optical powers.

configuration, in order that the power and frequency of the two beams can be varied without affecting the alignment of the MOT. All of the beams are either focused or telescoped down before going through the AOMs, in order to use only the active area of the AOM crystal. Telescopes are also used to keep the trapping and repumping beams of a similar diameter.

These two beams are recombined on a polarising cube and then split to form three separate beams, which are aligned into the MOT bulb in the three orthogonal directions. These beams are retro-reflected off mirrors on the other side of the bulb, in order to achieve the three sets of counter-propagating beams, which are necessary to form the optical molasses. In each arm of the MOT, the beams are overlapped with their retro-reflections, which are balanced in power by slightly over focusing the more dissipated beams, which pass through MOT bulb twice. Quarter wave plate retarders are also inserted into each arm of the trap to produce circularly polarised light of the required helicity. After laser light is transported to the MOT bulb from the laser head, the beams are elliptical, with major and minor diameters of 21mm and 12mm respectively. This results in maximum intensities in each arm of the trap of $10mW/cm^2$ for the trapping light and $12.2mW/cm^2$ for the repumping light, compared to the saturation intensity of these trapping and repumping transitions which is approximately $1.77mW/cm^2$.

3.1.2 The Trapping Chamber and Source of Potassium

The MOT bulb is a pyrex cell connected to an ion pump, it is an ultra high vacuum system with a pressure of 10^{-9} Torr. The bulb is constructed with good optical quality windows, through which the MOT laser beams can pass relatively unperturbed. Potassium vapour is produced in the cell by a dispenser, which consists of potassium chromate housed in a ZrAl alloy, through which a current is passed. The MOT beam frequencies are setup to trap ^{39}K because it is the most abundant isotope in the vapour (93.26 percent) and should therefore result in a higher number of atoms trapped. A dryfilm coating on the inside of the MOT bulb enhances the collection efficiency[28].

3.1.3 The Magnetic Field

The Anti-Helmholtz coils are placed either side of the MOT bulb in the vertical plane. They produce a modest field gradient of around 10 Gauss per cm along this vertical axis. The point of zero field and hence the centre of the trap can be adjusted by superimposing DC fields on the spherical quadrupole field. These DC fields, which are on the order of a few Gauss, are produced by two additional sets of Helmholtz coils around the x and y horizontal axes. However using these x and y trim coils, by varying the current flowing through them, distorts the shape of the trap as it moves far from its natural centre. A photograph of the MOT bulb, the laser beam optics and the magnetic field coils can be seen in figure 3.2.

Figure 3.2: A photograph of the MOT bulb, the laser beam optics and the magnetic field coils. The Anti-Helmholtz coils are the large black coils in the vertical plane and the trims coils are the green and grey, smaller coils in the other two planes.

3.1.4 Optimisation of the MOT Parameters

In order to load the FORT effectively, it is necessary to produce a MOT with as many atoms as possible, which are as cold as possible. These two criteria cannot be satisfied in one step. Therefore, the MOT is loaded in two stages; the maximum number of atoms are collected during a build stage, then the parameters of the MOT are changed, in order to cool the loaded atoms during a cooling stage. The number of atoms trapped in the MOT is determined by the amount of fluorescence emitted from the atoms when

they are illuminated by resonant probe light. The fluorescence is collected on a charge-coupled-device array (CCD camera). The camera has $192(\text{H}) \times 165(\text{V})$ active pixels in a 2.64mm square area. The camera is externally triggerable and comprises of a two lens system; one of focal length 100mm and a zoom lens with variable focal length. Between the two lenses are placed two filters to suppress unwanted background. There is a 1nm wide, 3-cavity, interference filter centred on the D_2 transition. Where the light is parallel, it provides 49 percent transmission at the D_2 and has less than 10^{-4} transmission at the D_1 . There is also an RG695 long-pass filter to suppress room light.

The atoms are illuminated using the MOT light itself as the probe. This exposure stage was first optimised to achieve the largest signal possible. In order that the amount of fluorescence reflects the number of atoms in the trap and not the frequency of the light which is illuminating the atoms, all pictures are taken with the MOT beam frequencies set to standard frequencies. In order to scan the MOT beam power and frequency during the various stages effectively, it is important to optimise the AOM efficiency by adjusting the Bragg angle to give power which is as constant as possible across the full frequency range. The trapping and repumping light are optimised individually. The trapping light can be scanned over a 65 MHz range and the repumping light can be scanned over a 115MHz range.

3.1.5 The Scan Procedure

- A picture is taken of the detection region under the conditions of the exposure stage; the MOT light is on, but the magnetic field is off.

This background signal is used to subtract off scattered light from the un-trapped vapour in the bulb.

- Atoms collect in the MOT during a 3s build stage.
- Loaded atoms are cooled during a 200ms cooling stage.
- Atoms are illuminated with the MOT light and a picture is taken with an exposure time of 10ms.
- In order to eliminate residual effects, the MOT is completely switched off between steps of a scan.

Note, when optimising the MOT cloud for temperature, the trap is completely switched off for a finite period of time. This is called the MOT-off time. After some time has elapsed, the warmer atoms, which have greater velocities, will have escaped the trapping region. This leaves only the colder, slower moving atoms. In principle it is important that the magnetic field is switched off a few ms before the laser fields. This is because the short resulting optical molasses can establish the lowest possible atom temperatures via sub-Doppler cooling[29]. There is a pause of 1.2ms to allow the magnetic field to switch off. Also from experience it was found that turning off the magnetic field and the MOT light together expelled many atoms.

3.1.6 Results of Optimisation

The results of optimisation of the MOT parameters are summarised in table 3.1 and the results of the frequency optimisation are displayed in figure 3.3.

Figure 3.3: The optimum MOT beam frequencies for the build, cooling and exposure stages. Frequencies are shown about the centre of gravity of the fine structure of ^{39}K in MHz. The various D_2 transitions in ^{39}K are shown as points of reference.

The trapping light is very close to resonance during the exposure stage, only one third of a linewidth to the red. The repumping light is also very close to resonance, at 2.5 linewidths to the red. These very small detunings, with both beams at full power, result in a high probability of photon scattering and hence a large amount of fluorescence. An expression for the photon scattering rate is given by equation 4.2.

During the build stage, the trapping light is further to the red, 4.2 linewidths detuned, but the repumping light is in a similar place, at 2.8 linewidths red-detuned. The larger detuning of the trapping light provides a larger atom velocity capture range. When the trapping light is further red-

detuned, it is able to compensate for larger Doppler shifts and can therefore interact with the faster moving atoms, cooling them down. Again the beam intensities are at a maximum for maximum probability of scattering.

The MOT beams are at full power throughout both the exposure and the build stages. However there is a difference in measured intensity between these stages because the AOM efficiency is not quite constant across its full frequency range. Consequently, there is a noticeable efficiency and therefore power reduction at the extremes of the frequency range.

From optimising the cooling stage, it is clear that there are two trapping light frequencies which produce noticeably cold MOT clouds. The temperature of these clouds has been determined and the details of these measurements can be found in section 3.2.1. There is a cold MOT cloud when the trapping light is just to the red of the trapping transition, at 1 linewidth detuned. Also there is a cold MOT cloud when the trapping light is further to the red, outside of the $F_g = 2$ to $F_e = 1, 2$ or 3 manifold, at 6.7 linewidths detuned. A considerably colder MOT cloud is produced when the trapping light is close in to the trapping transition. Here the repumping light is 6.5 linewidths red-detuned. The trapping light intensity is reduced to 48 percent of full power and the repumping light intensity is reduced to 7 percent of full power. For the warmer MOT cloud, outside of the manifold, the choice of repumping frequency seems to be fairly arbitrary as long as it is in the region of 1.8 linewidths red-detuned. The trapping light intensity is reduced to 6 percent of full power and the repumping light intensity is reduced to 1 percent of full power. Clearly the repumping light must be a source of heating as it is necessary to reduce it greatly in both cases. However, some level of

repumping light intensity is critical in order to sustain a MOT.

Table 3.1: Summary of the MOT optimisation results, cooling 1 is the very cold cloud just to the red of the trapping transition and cooling 2 is the cold cloud to the red of the $F_g = 2$ to $F_e = 1, 2$ or 3 manifold. The detunings are with respect to the trapping and repumping transitions. The intensities must be distributed between the three arms of the MOT.

Stage	Trapping Light		Repumping Light	
	Detuning/ γ	Intensity/ $\frac{mW}{cm^2}$	Detuning/ γ	Intensity/ $\frac{mW}{cm^2}$
Build	4.2	31.5	2.8	28.9
Cooling 1	1	14.2	6.5	2.5
Cooling 2	6.7	1.9	1.8	0.6
Exposure	0.3	24.9	2.5	32.5

3.2 The Characterisation of the MOT

3.2.1 Measuring the Temperature of the MOT Cloud

In order to get the highest FORT loading efficiencies, it would be preferable to transfer atoms from the coldest MOT achievable. Two local temperature minima have been identified and their temperatures can be determined by measuring the velocity of the atoms within the clouds. This was carried out using two independent methods, release and recapture and free expansion of the cloud. However, it must be emphasised that the former method, which involves much simpler data analysis to extract a result, was primarily used as a real time diagnostic for efficient temperature minimisation. Its results are very model dependent and therefore are unreliable as an absolute temperature measurement.

3.2.2 Method One: Release and Recapture

Despite its limitations, this is a commonly used method for temperature measurements[30]. Atoms collect in the MOT in the usual way during a build stage. The power and frequency of the MOT beams are set to the optimised values for the cooling stage, in order to produce one of the cold cloud candidates. The trapping forces, the MOT light and the quadrupole magnetic field, are switched off. The cloud expands due to ballistic expansion, the atoms in the cloud start to spread out at a rate determined by their velocity distribution. After variable lengths of time, the atoms which are still remaining in the trapping region are detected by turning the trapping forces back on. This assumes that any atoms in that region are re-trapped. The cloud expansion was modelled and the resulting theory for the number

of atoms in the trapping region as a function of time was fit to the data, with the initial cloud temperature as a free parameter.

It is assumed that the initial velocity distribution of the atoms is described by the Maxwell-Boltzmann distribution[3] given by

$$N(v)d^3v = \left(\frac{m}{2\pi K_B T}\right)^{3/2} \exp\left(\frac{-m(v_x^2 + v_y^2 + v_z^2)}{2K_B T}\right) d^3v, \quad (3.1)$$

where m is the mass of the ^{39}K atoms, $K_B (= 1.38066 \times 10^{-23} \text{ J/K})$ is the Boltzmann constant and v_x , v_y and v_z are the velocity of the atoms in each of the three dimensions resulting from the system of atoms being in equilibrium at a temperature, T . It should be noted that a MOT cloud is not really in equilibrium with a bath at temperature, T , but it nonetheless does produce a Maxwell-Boltzmann-like distribution. The integral of equation 3.1 over a velocity interval results in the average number of atoms in the system whose velocities lie within that range. Using Newton's equations for constant acceleration, equation 3.1, which is in terms of velocity space, can be transformed into position space[31]. The number of atoms in the trapping region as a function of time can thus be determined by integrating the resulting expression over the trapping region.

It is assumed that the MOT cloud is isotropic, that the cloud expands in the same way, and hence the temperature is the same, in all dimensions. The influence of gravity on the cloud as it expands is not included. It is justified to neglect gravity as the velocity increase which it produces in the vertical plane is 3 orders of magnitude smaller than the initial velocity of the atoms. It is also assumed that there is no friction in the high vacuum system because the low density background vapour would result in few atom-atom

collisions. Two other assumptions are made in order to build up a cloud expansion model, both of which have a large impact. They are concerned with the spatial distribution of atoms within the cloud before it is released and the form of the capture volume.

Initially, atoms are spread out over the whole MOT cloud volume. If the cloud is assumed to have a Gaussian cross-section in all dimensions, the origin is the most probable location for the atoms. Consequently, the unexpanded cloud can be crudely represented by a delta function, a point cloud, at the centre of the cloud region. In order to make this method more accurate, a more precise model should be considered, with details such as finite cloud size, varying atomic density distributions and asymmetrical cloud shapes.

The trapping region defines the integration region, so its definition is critical. The trapping region was defined as the spatial region where the three cylinders of the three pairs of MOT beams overlap. It is however quite possible that atoms which lie in a single pair of MOT beams could also be re-trapped. In order to simplify the limits of integration, they have been determined by calculating the cross-sectional area of the elliptical MOT beams and generating a square with the equivalent area. This results in a cubic trapping region. With this method, the measurement of the size of the MOT beams is the main source of experimental uncertainty. Their size is known to the nearest millimeter, therefore errors on the temperature values, resulting from the un-weighted fits, were assigned by varying the integration region by this amount and seeing the effect on the fit.

Many of these model assumptions, which result in systematic errors, can be eliminated by using the following method of free expansion.

3.2.3 Method Two: Free Expansion

The aim of this method is to obtain an accurate absolute temperature measurement. The experimental procedure is very similar to that for the release and recapture method, except that during the exposure stage, the quadrupole magnetic field is not switched back on. The cloud is merely illuminated with the molasses light and the atoms are consequently not re-trapped. Pictures of the expanded cloud are taken at various MOT-off times. By looking at the projections of the CCD camera pixel brightness in each of the two camera dimensions, cloud profiles are obtained. These were fit to Gaussian functions, in order to assign a diameter to the cloud. The details of the lens system on the camera were used to convert the fit results from the number of camera pixels to millimeters. Examples of Gaussian fits for determining the cloud width, for both possible cold clouds at various expansion times, are shown in figure 3.6. It must be noted that due to the nature in which the various elements of the experiment are triggered, it is not possible to image the cloud immediately after the trapping forces have been turned off, effectively when the MOT-off time is equal to zero. Therefore, even in the first image recorded, the cloud has had time to expand a finite amount.

Again it is assumed that the initial velocity distribution of the atoms is described by the Maxwell-Boltzmann distribution. Again gravity and friction are neglected. The diameter of the cloud, d , is given as a function of time, t , by

$$d(t) = 2v_{average}t + d_{initial}, \quad (3.2)$$

where the factor of 2 describes the fact that atoms travel out from their initial positions in both directions and the average atom velocity, $v_{average}$, is

calculated by integrating the one dimensional Maxwell-Boltzmann velocity distribution (equation 3.1) from zero to ∞ , where the equilibrium temperature, T , is the initial MOT cloud temperature. The advantage of this method is that a limited number of assumptions are made, the initial cloud size is now a free parameter in the fit along with the temperature. It is possible to assign different temperature values to the different dimensions of the cloud and it is not necessary to know the MOT beam size to any accuracy.

3.2.4 Results of Temperature Characterisation

A summary of the temperature measurement results is shown in table 3.2.

Table 3.2: Summary of the MOT temperature measurement results. Cooling 1 is the very cold cloud just to the red of the trapping transition and cooling 2 is the cold cloud to the red of the $F_g = 2$ to $F_e = 1, 2$ or 3 manifold.

	Release and Recapture		Free Expansion	
	Temperature/ μK	Error/ μK	Temperature/ μK	Error/ μK
Cooling 1	81	10	408	33
Cooling 2	236	30	4874	370

Release and recapture resulted in a temperature of $81 \pm 10 \mu K$ for the MOT cloud with trapping light just to the red of the cooling transition (cooling 1) and $236 \pm 30 \mu K$ for the other MOT cloud with the trapping light to the red of the entire manifold (cooling 2). However with the limitations of this method already described these numbers must be considered a lower limit on the MOT cloud temperature. Plots of the number of atoms as a function of MOT-off time are shown in figure 3.4. The data points have been plotted along with three theory curves representing the resulting temperature from the fit and the error boundaries on this fit. The theoretical curve for a single temperature does not match the data perfectly, a combination of curves for different temperatures is necessary. Apart from the first 10-15 ms, the fit lies within the error bars, represented by the dashed lines.

The free expansion method gives the temperature of the cloud in the longitudinal plane (the horizontal plane in which the FORT beam lies) and it resulted in a temperatures of $408 \pm 33 \mu K$ for the cooling 1 cloud and $4.87 \pm 0.37 mK$ for the cooling 2 cloud. The fits for the MOT cloud diameter as a function of MOT-off time are shown in figure 3.5. The experimental

(a) Cooling 1.

(b) Cooling 2.

Figure 3.4: Fits of the number of atoms in the MOT as a function of MOT-off time. The Data points are displayed with theory curves for the resulting fit temperature and the error boundaries on this fit. (a) cooling 1 is the very cold cloud just to the red of the cooling transition and (b) cooling 2 is the cold cloud to the red of the $F_g = 2$ to $F_e = 1, 2$ or 3 manifold.

errors are shown as error bars on the data points and also the error on the fit result is illustrated by the dashed lines. Both fits clearly lie within the error bars and the error on the resulting temperature is approximately 8 percent for both clouds.

The data points which represent the larger clouds have larger error bars because as a cloud expands, it becomes less well defined. In figure 3.6 it is possible to see a small side lobe on the cloud, which becomes more obvious at larger expansion times. Consequently larger errors result when fitting the Gaussian functions. There is also a much weaker signal at larger expansion times because a lot of the atoms have escaped the trapping volume, therefore noise on the signal plays a larger role.

It is not surprising that the temperature results for the less reliable release and recapture method do not agree with those for the free expansion method. However they do both clearly indicate that the cooling 1 cloud, just to red of the trapping transition, is considerably colder. A two level model which predicts the Doppler cooling limit[32] suggests that the temperature should be minimised when the trapping light is red-detuned by half a linewidth from the trapping transition. The optimised detuning of the $408\mu K$ cloud is very close to this, one linewidth red-detuned. However the temperature of this cloud is well above the Doppler limit, $146\mu K$. A more complex theory, taking into account the whole hyperfine structure of the D_2 transition[33], predicts that sub-Doppler temperatures are possible, but high intensity MOT beams strongly limit the minimum temperature achievable. For the $408\mu K$ cloud the MOT beams are at approximately 8 times saturation intensity. Low temperatures have been achieved experimentally in a

(a) Cooling 1.

(b) Cooling 2.

Figure 3.5: Fits of the MOT cloud diameter as a function of expansion time (MOT-off time). The Data points are displayed with theory curves for the resulting fit temperature and the error boundaries on this fit. (a) cooling 1 is the very cold cloud just to the red of the cooling transition and (b) cooling 2 is the cold cloud to the red of the $F_g = 2$ to $F_e = 1, 2$ or 3 manifold.

(a) Cooling 1 cloud at 1.39ms

(b) Cooling 2 cloud at 0.69ms

(c) Cooling 1 cloud at 9.72ms

(d) Cooling 2 cloud at 5.56ms

(e) Cooling 1 cloud at 18.06ms

(f) Cooling 2 cloud at 10.42ms

Figure 3.6: Gaussian fits of the projection of the CCD camera pixel brightness in the longitudinal direction, which are used to determine the MOT cloud width at various expansion times. The camera calibration is 0.256mm per pixel. Cooling 1 is the very cold cloud just to the red of the cooling transition and cooling 2 is the cold cloud to the red of the $F_g = 2$ to $F_e = 1, 2$ or 3 manifold.

MOT environment with ^{39}K without specific sub-Doppler cooling techniques, just by reducing the MOT beam intensity to around saturation intensity[33]. This is a definite real possibility for improving the MOT cloud temperature. In fact although ^{40}K has a slightly larger hyperfine structure, allowing sub-Doppler cooling mechanisms to be effective, a cloud with a temperature of $50\mu\text{K}$ was measured[20].

Also shown in figure 3.6 are the determined cloud widths. It is clear that the $408\mu\text{K}$ cloud is not only colder, but also more compact. A denser cloud is preferable for FORT loading. In order to determine the unexpanded cloud size, it is necessary to image the cloud with the trapping forces on. A picture of the $408\mu\text{K}$ MOT cloud taken with the CCD camera during the cooling stage is shown in figure 3.7. The cloud is 1.2 by 2mm in size, therefore in the first few milliseconds the cloud expands substantially to the 5mm diameter obtained from the Gaussian fits.

Figure 3.7: A CCD camera picture of the $408\mu\text{K}$ MOT cloud taken during the cooling stage. The picture shows the whole camera field of view, which is 2.1cm square.

3.2.5 Measuring the Lifetime of the MOT

The lifetime of the MOT is defined as the average length of time an atom stays in the MOT. It is determined by switching the trap off and back on again and then measuring the number of atoms in MOT cloud as it builds in time, t . A simple exponential function is fit to the rising slope given by

$$\text{Signal} = A \left(1 - e^{-\frac{t}{\tau}} \right) \quad (3.3)$$

where τ is the lifetime of the MOT and A is the maximum number of atoms which are built up in the trap. An example of such a fit is shown in figure 3.8.

Figure 3.8: A fit of the number of atoms building in the MOT cloud as a function of time. The dispenser current = 4Amps.

To do this measurement, the control code is greatly simplified in order to make it run as fast as possible. It uses a very short build time of 200ms and it skips the cooling and MOT-off stages.

The lifetime of the MOT is dependent on the number of atoms in the vapour available to trap. This parameter can be controlled by changing the residual potassium vapour pressure in the trapping volume, by adjusting the current on the potassium dispenser. Turning the dispenser down should result in less atoms in the MOT bulb and consequently a better vacuum. This means that MOT atoms collide less frequently with atoms in the background gas and hence longer MOT lifetimes result due to reduced heating. This assumes that potassium vapour is the dominant gas in the vacuum, although it is likely that hydrogen outgassing occurs. The MOT lifetime as a function of dispenser setting is shown in figure 3.9.

The MOT lifetime at various levels of vacuum has been measured to aid the understanding of the FORT lifetime. Both traps will be limited by background gas collisions. Also included in figure 3.9 is a plot of the relative MOT fluorescence as a function of dispenser current setting. This is just to prove that increasing this current actually increases the number of atoms trapped in the MOT, while decreasing the lifetime.

(a) MOT lifetime.

(b) Relative MOT fluorescence.

Figure 3.9: (a) MOT lifetime and (b) relative MOT fluorescence as a function of potassium dispenser current. Note that the line passing through the data is not a fit and is to guide the eye only.

Chapter 4

The Far Off Resonance dipole force Trap (FORT)

4.1 The Experimental Setup of the FORT

4.1.1 Characterising the FORT Beam

The FORT laser beam is provided by a Coherent MBR-110, a commercial CW Titanium Sapphire ring laser. It produces up to 1.5W of power output at a wavelength in the region of the D_1 transition in ^{39}K , $\approx 770nm$. As with the 899 ring laser, used for the MOT beams, the cavity is purged with nitrogen. It has an Argon Ion pump source operating at multi-lines visible and at 11.5W. It is possible to achieve stability of the FORT beam near resonance by externally frequency locking the laser light to a potassium cell using saturation spectroscopy. When the FORT beam is far off resonance minor instabilities in the frequency should not have a huge effect. A single cavity mode is used, and the laser frequency is tunable using the bi-refrigent filter and the thin etalon. The wavelength is measured with a Burleigh Wavemeter Junior, a Michelson interferometer, to an accuracy of 10-20GHz. The beam is passed through an AOM and the first diffraction order is used, which is typically 50 percent of the input power ($\approx 0.7W$).

It is necessary to focus this single Gaussian laser beam down to a diffraction limited spot. The lens selection is limited by the MOT bulb itself. Its

physical dimensions determine how close the lens can be to the centre of the MOT bulb, where the focus of the beam should lie. For the smallest waist, where deep traps can be achieved at low laser power, the focal length needs to be as small as possible. An achromatic cemented doublet lens of 200mm focal length is used. The lens is set on a translation stage fixed between two parallel rails, such that fine adjustments of the beam focus position with a micrometer screw can be made whilst keeping the lens perpendicular to the beam at all times.

A CCD camera was used to characterise the laser output. It uses a high resolution progressive scan chip with $1360(\text{H}) \times 1024(\text{V})$ $4.65\mu\text{m}$ square active pixels and is controlled by the 'WinCamD' software. This results in a measurement accuracy of less than $1\mu\text{m}$. The beam could be monitored and a log recorded over a given time interval. All the measured parameters are averages of this log. The beam profile was checked. It is vital that there are no distortions if a diffraction limited spot is to be achieved. It is a nice Gaussian which is in a TEM00 mode. The quality of the gaussian fit is 93 percent at the beam waist.¹ The pointing stability at the waist was also checked as the laser is transported a large distance of 3 to 4m from the laser head to the MOT bulb. It has a sufficiently small 0.7 micron mean deviation at the focus in a 20 minute monitoring period. These results are illustrated in figure 4.1.

The divergent properties of the beam were also investigated. Since an approximation was used to calculate the effect of the lens, an independent

¹The fit is performed by iteratively adjusting the height of the Gaussian until the total of the positive and negative differences between the actual profile and the Gaussian profile is zero. The percentage assigned to the fit = $1 - (\text{Sum of absolute differences} / \text{Gaussian profile area})$.

confirmation of the beam focus size and location after the lens was necessary, in order to check the final setup. The spot size was measured at various points along the beam from the output coupler. A fit was performed of the data to the Gaussian optics equation[34] for spot size, ω , as a function of distance along the beam, z . This expression is

$$\omega(z) = \left(\frac{z_0 \lambda}{\pi n} + \frac{\lambda z^2}{\pi n z_0} \right)^{1/2}, \quad (4.1)$$

where z_0 is the Rayleigh range, λ is the wavelength of the laser light and n is the refractive index of the medium through which the light propagates. The FORT beam waist was measured by carefully recreating the path length of the beam to the MOT bulb centre, in order to achieve a focus outside of the bulb. Measurements were also made to confirm that the optical elements in the beam path, such as the AOM and the optical windows of the bulb, do not adversely effect the beam quality. The glassblower-welded viewport was tested by using a lens of longer focal length and focussing the beam to a point beyond the cell. The beam is very symmetric and is focused to a waist of approximately $35.5\mu m$ in both the x and y planes. The exact fit results with errors are shown in table 4.1. The beam is non-astigmatic, i.e the foci in each plane are in the same place longitudinally. The effective focal length is $\approx 233mm$. A plot of the varying spotsize along the beam length is shown in figure 4.2. The fit also gives the Rayleigh range, $Z_0 = \frac{\pi n \omega_0^2}{\lambda}$, which is $\approx 5mm$. Over this range the spot size increases by $\sqrt{2}$. The AC Stark shift halves in magnitude, so this gives a rough indication of the effective trapping region for the FORT.

Use of a CCD camera for such a measurement relies on good beam at-

Figure 4.1: Pictures of the beam shape, the Gaussian fit for the beam profile at the waist and a plot of the pointing stability.

Figure 4.2: The fit of the varying spotsize of the MBR output along the length of the beam for both the x and y dimensions.

Table 4.1: Fit results for the characterisation of the FORT beam, including the waist size, ω_0 , the effective focal length of the lens, f and the Rayleigh range, z_0 .

Parameter	X Dimension	Y Dimension
ω_0	$35.4 \pm 0.7 \mu m$	$36.2 \pm 0.4 \mu m$
z_0	$5.1 \pm 0.2 mm$	$5.3 \pm 0.1 mm$
f	$233 \pm 0.2 mm$	$233 \pm 0.1 mm$

tenuation due to the high intensity of the FORT beam, especially at the focus $\approx 18.2 \times 10^6 mw/cm^2$. For an accurate characterisation, the attenuation method should not effect the beam. The best option is a half waveplate retarder followed by a polarizing beam splitter. Laser quality optics with wavefront distortion $\lambda/10$ were used.

Based on the conclusions of experiments carried out at JILA[24] with a rubidium FORT, it is critical for good loading efficiencies that the FORT beam be linearly polarized to a very high degree. Mirrors can induce large angle and polarization dependent phase shifts in reflected beams. They are not polarization preserving unless perfect planes of reflection are achieved. Therefore good linear polarization is achieved using a half wave plate and a polarising beam splitter just before the bulb, the same elements which are used to attenuate the beam.

4.1.2 The Resulting Trap Depth

At JILA the rubidium FORT was also loaded from a MOT. This MOT cloud had temperatures in the region of 30 to $120 \mu K$ [24]. Typical FORT trap depths which resulted in successful loading were around 2mK. Therefore in this work, with a substantially hotter MOT cloud, the FORT beam parameters will be set up in order to achieve at least 2mK FORT trap depths.

For a stable FORT cloud, it is necessary not only to have a deep trap in order to collect as many atoms as possible from the tail of the Maxwell-Boltzmann distribution, but also it is important to limit all possible heating mechanisms. The spontaneous scattering of photons due to real absorption of the trapping light results in a heating effect. This process, which is discussed in more detail in section 4.3.6, must be considered when choosing values for the FORT beam parameters. A two level expression for the scattering rate[3], Γ_{sc} , is given by

$$\Gamma_{sc} = \frac{\frac{I_0 \gamma \pi}{I_s}}{1 + \frac{I_0}{I_s} + \left(\frac{2\delta}{\gamma}\right)^2}, \quad (4.2)$$

where $I_0(= \frac{2P}{\pi\omega_0^2})$ is the laser beam intensity in terms of the total beam power, P , and the beam waist, ω_0 , for a gaussian beam. $I_s(= \frac{2\pi^2\hbar c\gamma}{3\lambda^3})$ is the saturation intensity for the relevant optical transition and is given in terms of the laser wavelength, λ . δ is the detuning of the laser light from the atomic transition and γ is the natural linewidth of the relevant optical transition, which is the spontaneous decay rate for the excited state of the atom. In ^{39}K $\gamma D_1 = 6.08MHz$ and $\gamma D_2 = 6.16MHz$.

In order to limit the scattering rate, the FORT beam should be operated as far off resonance as possible because the scattering rate is inversely proportional to the beam detuning squared. However, the scattering rate is less strongly dependent on the beam intensity, so the loss of trap depth can be compensated for by having the FORT beam as intense as possible. This means having the tightest possible waist and running at the maximum possible power. To recall the relationship between these parameters and FORT trap depth see equation 2.4. The trap depth is proportional to the beam intensity and inversely proportional to the beam detuning. With the beam

intensity fixed, a plot of the FORT trap depth as a function of FORT wavelength for the various m_f sublevels in the $F = 2$ hyperfine ground state is shown in figure 4.3 for a perfectly circularly polarised FORT beam.

Figure 4.3: The FORT trap depth as a function of FORT wavelength for the various m_f sublevels in the $F = 2$ hyperfine ground state for perfectly circularly polarised light.

Limiting the scattering rate by running far off resonance is essential to achieving a FORT. Initial attempts to load the FORT were unsuccessful because a laser, with much lower power, was used. The maximum power output was only 0.3W. In order to achieve a 2mK trap depth, the FORT beam had to run much closer to resonance, in the region of 1nm, and larger heating rates resulted. Plots of the FORT trap depth for linearly polarised

light for both the power available before and after the use of the MB are shown in figure 4.4. This plot focuses on the wavelength region of interest for this work, which is to the red of the D_1 transition.

Figure 4.4: The FORT trap depth as a function of detuning from the D_1 transition for linearly polarised light, with the power available before and after the use of the MBR.

The current FORT beam has a maximum power output of 0.7W and is focused to a $35\mu\text{m}$ waist. The resulting FORT trap depth is 2mK for ^{39}K atoms if the FORT detuning is 3nm to the red of the D_1 transition. This is 10^6 linewidths off resonance and results in an AC Stark shift of $\approx 40\text{MHz}$.

4.2 FORT Loading and Diagnostics

Once the atoms are cooled into a dense MOT cloud, they can be loaded into the FORT by simply overlapping the FORT focus continuously with the atomic cloud of the MOT. The MOT-FORT setup is shown in figure ??.

Figure 4.5: The MOT-FORT setup.

4.2.1 The Alignment of the FORT and the MOT

The FORT beam is aligned through the centre of the MOT bulb. The lens is fixed to a translation stage, which is mounted between two parallel rails, in order to keep the lens perpendicular to the beam. With the effective focal length known, the lens is carefully placed such that the FORT focus is at the bulb centre. The Helmholtz coils apply a uniform, magnetic trim field,

which displaces the location of the zero of the MOT quadrupole field and hence the MOT cloud location. Keeping the FORT beam fixed, the position of the MOT cloud is moved around in all three dimensions by controlling the current supplied to the three sets of magnetic field coils. Using an IR viewer to clearly see the MOT cloud, it is also overlapped with the bulb centre. All of this initial alignment is done by hand, using apertures. Confirmation of alignment is achieved by disturbing the MOT cloud with an on resonance FORT beam. Depending on the detuning and the power of the FORT beam, it is possible to either produce a contrail, a line of fluorescence through the MOT cloud, or completely destroy the cloud. Later a more precise automated alignment is performed, which is optimised on the FORT signal. The position of the MOT cloud in space strongly depends on the MOT beam frequencies. For this reason it is important to perform the overlap of the FORT focus with the cooling stage cloud.

4.2.2 The Sequence for Loading the FORT from the MOT

The loading procedure is split up into four key stages:

- The MOT fills during the 3s BUILD STAGE.
- The FORT is loaded from the $408\mu K$ cloud during a 200ms LOADING STAGE.
- The MOT cloud falls out of the trapping region during a STORAGE STAGE which is typically 200ms.

- The FORT cloud fluorescence signal is distinguished from any MOT background signal during a 10ms camera EXPOSURE STAGE.

The whole loading sequence is outlined in figure 4.6.

Figure 4.6: A time diagram of the duty cycle, including the MOT light, the quadrupole field, the FORT beam and the ready and fired signals from the CCD camera.

The FORT is on during the build stage, but because of its small volume, it has a negligible effect on the number of atoms collected in the MOT cloud. The previously called “cooling stage” now constitutes the “loading stage”. The MOT beams provide a cooling mechanism in the overlap region and cool the atoms sufficiently to fall into the FORT. During the storage stage the MOT light and the quadrupole magnetic field are switched off. The atoms are held in the FORT long enough for the MOT cloud to fall out of not just the detection region, but the MOT trapping region, before the exposure stage. This should eliminate any residual MOT cloud effects because the

FORT cloud is detected by switching the MOT back on and re-trapping any atoms in the MOT beam region. Less than one percent of the MOT atoms are left after 200ms. From the decay of the MOT signal with MOT-off time shown in figure 3.4, when one percent of the MOT atoms are left this is the tail of the decay. Therefore extending the storage stage would not reduce the MOT background much further compared to the reduction already achieved. This storage time was chosen because the residual MOT signal was small enough that a FORT signal could be seen above it.

The FORT beam goes off during the loading stage every other loading cycle. The FORT beam passes through an AOM and is switched on and off by turning the RF power to the AOM on and off. The AOM is flint glass and has a 3.5mm active area. It is possible to almost completely extinguish the first diffraction order. The region of interest on the camera was adjusted to minimise the FORT off signal. By subtracting the FORT beam off signal from the FORT beam on signal, the contribution from atoms in the background vapour which get re-trapped is removed. This is a small correction for optimised FORT signals, but a substantial correction when the FORT signal is small. The line of view of the camera is perpendicular to the FORT beam in order that the transverse and longitudinal properties of the FORT cloud can be observed. The power and frequency of the MOT beams during these various stages are set to the previously optimised values. All MOT and FORT parameters are controlled by DAC voltages and TTL logic signals from ISA boards in a PC, using C code.

4.2.3 Scattered Light Background

The high intensity, D_1 FORT beam creates a scattered light background. Despite the 1nm D_2 interference filter on the camera, the FORT beam is switched off during the exposure stage to eliminate this possible background contribution. In addition this will mean that there is no AC Stark shift present due to the FORT beam during the exposure time to interfere with the probe light. In order to avoid fluctuations in the AOM crystal temperature, which will effect the functioning of the AOM, the FORT beam is predominantly left on during the duty cycle. Switching the beam on and off briefly does not cause the beam to steer.

4.2.4 Triggering

It is important to have the camera fire as soon as the FORT is switched off, so the FORT cloud does not have a chance to decay before it is detected. This is achieved by special triggering of the camera and the FORT beam with logic signals. The software calls the “ascam” routine. This routine tells the camera to get ready. The camera asserts a ready signal and then waits for an external TTL signal trigger. The ready signal ends when the camera fires. The camera is triggered with the inverse of the ready signal and the camera returns an exposing signal when it fires. Switching the FORT beam off is triggered with the “ored” inverse of the camera ready and the camera exposing signals. Consequently the FORT goes off $20\mu s$ before the exposure stage. All of these logic signals are displayed in figure 4.6.

4.2.5 The Initial Signal

With an initial rough alignment and the parameters of the FORT set to achieve a 2mK trap, the loading cycle was tried. The MOT-off time was set to 1ms in order to get an un-decayed MOT signal, which is used to deduce the percentage of MOT atoms loaded. Then the MOT-off time was set to 200ms, in order to get a signal after the MOT had decayed. The initial difference between the FORT on and the FORT off signals resulted in a collection efficiency of 0.09 percent of the MOT atoms. An example of the raw CCD fluorescence signal for the FORT beam on and FORT beam off is shown in figure 4.7. This was in fact the first time a FORT signal was achieved.

Figure 4.7: The CCD fluorescence signal for the FORT beam on and FORT beam off. This represents the first time a signal from atoms in the FORT was observed.

Once a FORT signal is present the zero magnetic field position and therefore the MOT cloud position is moved around in all three dimensions by

controlling the current in the three sets of magnetic field coils. The current in these coils is DAC controlled so that it can be scanned for precise optimisation of overlap of the two traps. Plots of the FORT signal for scans of the MOT position in the longitudinal and in one of the transverse dimensions are shown in figure 4.8. These are the two dimensions which can be observed with the CCD camera. It is therefore possible to convert the coil current setting into a position in space by looking at pictures of the MOT.

Both the vertical and horizontal dimensions always show a sharp peak when scanned. Whereas the longitudinal dimension shows a much wider peak, indicating that the overlap in the transverse dimensions is more critical. The longitudinal trap position must be known to within 2-3mm and the transverse trap position must be known to within 0.5mm in order to get any signal. Therefore the initial crude alignment is key to getting the trap to work. It is also worth noting that the optimum trap position is very sensitive to local magnetic fields. It was in fact possible to detect if the TRIUMF cyclotron main magnet was on, as it leads to an increase in the vertical magnetic field by half a Gauss. The scanning of the trap position in all three dimensions lead to an improved collection efficiency of 1.3 percent.

(a) Vertical dimension (black coils).

(b) Longitudinal dimension, along the FORT beam (grey coils).

Figure 4.8: The CCD fluorescence signal as a function of MOT cloud position for the longitudinal and one of the transverse dimensions, for FORT beam on and FORT beam off.

4.2.6 The Warmer MOT Cloud

Figure 4.9 shows two scans of the MOT trapping light frequency. In 4.9(a) the frequency is scanned during the cooling stage. No FORT light is present and the y-axis is the number of atoms re-trapped in the MOT after a 30ms MOT-off time. In 4.9(b) the frequency is scanned during the loading stage. The y-axis is the number of atoms re-trapped in the MOT after a 200ms MOT-off time for FORT beam on and FORT beam off. When the MOT trapping light is to the red of the entire $F = 2$ to $F = 1, 2$ manifold, the situation in principle is much more favourable in terms of the AC Stark shifts that take place, compared to when the light is just to the red of the trapping transition. The effect of the Stark shift, due to the FORT beam, on the atomic energy levels will cause the laser light, which is fixed in frequency, to appear to lie more to the red of the atomic transitions. Within the range of Stark shifts produced, there are no other transitions to the red of this manifold, thus eliminating the potential for the trapping light to end up blue detuned with respect to a transition, where heating within the trap will occur. Despite this theoretical advantage it was not possible to load the FORT from this much warmer MOT cloud. The two peaks in 4.9(a) clearly show the existence of two optimum places in frequency space for a cold MOT cloud. However, in 4.9(b) only one peak is visible, which represents a FORT signal. It is just to the red of the trapping transition.

At a temperature of 4.9mK (see section 3.2.1), this cloud might simply not be cold enough in order to load atoms into the FORT!

(a) MOT fluorescence signal as a function of the trapping light frequency during the cooling stage (MOT-off time = 30ms).

(b) FORT on and FORT off fluorescence signals as a function of the trapping light frequency during the loading stage (MOT-off time = 200ms).

Figure 4.9: Scans of the trapping light frequency during (a) the cooling stage and (b) the loading stage. Frequencies are in reference to the centre of gravity of the fine structure of ^{39}K . The three D_2 transitions within the ^{39}K $F_g = 2$ to $F_e = 1, 2$ and 3 manifold are shown as black dots on the x-axis.

4.3 The Characterisation of the FORT: Loading and Loss Rates

4.3.1 Measuring the FORT Collection Efficiency

The key factor which determines the FORT loading efficiency is the relative depth of the FORT compared to the MOT temperature. Having optimised the MOT parameters for the loading stage, the temperature of the MOT is fixed. It has been measured to be $408\mu K$. The FORT depth can be varied by changing the FORT beam wavelength, power and ellipticity. A brief study of the loading efficiency was carried out by varying these FORT parameters. The loading efficiency is also dependent on the number of atoms available to trap, i.e. the flux of atoms in the trapping volume. This is determined by the MOT cloud density, which remains constant by the fixed loading stage MOT parameters, and the effective FORT trapping region, which is also kept constant by fixing the FORT beam waist size. Loading can be aided by having cooling mechanisms active in the MOT/FORT overlap region. However, in this work no additional cooling schemes, beyond that provided by the MOT, were implemented.

The loading efficiency is defined as the percentage of MOT atoms initially collected in the FORT. Exponential fits were performed to the decaying FORT fluorescence signal versus MOT-off time, in order to assign a value for the FORT lifetime. See section 4.3.7. The number of atoms initially trapped, $A(t=0)$, was obtained by extrapolating these fits back to when the MOT-off time equals zero. The fluorescence amplitude has been interpreted in terms of the percentage of MOT atoms trapped by making a baseline measurement

of the fluorescence signal from the undecayed MOT cloud with the MOT-off time set to 1ms.

In order to prevent the CCD camera from saturating, these measurements were often taken at different camera F-stops. When the camera is at F-stop 1.2, the aperture on the camera is all the way open, with a maximum diameter of 50mm. However a 48.2mm diameter retaining ring for the lens attached to the front of the camera provides an extra aperture. Therefore the true F-stop of the camera was measured with a light source at this setting for accurate conversion between it and other F-stops. F-stop 1.2 to 5.6 required a multiplication factor of 1/15 and F-stop 1.2 to 8 required a multiplication factor of 1/25.

4.3.2 FORT Collection Efficiency as a Function of Wavelength

The frequency tunable MBR was adjusted in wavelength using the bi-refrangent filter and was monitored with the Wavemeter Junior. The linearly polarised light was maintained at as constant a power as possible, approximately 700mW.

The number of atoms trapped in the FORT as a function of FORT detuning from the D_1 transition is shown in figure 4.10. This plot provides convincing proof that a FORT exists. Consider figure 4.10(a) first, when the FORT beam is to the red of the D_1 transition. When the FORT beam is closer to resonance a deeper trap results and hence more atoms are trapped, up to 1.1 percent of the MOT atoms. However, it is not optimum just to place the beam on resonance, because the higher rate of FORT photon scat-

(a) The FORT is detuned between 1 and 20nm to the red of the D_1 transition.

(b) The FORT is detuned between 1.75 to 2.5nm to the blue of the D_1 transition.

Figure 4.10: The FORT collection efficiency as a function of both red and blue detuning from the D_1 transition. The FORT beam was linearly polarised and at a power of approximately 0.7W. Note that the two data points with zero collection efficiency in (b) are the result of no trap forming.

tering greatly increases heating of atoms within the FORT and shorter FORT lifetimes result, see section 4.3.6. Recall that the scattering rate scales with $\frac{1}{\delta^2}$, while the FORT depth scales with $\frac{1}{\delta}$, where δ is the FORT detuning (see equations 4.2 and 2.4 respectively). This is the fundamental property of a FORT. A balance of these effects must be achieved in order to have the maximum number of atoms trapped for the longest time.

In principle, at $t = 0$, heating effects should not play a role in the number of atoms trapped. This is because in theory, no amount of time has elapsed in which the trap can decay. However, in practice this is not the case due to the nature in which the number of atoms in the FORT is diagnosed. After the trapping forces have been switched off and before the FORT cloud is imaged, the cloud has always had a finite amount of time in which to decay. Extrapolating the exponential fit from $t = 200\text{ms}$ (MOT-off time) back to $t = 0$ is an attempt to overcome this problem. However, the data point closest to resonance, which has a slightly lower value, is most likely an artifact of this.

The D_1 and the D_2 transitions are only 3.5nm apart in ^{39}K , hence when the FORT beam wavelength lies in between these transitions, figure 4.10(b), it is always closely detuned with respect to a resonance. The crucial point is the fact that the FORT is now blue-detuned with respect to the D_1 transition. The D_1 ground states will have a positive energy shift and an effective potential barrier will result. There is now a repelling force away from high intensity laser field regions. Unless the attractive force which is due to the FORT laser lying to the red of the D_2 transition dominates, no trap will form. 0.9nm to the blue of the D_1 transition no trap appears to form because the

repulsive potential dominates. The best loading efficiency in this wavelength region is 0.4 percent, achieved 2nm to the blue of the D_1 transition. This is much lower than efficiencies observed to the red of the D_1 transition. The best efficiency does not lie just to the red of the D_2 transition again because of the nature of the measurement. It is likely that heating due to FORT photon scattering, which is always substantial in this region, influences the much smaller efficiencies observed and maybe explains why no FORT appears to form at 0.81nm to the red of the D_2 .

4.3.3 FORT Collection Efficiency as a Function of Power

So far results have been discussed in which the FORT beam has been operating at full power. In order to observe the effect of the FORT beam power, the beam was attenuated using the same method of attenuation as was used during the characterisation of the FORT beam (a $\lambda/2$ wave plate and a polarising beam splitter). This method causes minimal disruption to the beam quality. However, decreasing the power greatly reduces signal strengths. In order to compensate for this, the MOT cloud was allowed to build for twice as long, up to 6s. More atoms are consequently collected in the MOT, which can then potentially be loaded into the FORT. The FORT light is linearly polarised and is detuned 3nm to the red of the D_1 .

The FORT collection efficiency as a function of FORT beam power is shown in figure 4.11. The number of atoms loaded increases with power. This is not surprising because the FORT trap depth is linearly proportional to power (equation 2.4). Unfortunately in this work the MBR, which provides

Figure 4.11: The FORT collection efficiency as a function of power. The FORT beam was linearly polarised and at a detuning of 3nm to the red of the D_1 transition.

the FORT light, is already operating at the maximum possible power output with the pump source available. The relatively low collection efficiencies achieved at present show the necessity of high power in the FORT beam in order to achieve measurable loading rates. Again increasing the power to achieve a higher collection efficiency also increases the heating effect due to FORT photon scattering. However, the effect is not so detrimental to the FORT lifetime compared with decreasing the detuning (equation 4.2).

4.3.4 FORT Collection Efficiency as a Function of Ellipticity

The ellipticity of the FORT beam, ϵ , is a parameter which characterises the level of polarisation of the beam. It is defined as

$$\epsilon = \frac{P_{max} - P_{min}}{P_{max} + P_{min}}, \quad (4.3)$$

where P_{max} and P_{min} are measured by placing a rotating analyzing polariser in the laser beam and recording the highest and lowest power transmitted through the polariser respectively. The polarisation of the beam can be varied by adding a rotating quarter wave plate to the half wave plate/polarising beam splitter setup. In this definition, $\epsilon = 1$ is perfect linearly polarised light and $\epsilon = 0$ is perfect circularly polarised light. The FORT light is detuned 3nm to the red of the D_1 transition and was maintained at a constant power of approximately 700mW.

The FORT collection efficiency as a function of FORT beam ellipticity is shown in figure 4.12. It is possible to load atoms directly into FORTs which have a range of different ellipticities. When the FORT light is elliptically polarised, optical Zeeman splittings lift the degeneracy of the ground state magnetic sublevels. Therefore the trap depth of each individual internal spin state varies with epsilon. Plots of the trap depth as a function of ϵ for the various m_f sublevels of the $F_g = 2$ and $F_g = 1$ hyperfine ground states are shown in figure 4.13.

The effective FORT trap depth would be the average trap depth of all the magnetic sublevels within the two hyperfine ground states, which, if the atoms are randomly distributed, is constant over the full range of ϵ from

Figure 4.12: The FORT collection efficiency as a function of ellipticity. The FORT beam was at a power of approximately 0.7W and at a detuning of 3nm to the red of the D_1 transition.

0 to 1. This should result in a constant number of atoms loaded into the FORT regardless of the level of FORT beam polarisation. Also heating due to FORT photon scattering should be constant across the range of ϵ because the scattering rate is not dependent on the polarisation of the FORT beam when averaged over m_f . The data show no obvious efficiency dependence on ϵ .

Real absorption of FORT photons will lead to the movement of atoms between sublevels and the timescale over which the FORT beam interacts with the atoms is such that an appreciable amount of this optical pumping can take place. Therefore to treat this problem properly, a full calculation

(a) $F = 2$ hyperfine ground state sublevels. (b) $F = 1$ hyperfine ground state sublevels.

Figure 4.13: The FORT trap depth as a function of ellipticity for the various m_f sublevels in the $F_g = 1$ and $F_g = 2$ hyperfine ground states.

of the distribution of the population among the internal spin states expected from optical pumping at various levels of ellipticity is required. The degree of optical pumping could be calculated with a full rate equation model. Thus the potential wells, representing the magnetic sublevels, could be averaged in a weighted way.

4.3.5 The Loading Curve

The best collection efficiency achieved so far is 1.3 percent. Unfortunately, even if such a loading efficiency could be achieved on-line with radioactive isotopes, it would not be sufficient for TRINAT's β decay experiments. For the spin asymmetry experiments an atomic sample with well defined polarisation is required. The overall polarisation of the sample depends on only on the polarisation of the FORT foreground, but also on the polarisation of atoms in the MOT background. The polarisation of this MOT background is much less well defined, so a minimum percentage of MOT atoms must be loaded into the FORT cloud so that the background from un-trapped atoms becomes unimportant. Currently about 0.3 percent of the MOT atoms provide a background. More atoms trapped would also result in better counting statistics.

In an attempt to improve the loading efficiency, the length of the loading stage was varied. This is the amount of time for which the cold MOT cloud is overlapped with the FORT focus. The number of atoms loaded into the FORT was monitored and a loading curve resulted. Such a curve for linearly polarised light ($\epsilon = 0.9993$) is shown in figure 4.14.

The number of atoms in the FORT increases rapidly and nearly linearly

Figure 4.14: The percentage of MOT atoms collected in the FORT as a function of loading time, for linearly polarised light ($\epsilon = 0.9993$). The FORT beam is 3nm red-detuned of the D_1 transition and has a power of approximately 0.7W.

in time until a maximum in the measured fluorescence signal is reached at around 55ms. At this point the loading saturates. The FORT signal just levels off and does not appear to decay. The timescale over which the FORT loads is very interesting. Reaching the optimum level of loading in as short a time as possible would be very beneficial for the ultimate use of this trap, which is the loading of radioactive potassium isotopes, which have half lives on the order of 1s. The loading signal saturates at a substantially shorter time than this and in fact at a shorter time than the 200ms which has been used up to this point as the standard loading time. The loading rate is currently not understood very well. Better understanding will certainly lead

to higher loading efficiencies. It is possible that the MOT light during loading decreases the FORT lifetime.

4.3.6 A FORT Lifetime Model

As previously stated, the FORT is a conservative potential. Therefore without any additional cooling mechanisms present, after atoms are collected in the FORT, the number of atoms trapped will decrease with time. This is due to heating effects, processes through which atoms gain enough energy to escape the potential well. The major sources of heating are the following two body events.

- Scattering of FORT light photons, where the rate depends on the intensity and the detuning of FORT beam (equation 4.2).
- Inelastic collisions between the cold trapped atoms. The rate will depend on the number of atoms trapped.
- Collisional processes with the room temperature background gas[35], which consists mostly of the un-trapped vapor, with a small component of hydrogen. The rate will depend on the amount of background gas present.

The amount of potassium in the bulb can be controlled by changing the current setting on the potassium dispenser. This will effect the amount of hydrogen outgassing and consequently the level of vacuum in the bulb.

Fluctuations in the FORT beam intensity and pointing instabilities could also result in heating[36]. The amount of heating required in order for the atoms to escape depends on the shape and depth of the optical potential. A

quantitative way to characterise the loss rate of the FORT is to measure the FORT lifetime.

In order to begin to understand the various contributions to the FORT decay rate, a model for the FORT lifetime was set up. It is based purely on one heating process, the spontaneous scattering of FORT photons, and on the changing trap depth.

Doppler cooling resulting from a net atomic momentum change is opposed by heating due to fluctuations in the radiation force. These fluctuations are caused by the random nature of the spontaneous scattering of trap photons. Fluctuations in absorption correspond to an increase in the thermal energy by exactly the recoil energy, E_{rec} , per scattering event. This occurs in the propagation direction of the light field and is anisotropic. $E_{rec} = K_B T_{rec}$, where K_B is the Boltzmann's constant and T_{rec} is the recoil temperature, given by equation 2.2. Fluctuations in spontaneous emission also result in an increase in the thermal energy by the recoil energy per scattering event, but due to the random direction of the photon recoil it is distributed anisotropically over all three dimensions. On average this results in heating per scattering event of $\frac{4E_{rec}}{3}$ in the longitudinal dimension and $\frac{E_{rec}}{3}$ in the two transverse dimensions. However, if it is assumed that the trap mixes the motional degrees on a time scale faster than the heating, it results in a simple expression for the total heating rate[23]. $\dot{T}$, the increase in mean temperature with time is given by

$$\dot{T} = \Gamma_{sc} T_{rec}, \quad (4.4)$$

where Γ_{sc} is the scattering rate, which is given by equation 4.2.

The initial temperature of the atoms, T_i , is known because the temperature of the MOT cloud has been carefully measured. Using the above described heating rate, the lifetime of the FORT can be calculated by assuming that if atoms become hotter than the FORT trap depth, they will escape. The FORT is assumed to be a square well potential with a constant depth equal to the maximum AC Stark shift, which occurs at the focus of the FORT beam. This trap depth can be interpreted as a cut-off temperature, T_{cutoff} , and therefore cut-off velocity, V_{cutoff} . It is calculated from the trap depth at a given detuning using the following expression,

$$\frac{3K_B T_{cutoff}}{2} = \frac{mV_{cutoff}^2}{2} \quad (4.5)$$

It is further assumed that the initial velocity distribution of the atoms in the FORT is given by the Maxwell-Boltzmann distribution, see equation 3.1. The initial number of atoms trapped can be computed by integrating this function over the range $\pm V_{cutoff}$ when $T = T_i$. The definition for the lifetime used is the 1/e lifetime. It is defined in terms of an exponentially decaying signal and is when $t = \tau$, i.e. when $N(t) = N_o \exp(t/\tau) = N_o \exp(-1)$. At this point, 37 percent of the initial atoms trapped are still present. Equating the above described integral over the Maxwell-Boltzmann distribution to 0.37 and solving for T results in the amount of heating required for 63 percent of the initially trapped atoms to escape.

Assuming that the number of atoms in the FORT decays exponentially in time is not a valid assumption to make under all FORT parameter conditions. In most of the FORT wavelength region, particularly far from the D_1 resonance, the decaying fluorescence signal can be fit with an exponen-

tial function and good agreement results. An example of such a good fit to the data is shown in figure 4.15(a), where the FORT beam is 9.89nm red-detuned off the D_1 . However, when the wavelength of the FORT beam is close to resonance, the decay deviates from an exponential. At longer storage times the decaying fluorescence signal exhibits a shallower gradient. This effect is demonstrated by the data in figure 4.15 (b), where the FORT beam is 1.41nm red-detuned from the D_1 . Also shown in figure 4.15 are curves representing the number of atoms in the FORT as a function of storage time, predicted by the FORT photon scattering theory described in section 4.3.6. Note that these curves have not been fit to the data. This FORT photon scattering theory exhibits an exponential-like decay when the FORT light is far detuned from resonance, but when the FORT light is detuned close to resonance it produces a decaying fluorescence signal which demonstrates a shallower gradient at larger storage times. In fact, according to this theory, at all wavelengths such a change in the gradient of the decaying signal is present, but it does not establish itself during the MOT-off time scale over which the data was taken. Theory curves at wavelengths which span an approximately 9nm range, 1.41nm to 9.89nm red-detuned from the D_1 transition, are shown in figure 4.16. (a) is for the experimental timescale and (b) is over a much extended timescale. A change in the gradient of the decaying signal is evident in all curves over this extended timescale. The trend demonstrated by this theory is consistent with all the data sets, but the reason for the effect is unknown.

(a) The FORT is detuned 9.89nm to the red of the D_1 transition. (b) The FORT is detuned 1.41nm to the red of the D_1 transition.

Figure 4.15: The fluorescence signal from atoms in the FORT as a function of storage time, MOT-off time. The exponential fit and the FORT scattering theory are shown. The FORT scattering theory has not been fit to the data.

(a) Decaying fluorescence signal over the MOT-off timescale of the experiment.

(b) Decaying fluorescence signal over an extended MOT-off timescale. signal

Figure 4.16: The decaying fluorescence signal from atoms in the FORT as a function of MOT-off time as predicted by the FORT scattering theory. Curves for various FORT detunings to the red of the D_1 are displayed.

4.3.7 Measuring the FORT Lifetime

The number of atoms in the FORT was measured as a function of the storage stage, the amount of time, t , for which the atoms are stored in the FORT with no optical or magnetic MOT fields present. This results in a lifetime curve. Despite the comments in the previous section, a simple exponential fit was performed to the decaying fluorescence signal in order to assign a value for the lifetime, because fitting an exponential is valid over the majority of the FORT wavelength range. Whilst the FORT photon scattering model would be more appropriate, it is unfortunately not currently calculated in a form which would allow fitting. The fit expression is given by

$$Signal = Ae^{-\frac{t}{\tau}}, \quad (4.6)$$

where τ is the lifetime of the FORT and A represents the maximum number of atoms trapped.

The lifetime was measured as a function of the FORT parameters; FORT beam detuning, power and ellipticity. At each parameter setting, many scans of the MOT-off time were performed. This is important for integrating out noise effects when the signal becomes very weak. Also the variance on the lifetime resulting from many different scans can be determined and the square root of this variance was used to assign an error to the lifetime.

4.3.8 The FORT Lifetime as a Function of Wavelength

The FORT lifetime as a function of FORT detuning from the D_1 transition is shown in figure 4.17. Also plotted is a theory curve representing the

FORT lifetime model, which includes FORT photon scattering as the only heating mechanism. Note that no fit has been performed. In figure 4.17(a), the FORT lifetime increases as the FORT beam is detuned further to the red of the D_1 transition. The scattering rate model agrees well with this trend at small detunings and suggests that this heating mechanism dominates in this wavelength region. It is unsurprising as the FORT scattering rate is very large at small detunings, resulting in shorter lifetimes. Further to the red of resonance, the lifetime increases less rapidly. The value for the lifetime seems to level off at around 2s, whilst the lifetime in the theory curve continues to increase at the same rate. This disagreement indicates that some other heating mechanism dominates. An upper limit could be imposed on the experimental data by heating due to background gas collisions. This mechanism is dependent on the number of atoms in the bulb and as yet has not been incorporated into the model. The lifetime and the collection efficiency are maximised at 6nm to the red of the D_2 transition, the lifetime is 1s and the collection efficiency is 0.7percent.

Now consider 4.17(b), when the FORT beam wavelength lies in between the D_1 and the D_2 transitions. The theory predicts the order of magnitude of the lifetimes quite well, therefore FORT photon scattering is likely the dominant heating process in this wavelength region. The FORT light is closely detuned with respect to one or other of the resonances, so scattering rates are high and lifetimes short.

The optimum detuning from each of the two resonances results in a peak for the best lifetime where the attractive potential outweighs the repulsive potential giving the deepest possible trap depth, but at the same time heating

(a) The FORT is detuned between 1 and 20nm to the red of the D_1 transition.

(b) The FORT is detuned between 1.75 to 2.5nm to the blue of the D_1 transition.

Figure 4.17: The FORT lifetime as a function of detuning from the D_1 transition. The theory curve shown includes the FORT photon scattering contribution to the heating rate only. No fit has been performed. Note that the two data points with zero lifetime in (b) are the result of no trap forming.

due to the D_2 transition is minimised. The model clearly demonstrates such a peak in the lifetime, although its position does not agree with the data. Many more measurements are required in this region for a careful study, but presently the optimum place seems to be 2nm to the blue of the D_1 transition with a lifetime of 0.125s and a collection efficiency of 0.4 percent.

It is possible to experimentally see the effect of background gas collisions by changing the level of vacuum in the bulb. The potassium dispenser was turned down from 4 to 3.5A. Fewer potassium atoms in the bulb and less hydrogen outgassing and hence less collisions, improved the MOT lifetime from 2.6 to 10.4s, see section 3.2.5. It was expected that the FORT lifetime would be similarly lengthened and would have a higher upper limit at the larger detunings. However such a change was not observed. The difference in cloud density between the two traps could mean that the collisional processes which result in decay are different. The FORT lifetime as a function of red-detuning from the D_1 transition for the two potassium dispenser current settings is shown in figure 4.18. The agreement between the two data sets is quite striking. It is only the last data point which shows any kind of deviation. However at large detunings the trap depth is diminished and less atoms are trapped, as was discussed in section 4.3.2. Consequently signals are reduced and noise plays a bigger role. The variation on the resulting lifetime from scan to scan is larger and this is obvious from the error on this point. This evidence would indicate that background gas collisions are not a major contribution to heating in the FORT. This is not conclusive as the 3.5A data was taken on a different day, so it is possible that some other condition of the system changed.

Figure 4.18: The FORT lifetime as a function of red-detuning from the D_1 transition for potassium dispenser current of 3.5 and 4A.

4.3.9 The FORT Lifetime as a Function of Power

The FORT lifetime as a function of FORT beam power, for both 3 second and 6 second build times is shown in figure 4.19. The theory curve, which represents FORT scattering heating only, has not been fit to the data. Both the theory curve and the data are essentially flat at around 0.6s. The lifetime is independent of power. This relationship can be deduced from the dependence of the trap depth and heating rate on power. Both are proportional to the beam intensity, so with a fixed beam waist the opposing effects lead to the power dependence cancelling out. The model predicts the order of magnitude of the lifetime very well as the FORT is operating in the wavelength

Figure 4.19: The FORT lifetime as a function of power. The theory curve includes the contribution of FORT scattering to heating only. No fit has been performed.

region where the FORT photon heating dominates.

4.3.10 The FORT Lifetime as a Function of Ellipticity

The FORT lifetime as a function of FORT ellipticity is shown in figure 4.20. The theory curve, which represents FORT scattering heating only, has not been fit to the data. The lifetime is longest for perfect linear light, $\epsilon = 1$, and the lifetime drops off as the light becomes more elliptical, $\epsilon < 1$. There is clearly a loss mechanism related to the polarisation of the FORT beam. As previously stated the trap depth of each individual magnetic sublevel varies with ϵ , see figure 4.13. Also the timescale over which the FORT beam interacts with the atoms is such that an appreciable amount of optical

Figure 4.20: The FORT lifetime as a function of ellipticity. The theory curve includes the contribution of FORT scattering to heating only. In addition it assumes that through optical pumping, the atoms occupy the $F_g = 2$, $m_f = 2$ sublevel. No fit has been performed.

pumping can take place. A calculation of the effective trap depth must take this biasing in the distribution of atoms into account.

For a given FORT beam helicity, when detuned to the red of both the D_1 and the D_2 transitions, atoms are optically pumped towards the shallowest $m_f = 2$ fully stretched sublevel of the $F_g = 2$ hyperfine ground state. The theory curve included in figure 4.20 assumes that all the atoms predominantly occupy this fully stretched internal spin state. This theory correctly predicts the general trend of the decreasing FORT lifetime as ϵ approaches zero. The $F_g = 2$ $m_f = 2$ sublevel's potential depth becomes shallower as ϵ approaches

zero. Its depth varies by about 0.4mK over the full range. This theory also correctly predicts the order of magnitude of the lifetime. Throughout this set of measurements the FORT was operating in the wavelength region where FORT photon scattering has shown to be the dominant heating mechanism. Whilst the agreement between data and theory is good at $\epsilon = 1$, it must be noted that the assumption upon which the model is based is not valid for the case of perfectly linear light, as no optical pumping will take place.

The FORT photon scattering rate is not dependent on polarisation, therefore the heating rate resulting from this mechanism is constant over the full range of ϵ . It is possible that some other loss mechanism, other than changing trap depth, is responsible for the trend in lifetime. The level of optical pumping assumed is only strictly true for perfectly circularly polarised light. True population distributions for $\epsilon > 0$ are likely to increase the well depth and make the disagreement between data and theory worse, so other heating processes, such as dynamical heating will be considered.

4.3.11 Ground State Dipole Force Fluctuation Heating

Thus far the theory calculation does not consider the motion of atoms within the potential wells. It assumes that the rate of optical pumping is much faster than “sloshing” of atoms within the potentials. Perhaps the inclusion of this effect could provide better agreement with the data. At JILA a model was developed incorporating a dynamic heating effect called ground state dipole force fluctuation heating. Changes between internal spin states cause instantaneous changes in the dipole force acting on the atom. These changes

result in heating, which evaporates atoms from the trap.

JILA's simple model[37] was developed for ^{85}Rb . It assumes a two level system comprising of the two fully stretched magnetic sublevels, one in each of the hyperfine ground states. In ^{39}K the corresponding levels would be the $F_g = 2, m_f = 2$ and the $F_g = 1, m_f = 1$ sublevels. These sublevels are closely coupled by off resonant excitation due to the FORT beam. Atoms are transferred between these potentials, which are treated as harmonic and of different spring constants. If the atoms are initially in the potential with the smaller spring constant, they spread out in space when they are transferred to the other potential. When the atoms re-enter the initial potential with a larger spatial extent and therefore larger potential energy, there is a heating effect as this energy is converted to kinetic energy when the atoms roll toward the centre of the well. It is assumed that the atoms hop between these potentials at a constant rate, Γ_{hop} .

JILA's expression for the FORT decay rate[37], which is the reciprocal of the lifetime, in terms of this hopping rate is given by

$$decayrate = \frac{\Gamma_{hop} \ln(\frac{U_a}{U_b})}{\ln(\frac{T_f}{T_i})}, \quad (4.7)$$

where T_i is the initial temperature of the atoms in the MOT ($= 408\mu\text{K}$) and T_f is the final temperature of the atoms in the FORT, related to the trap depth of the sublevel being occupied ($\approx 2\text{mK}$). U_a and U_b are the trap depths of the two harmonic potentials between which the atoms hop. The expression for trap depth is given by equation 2.4.

Obviously in reality, atoms will hop between many different sublevels, not just the two being considered. However these fully stretched states are the

furthest apart in energy, there is a maximum difference in energy of 0.8mK when $\epsilon = 0$, see figure 4.13. They therefore have the largest contribution to the heating rate, which justifies neglecting the contributions of all other states.

This model predicts that the decay rate is smallest when the polarization is perfectly linear because in a linear FORT the ground state potentials are degenerate, so there is no heating associated with changing the ground m_f level. There are larger losses at increasingly imperfect polarisations as the energy difference between the two states of interest increases.

A fit of JILA's model to the data for the decay rate as a function of ellipticity is shown in figures 4.21.

The dipole force ground state fluctuation heating describes the data very well, better than the scattering rate model, except for perfectly linear light. At $\epsilon = 1$ this kind of heating is not present, but other heating effects result in a finite decay rate, like FORT photon scattering.

The hopping rate, Γ_{hop} , was the only free parameter in the fit and a value of $13.1 \pm 1.5 s^{-1}$ resulted. Such a low hopping rate produces substantial heating because the optical Zeeman splitting between sublevels is on the order of the trap depth. Thus atoms can only tolerate a few hops before being heated out of the trap. The heating rate depends on the rate at which the atoms change state, which in turn depends on the FORT scattering rate. Therefore this hopping rate can be interpreted in terms of the FORT scattering rate, by dividing by the probability for the four photon heating process. This is calculated using the Clebsch-Gordan coefficients for the various possible transitions. If atoms are allowed to hop via the D_1 and the

Figure 4.21: A fit of the FORT decay rate as a function of ellipticity to a dynamic heating theory curve, which is based on JILA's ground state dipole force fluctuation heating model. The FORT photon scattering theory curve is also included, but no fit has been performed. Note it assumes that the atoms occupy the $F_g = 2$, $m_f = 2$ sublevel as a result of optical pumping.

D_2 transitions, it is straight forward to compute the probability of hopping between the hyperfine ground states, this gives 30.5 percent. Diagrams of the various hyperfine levels showing the relevant transition probabilities are shown in figure 4.22. However this calculation includes all the magnetic sublevels. A correct treatment would consider only the two m_f sublevels of interest, which would result in a much reduced probability. If the values for the measured and calculated scattering rates are to agree, the probability of the four photon heating process should be on the order of 1.5 percent.

For perfectly circularly polarised light only $\Delta m_f = 1$ transitions can

(a) D_1 -line: ($4S_{1/2} \rightarrow 4P_{1/2}$). (b) D_2 -line: ($4S_{1/2} \rightarrow 4P_{3/2}$).

Figure 4.22: The transition probabilities between the various hyperfine levels of ^{39}K where $I = 3/2$.

be excited and the atoms are all pumped into the $m_f = 2$ fully stretched sublevel, after which they can no longer change their ground state sublevel. Hyperfine changing collisions are suppressed and this heating process should turn off. Neither the present data nor the hopping theory reflect this. At JILA this effect was seen in rubidium when running between the D_1 and the D_2 transitions, where optical pumping moves atoms to the deepest-bound level. They modified their hopping model to include this optical pumping. The data in this work was taken to the red of the D_1 transition, where optical pumping moves atoms to the shallowest-bound level, perhaps making this effect more difficult to observe. It is possible that the model could not be fully tested in this region because of limitations in the quality of optics used. The pyrex cell windows did not noticeably degrade the level of FORT beam polarisation. The highest level of circular polarisation that could be achieved was $\epsilon = 0.12$.² This restriction could have further implications for future development because in order to optimise lifetimes of a “purely polarised trap” in rubidium, JILA required ϵ in the region of 0.005[26].

²However this does result in $S_3 = 0.993 (= \sqrt{1 - \epsilon^2})$, one of the Stokes parameters. With a full optical pumping model this predicts a nuclear polarisation of 0.997.

Chapter 5

Summary, Conclusions and Future Work

In this thesis the ground work required to achieve a fully polarising CFORT with radioactive potassium isotopes at TRINAT has been presented. A FORT has been successfully loaded with stable ^{39}K . It has been possible to load the FORT with various levels of FORT beam ellipticity, from $\epsilon = 0.12$ to $\epsilon \approx 1$. It has also been possible to load the FORT with detunings between 1 and 20nm to the red of the D_1 transition and also at 2.2 and 1.4nm to the blue of the D_1 transition. However, so far with detunings between the D_1 and the D_2 transitions only linearly polarised light, $\epsilon = 1$, has been used.

To be useful in the β - *decay* experiments the FORT lifetime needs to be long enough that a sufficient level of β decay can be observed. TRINAT has performed experiments with ^{80}Rb in a MOT where $\tau_{\text{MOT}} = \tau_{\text{decay}}$. So the FORT lifetime needs to be as long as the half lives of the radioactive isotopes of interest, which is on the order of 1s. It is also necessary to load as many atoms into the trap as possible. The yields for radioactive isotopes are quite small, so good loading efficiency from the MOT to the FORT are very important. A minimum number of atoms trapped in the FORT cloud is required so that background, from untrapped atoms which have less well defined polarisation, becomes unimportant. More atoms trapped would also result in better counting statistics. In order to simultaneously maximise both

the FORT lifetime and FORT collection efficiency, the opposing effects of trap depth and heating mechanisms must be considered. So far the optimum FORT was achieved with a FORT beam waist of $35\mu m$, a FORT beam power of 0.7W and a FORT beam detuning of 6nm to the red of the D_1 transition, which gives a theoretical trap depth of 1.1mK and results in a lifetime of 1s and a collection efficiency of 0.7 percent. In between the D_1 and the D_2 transitions the optimum FORT was achieved with a FORT beam detuning of 2.2nm to the blue of the D_1 transition, which gives a theoretical trap depth of 3.4mK and results in a lifetime of 0.13s and a collection efficiency of 0.4 percent. However many more measurements are required in this wavelength region.

To the red of the D_1 transition the FORT lifetime is sufficiently long just by running the FORT beam off resonance. However, to the blue of the D_1 transition it is not possible to run the FORT beam in this regime because of the very narrow splitting between the D_1 and D_2 transitions in potassium. The FORT lifetime may therefore be limited in this wavelength region. In both cases the collection efficiency needs to be better. In fact the best collection efficiency achieved so far, 1.3 percent, is not good enough. It is not sufficiently better than the 0.3 percent of MOT atoms which currently provide a background. Also this maximum efficiency was achieved within one nanometer of resonance where the lifetime is less than 0.5s.

With the ability to scan the MOT cloud position in all three dimensions the alignment of the MOT and the FORT is already optimised. Higher collection efficiencies, without adversely affecting the lifetime, can be achieved with more power and a tighter waist. Both of these factors will increase the

trap depth. The MBR is operating at its maximum power output with the current level of pumping of 11.5W from the Argon ion laser. It has been possible to achieve 2.7W MBR output with 22W of Argon ion pumping. However, the beam quality was not checked and thermal blooming could become a problem. Conversely it may be that a larger effective FORT trapping region is beneficial. This parameter has not yet been explored. Varying the beam waist will also in turn effect the Rayleigh range.

The loading rate is currently not well understood. Better understanding of this should lead to higher loading efficiencies. For a linearly polarised FORT beam which is 3nm to the red of the D_1 transition the loading curve signal saturates at 55ms. It is encouraging that the timescale for optimal loading is within the half lives of the radioactives of interest. A more detailed investigation of the loading curve should be carried out. If the presence of the MOT light is detrimental to the FORT lifetime, this will complicate the loading process.

In terms of addressing the impact of the loading efficiency on the ability to do the nuclear physics experiments, if the loading efficiency cannot be greatly improved then the MOT background must be significantly reduced. The obvious solution is to extend the storage stage so that more MOT atoms can escape the trapping region. This may not reduce the MOT background much further compared to the reduction already achieved because the tail of the MOT decay has already been reached. The MOT could be caused to decay faster by adding a MOT “heating” stage which does not affect the AC Stark shifted FORT atoms. Or the FORT cloud could be moved to a MOT background free region by simply moving the FORT focus after loading. It

must be noted that with the on-line, two MOT setup for radioactives, there is much less background gas in the second MOT. It is possible that the process of re-trapping atoms in the MOT in order to determine the number of atoms in the FORT creates an enhanced background. This issue could be resolved by imaging the FORT with an external probe beam (see appendix A). Ultimately if the MOT background cannot be sufficiently reduced then it will be necessary to characterise its polarisation, so that a correction can be applied.

It would also be beneficial to better understand the heating mechanisms present in order to combat them. FORT scattering can be combated by simply running far off resonance as this is the dominant heating mechanism for detunings of less than 6nm from resonance. The FORT scattering model had good agreement with the lifetime data in this wavelength region. It also describes the shape of the decaying fluorescence signal from atoms in the FORT as a function of MOT-off time quite well. However, it does not deal well with describing how the FORT lifetime changes with ellipticity. The dynamic dipole force ground state fluctuation heating model describes this effect, except for perfectly linear light. At $\epsilon = 1$ this kind of heating is not present, but other heating effects result in a finite decay rate, like FORT photon scattering. When $\epsilon = 0$ hyperfine changing collisions are suppressed and this heating process should turn off. Neither the current data nor the hopping theory reflect this. Instead the lifetime continues to decrease as ϵ tends to 0. However, this is a very small effect so it should not have huge implications for the lifetime of a well polarised CFORT. Such lifetime as a function of ellipticity measurements should be continued between the D_1 and

the D_2 transitions.

The effects of background gas have not been confirmed. Turning down the potassium dispenser results in fewer potassium atoms in the bulb and less hydrogen outgassing and hence less collisions. The MOT lifetime was improved from 2.6 to 10.4s by changing the dispenser current from 4 to 3.5A. However, the FORT lifetime did not change. This evidence would indicate that background gas collisions are not a major contribution to heating in the FORT. This is not conclusive though as the two data sets were taken on different days, so it is possible that some other condition of the system changed. On-line in the second MOT the level of vacuum is much higher, on the order of a few 10^{-10} Torr, resulting in mean MOT lifetimes of 45seconds, so background collisions should be less important.

Fluctuations in the FORT beam intensity such as power instabilities could also result in heating. The FORT beam power could be stabilised by setting up a feedback loop to the Argon ion pump source. Alternatively it would be possible to feed back to the amplitude of the RF going to the AOM, which switches the FORT beam on and off. The pointing and frequency stabilities should be sufficient.

The FORT was loaded from a MOT, which is $408 \pm 33 \mu K$ in temperature and is 1.2 by 2mm in size. It was not possible to load from the warmer 4.9mK MOT cloud, which is to the red of all the $P_{3/2}$ lines. It could therefore be crucial to decrease the MOT temperature. This could be achieved by simply using less intense MOT beams, where their intensity is less than the saturation intensity. Maybe a more sophisticated sub-Doppler cooling technique could be employed, although such techniques may not be appropriate with

the limitation of the timescale of the radioactives. The MOT parameters were optimised in order to give the coldest cloud possible during the loading stage. Perhaps it would be more beneficial to optimise the MOT parameters for FORT loading by scanning these parameters during the loading stage with the FORT signal as the diagnostic. So far only the MOT trapping light frequency has been optimised in this way.

Further measurements could be made to better characterise the FORT. For example, the in situ cloud temperature could be measured. A direct image of the cloud in order to determine its size was attempted; however, the triggering of the camera was not sufficient to image the cloud before it had expanded or decayed. An external pulsed probe was used in order to achieve very short relatively unperturbing exposure times. However, a more sophisticated imaging system with better resolution would be required.

Once efficiencies have been improved, in order to progress towards achieving a FORT with radioactive isotopes, the FORT and MOT parameters will be adjusted such that ^{41}K can be trapped. ^{41}K is 7 percent naturally abundant and has a similar hyperfine structure to ^{37}K , one of the radioactive isotopes of interest.

Finally, further development in order to achieve a high level of spin polarisation is required. As found in this work, it has been shown at JILA[26] with rubidium that it is not possible to directly load a FORT just to the blue of the D_1 transition because most of the states are anti-trapped, and there has not been sufficient build up of spin polarisation in the sample to trap atoms in the maximally spin polarised state, the only trapped state. Their strategy for efficiency reasons is to load a CFORT to the red of the D_1 transition, wait

for CFORT photon scattering to spin polarise the sample and then jump the laser wavelength across the D_1 transition to the blue. It has already been discussed above what steps will be taken to achieve a sufficiently long lived CFORT to the red of the D_1 transition, with enough atoms trapped to carry out the β decay experiments. In addition to this, two more key steps need to be taken.

A means of frequency hopping the MBR ring laser is required. Potentially this could be achieved using a pockel cell, which is a crystal where the optical axis is rotated with an applied voltage. This should be quicker than rotating the bi-refrangent filter mechanically. The index of refraction is altered along one of the crystal axis and consequently there is an induced birefringence dependent on the applied voltage.

Also at JILA it was found that the FORT storage time was dependent on the level of FORT beam polarisation. If $\epsilon > 0.005$ then high levels of optical pumping of atoms into the anti-trapped states results in a loss of atoms and consequently shorter storage times. Hopefully better quality optics will improve the current lower limit on ϵ , which is 0.12. It is also important to test trap lifetimes as a function of ϵ between the D_1 and the D_2 transitions, in hopes of observing the increased lifetimes observed at JILA.

Bibliography

- [1] T. Hänsch and A. Schawlow, "Cooling of gases by laser radiation", *Opt. Commun.*, vol. 13, pp. 68, 1975.
- [2] S. Chu, L. Hollberg, J. Bjorkholm, A. Cable, and A. Ashkin, "Three-dimensional viscous confinement and cooling of atoms by resonance radiation pressure", *Phys. Rev. Lett.*, vol. 55, pp. 48, 1985.
- [3] H. J. Metcalf and P. van der Straten, *Laser Cooling and Trapping*, Springer, 1999.
- [4] E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, "Trapping of neutral sodium atoms with radiation pressure", *Phys. Rev. Lett.*, vol. 59, pp. 2631, 1987.
- [5] D. Boiron, A. Michaud, J. M. Fournier, L. Simard, M. Sprenger, G. Grynberg, and C. Salomon, "Cold and dense cesium clouds in far-detuned dipole traps", *Phys. Rev. A*, vol. 57, pp. R4106, 1998.
- [6] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, "Observation of bose-einstein condensation in a dilute atomic vapor", *Science*, vol. 269, pp. 198, 1995.

-
- [7] S. Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable, "Experimental observation of optically trapped atoms", *Phys. Rev. Lett.*, vol. 57, pp. 314, 1986.
- [8] J. D. Miller, R. A. Cline, and D. J. Heinzen, "Far-off-resonance optical trapping of atoms", *Phys. Rev. A*, vol. 47, pp. R4567, 1993.
- [9] A. Ashkin, "Trapping of atoms by resonance radiation pressure", *Phys. Rev. Lett.*, vol. 40, pp. 729, 1978.
- [10] T. Takekoshi and R. J. Knize, " CO_2 laser trap for cesium atoms", *Opt. Lett.*, vol. 21, pp. 77, 1996.
- [11] C. S. Adams and E. Riis, "Laser cooling and trapping of neutral atoms", *Prog. Quant. Electr.*, vol. 21, pp. 1, 1997.
- [12] J. A. Behr A. Gorelov T. B. Swanson, D. Asgeirsson and D. Melconian, "Efficient transfer in a double magneto-optical trap system", *J. Opt. Soc. Am. B*, vol. 15, pp. 2641, 1998.
- [13] M. Stephens and C. Wieman, "High collection efficiency in a laser trap", *Phys. Rev. Lett*, vol. 72, pp. 3787, 1994.
- [14] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, "Experimental test of parity conservation in beta decay", *Phys. Rev.*, vol. 105, pp. 1413, 1957.
- [15] E. D. Commins and P. H. Bucksbaum, *Weak interactions of leptons and quarks*, Cambridge University Press, 1983.

-
- [16] A. Gorelov, D. Melconian, W. P. Alford, G. Ball, J. A. Behr, P. G. Bricault, J. M. D'Auria, J. Deutsch, J. Dilling, M. Dombsky, P. Dubé, J. Fingler, U. Giesen, F. Glück, S. Gu, O. Häusser, K. P. Jackson, B. K. Jennings, M. R. Pearson, T. J. Stocli, T. B. Swanson, and M. Trinczek, "Scalar interaction limits from the $\beta - \nu$ correlation of trapped radioactive atoms", *Phys. Rev. Lett.*, vol. 94, pp. 142501, 2005.
- [17] D. Melconian, D. Ashery, G. Ball, J. A. Behr, P. Bricault, B. A. Brown, M. Dombsky, K. P. Jackson, S. Fostner, A. Gorelov, M. N. Groves, S. Gu, M. R. Pearson, I. S. Towner, M. Trinczek, and I. Vollrath, "Measuring isospin mixing in ^{36}Ar using a polarized, neutral atom trap", *Nucl. Instru. Meth. B*, vol. 204, pp. 540, 2003.
- [18] D. J. Griffiths, *Introduction to Quantum Mechanics*, Prentice Hall, 1995.
- [19] R. S. Williamson III and T. Walker, "Magneto-optical trapping and ultracold collisions of potassium atoms", *J. Opt. Soc. Am. B*, vol. 12, pp. 1393, 1995.
- [20] F. S. Cataliotti, E. A. Cornell, C. Fort, M. Inguscio, F. Marin, M. Prevedelli, L. Ricci, and G. M. Tino, "Magneto-optical trapping of fermionic potassium atoms", *Phys. Rev. A*, vol. 57, pp. 1136, 1998.
- [21] J. A. Behr, A. Gorelov, T. Swanson, O. Häusser, K. P. Jackson, M. Trinczek, U. Giesen, J. M. D'Auria, R. Hardy, T. Wilson, P. Choboter, F. Leblond, L. Buchmann, M. Dombsky, C. D. P. Levy, G. Roy, B. A. Brown, and J. Dilling, "Magneto-optic trapping of β -

- decaying $^{38}k^m$, ^{37}k from an online isotope separator", *Phys. Rev. Lett.*, vol. 79, pp. 375, 1997.
- [22] A. Ashkin and J. P. Gordon, "Stability of radiation-pressure particle traps: an optical earnshaw theorem", *Opt. Lett.*, vol. 8, pp. 511, 1983.
- [23] R. Grimm, M. Weidemüller, and Yu. B. Ovchinnikov, "Optical dipole traps for neutral atoms", *Adv. At. Mol. Opt. Phys.*, vol. 42, pp. 95, 2000.
- [24] S. J. M. Kuppens, K. L. Corwin, K. W. Miller, T. E. Chupp, and C. E. Wieman, "Loading an optical dipole trap", *Phys. Rev. A*, vol. 62, pp. 013406–1, 2000.
- [25] D. Cho, "Analogous zeeman effect from the tensor polarizability in alkali atoms", *J. Korean Phys. Soc.*, vol. 30, 1997.
- [26] K. W. Miller, S. Dürr, and C. E. Wieman, "rf-induced sisyphus cooling in an optical dipole trap", *Phys. Rev. A*, vol. 66, pp. 023406–1, 2002.
- [27] M. Weel and A. Kumarakrishnan, "Laser-frequency stabilization using a lock-in amplifier", *Can. J. Phys.*, vol. 80, pp. 1449, 2002.
- [28] C. Wieman M. Stephens, R. Rhodes, "Study of wall coatings for vapor-cell laser traps", *Journal of Applied Physics*, vol. 76, pp. 3479, 1994.
- [29] M. Walhout, J. Daalibard, S. L. Rolston, and W. D. Phillips, " $\sigma_+ - \sigma_-$ optical molasses in a longitudinal magnetic field", *J. Opt. Soc. Am. B*, vol. 9, pp. 1997, 1992.

-
- [30] P. D. Lett, W. D. Phillips, S. L. Rolston, C. E. Tanner, R. N. Watt, and C. I. Westbrook, "Optical molasses", *J. Opt. Soc. Am. B*, vol. 6, pp. 2084, 1989.
- [31] I. Yavin, M. Weel, A. Andreyuk, and A. Kumarakrishnan, "A calculation of the time-of-flight distribution of trapped atoms", *Am. J. Phys.*, vol. 70, pp. 149, 2002.
- [32] W. D. Phillips E. Arimondo and F. Strumia, *Laser Manipulations of Atoms and Ions*, North Holland, 1992.
- [33] C. Fort, A. Bambini, L. Cacciapuoti, F. S. Cataliotti, M. Prevedelli, G. M. Tino, and M. Inguscio, "Cooling mechanisms in potassium magneto-optical traps", *Eur. Phys. J. D*, vol. 3, pp. 113, 1998.
- [34] A. E. Siegman, *Lasers*, University Science Books, 1986.
- [35] H. C. W. Beijerinck, "Rigorous calculation of heating in alkali-metal traps by background gas collisions", *Phys. Rev. A*, vol. 61, pp. 033606–1, 2000.
- [36] M. E. Gehm, K. M. O'Hara, T. A. Savard, and J. E. Thomas, "Dynamics of noise induced heating in atom traps", *Phys. Rev. A*, vol. 58, pp. 3914, 1998.
- [37] K. L. Corwin, S. J. M. Kuppens, D. Cho, and C. E. Wieman, "Spin-polarized atoms in a circularly polarised optical dipole trap", *Phys. Rev. Lett.*, vol. 83, pp. 1311, 1999.

Appendix A

An External Probe Beam

A.1 Probe Beam Applications

An external probe beam was setup primarily for two reasons.

- Detecting the FORT atoms
- Measuring the AC Stark shift

These applications are described in some detail below.

A.1.1 Detecting the FORT Atoms

The main reason for developing an external probe beam was to illuminate the FORT cloud such that residual MOT effects would be eliminated. When the MOT light is used to detect the FORT atoms, the MOT re-traps all the atoms in its effective trapping volume. Whilst this does not happen until after a pause to allow the MOT atoms to fall out of the trapping region, it is difficult to be sure that the MOT cloud has completely decayed. However for the results outlined in this work this method was not used. The resulting FORT signal was reduced and consequently it requires many more atoms to be loaded into the FORT.

A.1.2 Measuring the AC Stark Shift

Before a FORT signal was observed, there was a concern that the FORT beam was not perturbing the atoms as expected. A check was performed by using this probe beam to also measure the AC Stark shift produced by the FORT beam. This is an indirect measurement of FORT trap depth. This measurement involves illuminating the atoms within the FORT cloud with the probe beam and producing a fluorescence spectrum from those atoms by scanning the probe light in frequency space. The FORT beam is left on during the exposure time. By looking at those same atoms with the FORT beam off it should be possible to detect a frequency shift between the two observed spectrums due to the AC Stark shift produced by the FORT beam.

However, the AC Stark shift varies with FORT beam intensity, it is largest at the FORT beam focus. Longitudinally it varies according to the Rayleigh range. Over this distance the AC Stark shift drops by a factor of one half. Radially it varies according to the Gaussian beam profile. The resulting spectrum observed will be a weighted average of spectrums from all the atoms illuminated by the probe light, which are AC Stark shifted by different amounts according to their position in the FORT beam. It is therefore necessary to be selective about which atoms get illuminated. Contributions from unshifted atoms can be eliminated by focussing the probe beam along with the FORT beam so these the beams are comparable in size.

The two focussed beams which lie on the same approximate path were reflected away from the MOT bulb such that they came to a focus outside of the bulb. They were then carefully overlapped as close as possible to their foci on a 100 micron pinhole. Illuminating only atoms within the effective

FORT beam region in this way requires a manipulable probe beam. It is not possible to adjust the size and position of the MOT beams, if the MOT is still to function. When the resonant, focussed probe beam is overlapped with the MOT cloud it produces a contrail and hence results in another diagnostic for overlap between the two traps. In order to pick out different magnitudes of shifts along the length of the beam, the region of interest for the CCD camera was sliced up. Cuts were made as tight as statistics would allow in the longitudinal direction in order to limit the averaging effect.

There are unfortunately some problems which have so far made this measurement unsuccessful. It was not possible to observe an AC Stark shift because the effect gets “washed out” due to the averaging over many contributing spectrums. The probe beam produces a wide jet of illumination, therefore too many unshifted atoms are sampled. Also the resolution of the spectrums is degraded by power broadening. Trying to perform this measurement proved harder than achieving a FORT itself.

A probe beam focused to a tight waist will inherently have a short Rayleigh range. Therefore the probe beam only has a small spotsize over this short range. CCD pictures illustrate the wide jet of illuminating probe light which is formed. In order to overcome this problem the probe should be telescoped down to produce a narrow parallel beam. This light should be brought into the MOT bulb from the opposite side of the bulb so as to avoid the FORT lens.

Good resolution of the peaks within the observed absorption spectrums is very advantageous when looking for differences between spectrums. The resolution can be increased by reducing power broadening.[3]. As the probe

beam intensity increases the absorption increases. At the centre of the spectral profile, close to zero detuning, the maximum number of photons are absorbed and half the atoms end up in the excited state. Absorption is saturated here. However absorption can continue to increase in the wings of the spectral profile. This effect can be limited by reducing the probe beam intensity below the saturation intensity, I_s , for the transition of interest. I_s for the D_2 transition in ^{39}K is $1.77\text{mW}/\text{cm}^2$. However, with a focussed probe high power densities result and the probe beam needs to be attenuated. Even with the total probe beam power reduced to less than 0.01mW the intensity at the focus is still nearly 300 times I_s .

It is also possible that Zeeman shifts due to the magnetic fields present also interfere with the spectrums produced.

A.1.3 Potential Applications for the Probe Beam

Although not yet realised, there are several other uses for this probe beam. It could be used for spin alignment by providing optical pumping within the FORT environment. It could also be scanned in frequency while illuminating the CFORT in order to look for the population of the various AC stark-shifted transitions. Such a measurement was already performed at JILA[37].

A.2 Probe Beam Setup

When atoms are illuminated for periods of time comparable to the exposure times in this experiment, on the order of milliseconds, many photon interactions take place. It is very likely therefore, that the atoms could get optically excited from the $F_g = 2$ hyperfine ground state ground to an excited state

and then decay to the other $F_g = 1$ hyperfine ground state. In the frequency region in which the probe operates atoms can no longer be excited from this other ground state. Therefore, in order to achieve the maximum amount of fluorescence and hence the largest signal strength possible, it is necessary to have repumping light to bring the atoms back to the $F_g = 2$ ground state.

The repumping light is not focussed down so is brought into the MOT bulb from the opposite side as the FORT beam in order to avoid the FORT lens. The probe is produced by a D_2 diode laser and the repumping beam is produced by a D_1 diode laser. The typically 2mm diameter beams produced have maximum powers outputs of around 1mW. These two lasers are frequency locked by means of saturation spectroscopy. An AOM double pass is setup for the probe light such that frequency control does not effect the beam steering. This probe light is scanned over the entire $F_g = 2$ to $F_e = 1, 2$ or 3 manifold. As the repumping beam is purely for redistributing the atoms this beam is not scanned, but is left on the $F_g = 1$ to $F_e = 2$ transition. Power in these beams is adjusted by controlling the RF amplitude going to the AOMs. Beam intensity is limited so as not to push or destroy the trapped cloud. The probe is pulsed in order to achieve much shorter exposure times and consequently disturb the trapped atoms less. The probe is triggered by the camera ready signal. The three beams must be carefully combined on the MOT bulb using polarising beam splitters so as to not allow reflections of the powerful FORT beam back to the diode laser heads.

A.3 Probe Beam Characterisation

In order to check the setup of the simultaneously focussed probe and FORT beams, the probe beam was characterised in the same way that the FORT beam was originally characterised using a CCD camera. First the probe beam profile was checked. Pictures of the probe beam shape and the Gaussian fit for the probe beam profile at its waist are shown in figure A.1 . It is a nice

Figure A.1: Pictures of the probe beam shape and the Gaussian fit for the probe beam profile at its waist.

Gaussian beam which is in a TEM00 mode. The quality of the gaussian fit is 92 percent at the beam waist.

Also the spot size of the probe beam after the FORT lens was measured at various points along the beam and a fit was performed of the data to the Gaussian optics equation for spotsize, ω , as a function of distance along the beam, z , see equation 4.2. The size and position of the probe beam waist was consequently determined. The fit of the varying spotsize of the probe after the FORT lens in the x and y dimensions is shown in figure A.2

and the fit results with errors are shown in table A.1. The probe beam

Figure A.2: The varying spotsize of the probe beam in the x and y dimensions.

Table A.1: Fit results for the characterisation of the probe beam, including the waist size, ω_0 , the effective focal length of the lens, f and the Rayleigh range, z_0 .

Parameter	X Dimension	Y Dimension
ω_0	$55.2 \pm 0.4 \mu m$	$39.8 \pm 1.0 \mu m$
z_0	$12.5 \pm 0.15 mm$	$6.5 \pm 0.3 mm$
f	$241 \pm 0.15 mm$	$225 \pm 0.3 mm$

is not very symmetric. The beam focuses to a different waist in the two dimensions. Consequently the Rayleigh range, which is dependent on the waist ($Z_0 = \frac{\pi n \omega_0^2}{\lambda}$), is also quite different in the two dimensions. The probe beam is also a little astigmatic as the foci in each plane are not in the same place longitudinally, hence the effective focal length is slightly different in the two planes.

The characteristics of the probe and FORT beams were compared in order

to determine how well their profiles were matched and how well they were overlapped. A plot of the varying spot size after the FORT lens of both the probe and the FORT beams is shown in figure A.3. The probe beam waist is

Figure A.3: The varying spotsize of the probe and the FORT beams in the x and y dimensions.

between 5 and 20 microns bigger than the FORT beam waist. The overlap of the beam foci is extremely good in the x dimension, but there is quite a large discrepancy of approximately 2cm for the probe beam in the y dimension. It might be possible to insert a telescope or a single lens into the probe beam line to move the probe focus.