Appendix A

Abbreviations used

Abbreviation	Meaning
AOM	Acousto-optical modulator
BEC	Bose Einstein condensate
CCD	Charge coupled device
DAVLL	Dichroic atomic vapour laser lock
ECDL	External cavity diode laser
EMCCD	Electron multiplied charge couple device
LCD	Liquid crystal device
MOT	Magneto optical trap
Nd:YAG	Neodymium-doped yttrium aluminium garnet
ND	Neutral density
PBS	Polarising beam splitter
P-MOT	Pyramid magneto optical trap
QIP	Quantum Information Processing
QUEST	Quasi electrostatic
rf	Radio frequency
rms	Root mean square
RWA	Rotating wave approximation
SFS	Strong field seeking
S-MOT	Science magneto optical trap
UHV	Ultra high vacuum
WFS	Weak field seeking

Table A.1: Abbreviations and acronyms used in the thesis.

Appendix B

Symbol definitions

In Table B.1 the majority of the symbols used in the thesis are tabulated in alphabetical order with their definition. Some symbols have dual definitions but the context is sufficient to work out which one is relevant. The rules for subscripts are: i denotes an initial value; x, y, z are the Cartesian components; r is the radial component. Vectors have a bold font. Primes are used in four contexts: to distinguish 'thin lens' times from their 'thick lens' counterparts; to indicate excited states; to distinguish currents in coils and bars; to distinguish harmonic trap and laser guide angular frequencies.

Symbol	Physical meaning
α	Polarisability
α_0	Scalar polarisability
α_2	Tensor polarisability
a	Coil radius
a_0	Bohr radius
$\mathbf{a}_0$	Acceleration due to B-field gradient
$\mathbf{a}_\mathrm{F}$	Full Biot-Savart lens acceleration
$\mathbf{a}_\mathrm{H}$	Acceleration from harmonic fit to B-field
a_S	Scattering length
$\mathcal{A}, \mathcal{B}, \mathcal{C}, \mathcal{D}$	$\mathcal{ABCD}$-matrix elements
A_hfs	Hyperfine structure constant
β	Viscosity constant
$B(x, y, z)$	Magnetic field magnitude
$\mathbf{B}(x, y, z)$	Magnetic field
B_0	Bias field of magnetic field
B_1	Gradient of magnetic field
B_2	Curvature of magnetic field
B_hfs	Hyperfine structure constant
$\mathbf{BZ}(x, y, z)$	Magnetic field of current bar along z-axis

Table B.1: Symbols used and their meanings.

Symbol	Physical meaning
χ	Loading efficiency
c	Speed of light
Δ	Angular detuning ($\Delta = 2\pi\delta$)
d	Grating line spacing
$\epsilon(R, Z)$	Harmonicity
ϵ_0	Permittivity of free space
η	$\eta = \mu_0 NI/2$
E	Energy
$E(k)$	Complete elliptic integral (1st kind)
$\mathbf{E}$	Electric field
E_{hfs}	Hyperfine interaction matrix
f	Focal length of lens
$\mathcal{F}$	Fraction of atoms in the Gaussian focus
F	Total atomic angular momentum
$F_{\pm,\mathrm{tot}}$	Scattering forces in a MOT
$\mathbf{F}_{\mathrm{Dip}}$	Dipole force
Γ	Natural line width. Excited state decay rate.
$\Gamma(a, b, c)$	Generalised incomplete gamma function
$\Gamma_{\mathrm{sc}}(\mathbf{r})$	Scattering rate
g	Acceleration due to gravity
g_{n}	Gain of photodiode circuit
G	Total transimpedance
h	Height
$\hbar$	Plank's constant/2π
$\mathbb{I}$	Identity matrix
I	Current in coil
I'	Current in bar
$I(\mathbf{r})$	Intensity
I_{AH}	Current in the opposite sense ($2I_{\mathrm{AH}} = I_1 - I_2$)
I_{H}	Current in the same sense ($2I_{\mathrm{AH}} = I_1 + I_2$)
I_{n}	Nuclear quantum number
I_{sat}	Saturation intensity
J	Total electronic angular momentum
κ	fractional solid angle
k	Substitution used in circular coil expression (eqn. (4.10))
$\mathbf{k}$	Wavevector
k_{B}	Boltzmann's constant
K	Sum of quantum numbers (eqn. (2.17))
$K(k)$	Complete elliptic integral (2nd kind)
λ	Focusing parameter (single-impulse)
$\lambda_{1,2}$	Focusing parameter (double-impulse)
λ_{C}	Wavelength of cooling laser
λ_{T}	Wavelength of trapping laser
$L = l/a$	Scaled length of current bar in baseball lens
μ_0	Permeability of free space
μ_{B}	Bohr magneton
m	Mass
m_F	Magnetic quantum number

Symbol	Physical meaning
M	System matrix
M_{ag}	Magnification
n	Density OR Diffraction order
N	Number of atoms OR coil turns
$\Phi(r,p)$	Phase space distribution
p	Radial momentum
$\mathbf{p}$	Dipole moment
P	Laser power
P_{MOT}	Power emitted by MOT
P_{PD}	Power measured by photodiode
q	Integral substitution (Section 3.3)
Q	Q-matrix
r	Polar coordinate
σ	Spatial standard deviation
σ_{el}	Collision cross section
σ_v	Velocity standard deviation
σ_R	Initial isotropic spatial standard deviation
σ_V	Initial isotropic velocity standard deviation
$S = s/a$	Scaled coil separation
S	Photodiode sensitivity
τ	Pulse duration (single-impulse)
$\tau_{1,2}$	Pulse duration (double-impulse)
θ	Angle of diffraction
t	Time
$t_{1,2}$	Time of lens pulse
$\mathcal{T}$	Temperature
$\mathcal{T}_{\mathrm{D}}$	Doppler limit
T	Total focusing time
T_{osc}	Laser guide oscillation period
T_{r}	Transmission
U_{Dip}	Dipole potential
$v_{z_{\mathrm{i}}}$	Vertical launch velocity
$\mathbf{v}$	Velocity
V	Photodiode voltage
ω	Lens angular frequency (single-impulse)
ω'	Harmonic trap angular frequency
ω_0	Atomic transition angular frequency
$\omega_{1,2}$	Lens angular frequency (double-impulse)
$\omega_{r_{\mathrm{L}}}$	Laser light's angular frequency
$w(z)$	$1/e^2$ intensity radius
w_0	Beam waist
$W = w/a$	Scaled length of current bar in baseball lens
$\xi = \sigma_z/\sigma_r$	Cloud aspect ratio
x, y, z	Cartesian coordinate
X, Y, Z, R	Scaled position coordinate (eg. $X = x/a$)
z_0	Focal point
z_{c}	Vertical position of the lens centre
z_{R}	Rayleigh length

Appendix C

Values and constants

Quantity	Symbol	Value	Unit
Acceleration due to gravity	g	9.807	m s^{-2}
Atomic mass unit	u	1.661×10^{-27}	kg
Boltzmann's constant	k_{B}	1.381×10^{-23}	J K^{-1}
Bohr magneton	μ_{B}	9.274×10^{-24}	J T^{-1}
Bohr radius	a_0	5.292×10^{-11}	m
Electron charge	e	1.602×10^{-19}	C
Electron mass	m_e	9.109×10^{-31}	kg
Permeability of free space	μ_0	$4\pi \times 10^{-7}$	N A^{-2}
Permittivity of free space	ϵ_0	8.854×10^{-12}	F m^{-1}
Planks constant/2π	$\hbar$	1.055×10^{-34}	J s
Speed of light in a vacuum	c	2.999×10^{8}	m s^{-1}
Rubidium natural linewidth [126]	Γ	$2\pi \times 5.9$	MHz
Hyperfine structure constants [132]	A_{hfs}	$2\pi \times 25.009$	MHz
	B_{hfs}	$2\pi \times 25.88$	MHz
D2 line wavelength [123]	λ_{C}	780.24	nm

Table C.1: Values and constants used. Values for the fundamental constants are the CODATA recommended values [190].

Appendix D

Atomic structure of Rb

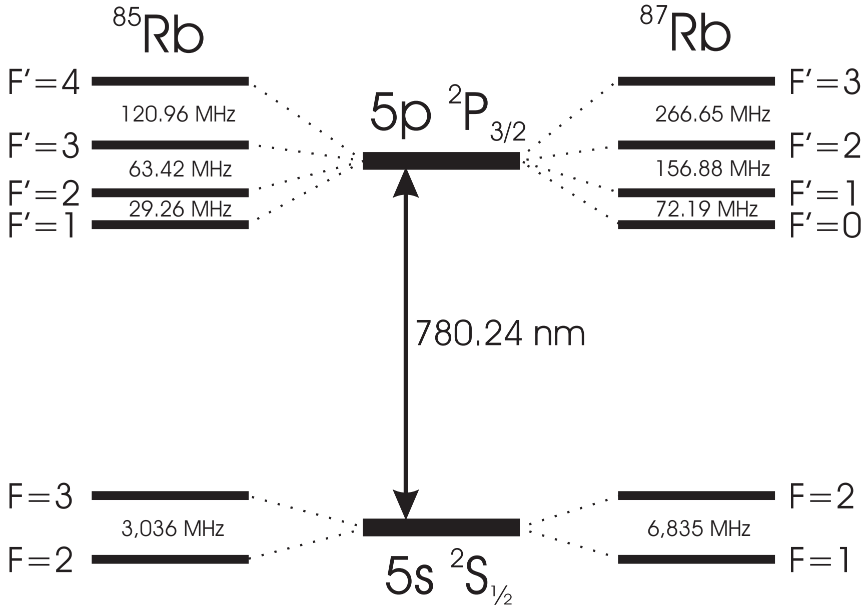

Figure D.1: The hyperfine energy level diagram on the D2 line for the ^{85}Rb and ^{87}Rb isotopes [191, 192].

Appendix E

Collision rate

Following the approach taken in ref. [154] to calculate the collision rate within a MOT. The density of a spherically symmetric Gaussian spatial distribution with N atoms and a spatial standard deviation of σ_R is:

$$n(\mathbf{r}) = n_0 \exp\left(-\frac{x^2+y^2+z^2}{2{\sigma_R}^2}\right), \tag{E.1}$$

where the peak density is:

$$n_0 = \frac{N}{(2\pi)^{3/2}{\sigma_R}^3}. \tag{E.2}$$

The spatially averaged elastic collision rate is:

$$\begin{aligned} \Gamma_{\text{el}} &= \sigma_{\text{el}} \frac{\int n^2(\mathbf{r}) v_{\text{rel}}\ d^3r}{\int n(\mathbf{r})\ d^3r} = \sigma_{\text{el}} \langle n \rangle \langle v_{\text{rel}} \rangle, \\ &= \sigma_{\text{el}}\, n_0 \sqrt{\frac{3k_{\text{B}}\mathcal{T}}{4m}}, \end{aligned} \tag{E.3}$$

where the density-weighted density for a Gaussian distribution is $\langle n \rangle = n_0/\sqrt{8}$ and the rms average velocity between atoms of mass m is $\langle v_{\text{rel}} \rangle = \sqrt{6k_{\text{B}}\mathcal{T}/m}$. The dominant collision at ultracold temperatures is s-wave elastic collisions:

$$\sigma_{\text{el}} = \frac{8\pi {a_{\text{S}}}^2}{1+k^2{a_{\text{S}}}^2}, \tag{E.4}$$

where $k = \sqrt{2\pi m k_{\text{B}}\mathcal{T}}/\hbar$ and a_{S} is the scattering length. Combining eqns. (E.2), (E.3) and (E.4), and using the experimentally measured ^{85}Rb background scattering length $a_{\text{S}} = -433\ a_0$ from ref. [193], the MOT average collision rate is: $\Gamma_{\text{el}} = 3\ \text{s}^{-1}$.

Appendix F

Mathematica computer code

Below is an example *Mathematica* computer code that calculates the trajectories of atoms passing along a laser guide.

Define fundamental constants.

```
Bohr = 0.5292 * 10^-10;
c = 2.999 * 10^8; g = 9.807;
kb = 1.381 * 10^-23; m = 85 × 1.661 × 10^-27;
```

Calculate the laser beam potential using the ground state polarisability of Rb.

```
waist = 250 * 10^-6; z0 = 0.0;
λ = 1064 * 10^-9; ray = π waist^2 / λ;
power = 19;
w1[z_] := waist Sqrt[1 + (z - z0)^2/ray^2];
int[r_, z_] = (2 * power)/(π w1[z]^2) Exp[-2 (r/w1[z])^2];
α0 = 693.5;
U0 = (α0 * 4 * Pi)/(2 c) Bohr^3;
U[x_, y_, z_] := -U0 int[√(x^2 + y^2), z];
```

Calculate the acceleration due to the dipole potential. The dummy variables used in the differentiation are replaced with the correct coordinate at the end.

```
(*Calculates acceleration on atoms*)
accx[x_, y_, z_] = -D[U[ρ, y, z], ρ] / m /. {ρ → x} // Evaluate // Simplify;
accy[x_, y_, z_] = -D[U[x, ϒ, z], ϒ] / m /. {ϒ → y} // Evaluate // Simplify;
accz[x_, y_, z_] = -D[U[x, y, ξ], ξ] / m /. {ξ → z} // Evaluate // Simplify;
```

Setup the Gaussian spatial and velocity distributions for the atomic sample. Table "mix1" contains the x-direction data, "mix2" y-direction and "mix3" z-direction.

```
atoms = 25;
cloudradius = 0.0002;
temp = 20 * 10^-6; thermalvel = Sqrt[kb * (temp / m)];
<< "Statistics`NormalDistribution`"
ndistpos := Random[NormalDistribution[0, cloudradius]];
ndistvel := Random[NormalDistribution[0, thermalvel]];
xcom = 10^-8; xvcom = 0; ycom = 10^-8; yvcom = 0; zcom = 0;
mix1 = Table[{xcom + ndistpos, xvcom + ndistvel}, {atoms}];
mix2 = Table[{ycom + ndistpos, yvcom + ndistvel}, {atoms}];
mix3 = Table[{zcom + ndistpos, ndistvel}, {atoms}];
```

Calculate the launch velocity and flight duration based on a given height.

```
height = 0.22;
zvcom = Sqrt[2 * g * height];
tfocus = Sqrt[(2 * height) / g];
tmx = 0.02 + tfocus;
```

The equations of motion for the system. *Mathematica* produces interpolating functions for each atom. Only the x-direction table is generated in this example.

```
Clear[Coord];
Coord[xpos_, xvel_, ypos_, yvel_, zpos_, zvel_] :=
  Coord[xpos, xvel, ypos, yvel, zpos, zvel] =
   NDSolve[{vx'[t] == accx[x[t], y[t], z[t]], x'[t] == vx[t], vx[0] == xvel, x[0] == xpos,
     vy'[t] == accy[x[t], y[t], z[t]], y'[t] == vy[t], vy[0] == yvel, y[0] == ypos,
     vz'[t] == accz[x[t], y[t], z[t]] - g, z'[t] == vz[t], vz[0] == zvel, z[0] == zpos},
    {x[t], vx[t], y[t], vy[t], z[t], vz[t]}, {t, 0, tmx}, MaxSteps → 10000];

xtraj = Table[{x[t] - (xvcom * t + xcom) /.
      Coord[mix1[[shelf, 1]], mix1[[shelf, 2]], mix2[[shelf, 1]], mix2[[shelf, 2]],
       mix3[[shelf, 1]], mix3[[shelf, 2]] + zvcom]}[[1]], {shelf, 1, atoms}];
```

Plots the x position against time and generates a data table that can be further analysed or exported.

```
Plot[Evaluate[xtraj], {t, 0, tmx}]; dt = 2000;
xstatdata = Table[Evaluate[Flatten[xtraj]], {t, 0, tmx, 1 / dt}];
```

Appendix G

Fibre optic alignment

Due to the elliptical cross-section, polarisation preserving fibre optics will only function properly if the incoming linearly polarised light is aligned to one of the two orthogonal axes running along the fibre (semi-major or semi-minor axis). If the axes are not marked, a simple way to determine the correct polarisation is outlined in this Appendix. The experimental setup is shown in Figure G.1.

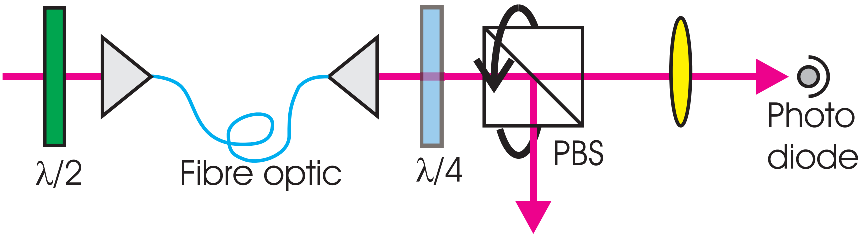

Figure G.1: Experimental setup used to align the polarisation of light going into the fibre optics. The $\lambda/4$ waveplate is only used when converting the light into circular polarisation.

The initial alignment does not make use of the $\lambda/4$ waveplate. A rotatable polarising beam splitting (PBS) cube is used with a either a photodiode or power meter (Coherent Field Master) to analyse the polarisation of the light exiting the fibre. The PBS cube is rotated to obtain values for the maximum and minimum powers measured by the photodiode. The signature of linear light exiting from the fibre optic is that the ratio of maximum power to minimum power is maximised. The initial $\lambda/2$ waveplate is used to rotate the polarisation of the light entering the fibre. A plot of the max/min power ratio against $\lambda/2$ waveplate rotation angle is given in Figure G.2 (a). As expected from the 2θ rotation property of the waveplate, one finds a maximum every 45°. A close-up of the first maximum is shown in Figure G.2 (b).

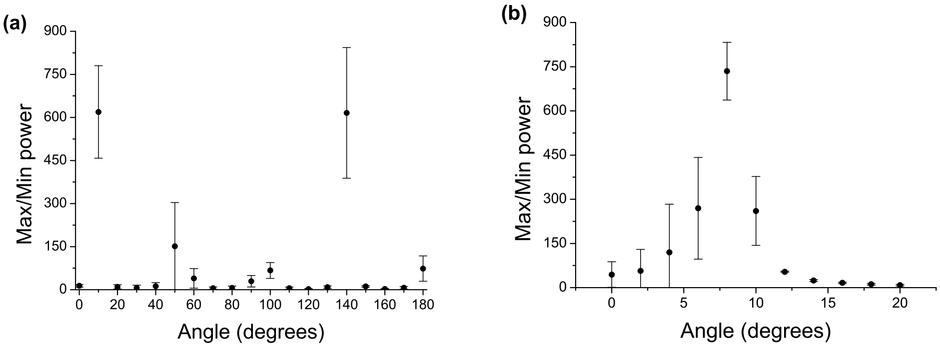

Figure G.2: The maximum to minimum power ratio is plotted against $\lambda/2$ waveplate angle. Plot (b) examines the first maximum in (a).

The correct angle of a $\lambda/4$ waveplate to convert linear light into circular polarisation can be similarly determined. In this case the $\lambda/4$ waveplate is rotated and the ratio of minimum to maximum power is plotted, see Figure G.3. In this case the waveplate is set to one of the maximum angles.

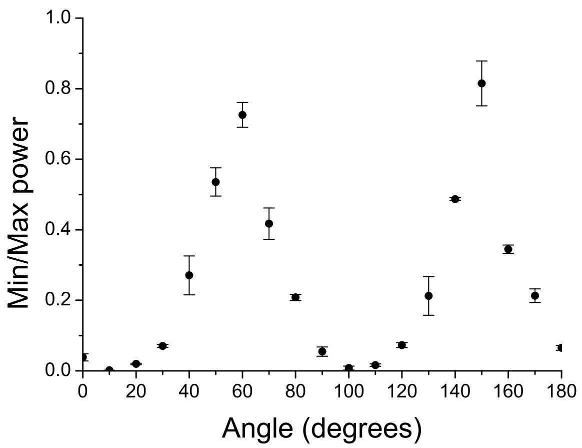

Figure G.3: The minimum to maximum power ratio is plotted against $\lambda/4$ waveplate angle.

Another method to align the linear polarisation into the fibre that does not involve rotating the PBS cube is to plot the peak-to-peak noise on the photodiode voltage against the rotation angle of the $\lambda/2$ waveplate. During the measurement, the fibre is deliberately stressed and heated by gently massaging the fibre. When the light is propagating down one of the orthogonal axes the effect of the perturbation is minimised and is seen by a dramatic reduction in the photodiode noise.

Appendix H

Knife edge measurements

A crude, but nonetheless effective, method of measuring a laser beam's profile is now described. A knife edge is translated through the beam's cross-section. The resulting change in power as a function of knife edge position allows the $1/e^2$ beam radius $w(z)$ to be calculated (see Section 3.1). Multiple readings at different z positions allow a full description of the laser beam's spatial profile. Treating the x- and y-direction beam waists as being independent i.e. an elliptical beam profile, the total power in the beam is given by integrating eqn. (3.1) on page 26:

$$P_{total} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)dydx = \frac{\pi}{2} I_0 w_x w_y. \tag{H.1}$$

As the knife edge moves across the beam in the x-direction the power measured at the photodiode varies as:

$$P(X) = P_{total} - \int_{-\infty}^{X}\int_{-\infty}^{\infty} I(x,y)dydx. \tag{H.2}$$

After integration and substituting in the error function:

$$\mathrm{erf}(u) = \frac{2}{\sqrt{\pi}} \int_0^u e^{-u^2}\, du\,, \tag{H.3}$$

the power measured by the photodiode vs. knife edge position, X, will have the following form:

$$P(X) = \frac{P_{total}}{2}\left(1 - \mathrm{erf}\left(\frac{\sqrt{2}\,X}{w_x}\right)\right). \tag{H.4}$$

An example of this measurement can be found in Figure H.1. The data were recorded by translating the knife edge through one of the three arms of the

S-MOT cooling beams; see Figure 8.22. A fit to the data gives the $1/e^2$ beam radius as 7.5 mm and the peak intensity as 7.1 mW/cm^2.

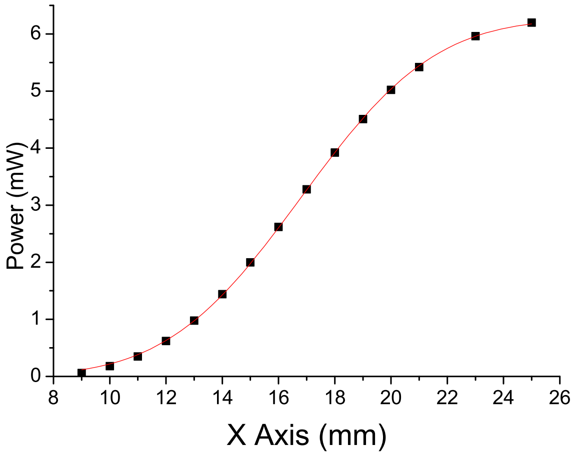

Figure H.1: Knife edge measurement of the S-MOT laser beam.

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