Chapter 1

Introduction

"I think I could, if I only knew how to begin. For, you see, so many out-of-the-way things had happened lately that Alice had begun to think that very few things indeed were really impossible." Lewis Carroll

When the laser was first invented in 1960 it was described as "a solution looking for a problem." It has since become arguably one of the most significant and widely used measurement tools of the 20th century. The atom-laser interaction provides a powerful way of controlling and probing the properties of matter. The ability to laser cool atoms, ions and molecules to ultracold temperatures started a scientific revolution that is going from strength to strength [1, 2]. Research labs around the world routinely cool down atoms to μK temperatures [3]. This has led to the production of new forms of matter: Bose-Einstein Condensates (BEC) [4, 5], and quantum degenerate Fermi gases [6]. Furthermore, an atom is a very sensitive probe of the external world. This fact is exploited in measuring weak magnetic [7] and gravitational [8, 9] fields, and is used in producing the most accurate atomic clocks [10, 11]. Another important application of ultracold atoms is in Quantum Information Processing (QIP), whereby neutral atoms are used as qubits, one of the basic building block of quantum computers [12, 13, 14].

1.1 Atom optics

Whatever use ultracold atoms are put to, there is a need for tools and techniques to manipulate them in a non-destructive manner. One of the goals in the field of atom optics is to realise atom-optical elements that are analogues of conventional optical devices, such as mirrors, lenses and beam-splitters [15, 16]. An atom mirror reverses the component of velocity perpendicular to the surface and maintains the component parallel to the surface. An atom lens can modify both the transverse velocity component and the longitudinal component. It is now possible to drastically modify the centre-of-mass motion of atoms, in direct contrast with the small angular deflection of fast beams studied prior to the development of laser cooling [17]. Four main types of interactions have been used to focus ultracold atoms and molecules: matter, electric, magnetic, and light.

1.1.1 Matter interactions

The interaction with other matter has historically concentrated on diffracting atoms off structures. Building on Stern's work on atoms diffracting off crystal structures in the 1930s [18, 19] and later micro-fabricated periodic structures [20], a Fresnel zone plate was used to achieve atom focusing in 1991 [21]. A different focusing approach involves reflecting hydrogen atoms off a liquid helium-vacuum interface [22]. Nowadays focusing using matter interactions has largely been abandoned due to the large atom number losses suffered, however some work on Helium scattering off atomic mirrors continues [23, 24].

1.1.2 Electric field interactions

The interaction between an inhomogeneous electric field and an atom's induced, or a heteronuclear diatomic molecule's permanent, electric-dipole moment can be used for focusing. Making use of static electric fields Gordon *et al.* focused ammonia molecules [25]. In 1999 Maddi *et al.* demonstrated slowing, accelerating, cooling and bunching of molecules and neutral atoms using time varying electric field gradients [26]. The use of this technique is a very active field of research [27, 28, 29], with particular applications in measuring a permanent electron electric-dipole moment [30].

1.1.3 Magnetic field interactions

The magnetic dipole moment of paramagnetic atoms interacts with a magnetic field. If there is a spatial variation in the field, a force arises called the Stern-Gerlach force (see ref. [31] for a review of magnetic manipulation of cold atoms). To date, the Stern-Gerlach force has been used to realise flat atomic mirrors [32, 33, 34], curved atomic mirrors [35, 36, 37, 38], and pulsed mirrors for both cold (thermal) [39] and Bose condensed atoms [40, 41, 42]. It has also been demonstrated that the surface of a magnetic mirror can be adapted in real time with corrugations that can be manipulated in times shorter than the atom-mirror interaction time [43, 44].

An atomic beam was focused in 1951 by Friedburg and Paul using a hexapole magnetic field [45, 46]. Over 30 years later the first laser-cooled atomic beam was focused using an electromagnetic lens in 1984 [47]. Developing this further, two lenses built from strong rare-earth permanent magnets were used to increase the atomic flux density of a laser-cooled atomic beam [48].

The first demonstration of 3D focusing using pulsed magnetic lenses was conducted in 1991 by Cornell *et al.* [49]. The group of Gorceix have made experimental and theoretical studies of cold atom imaging by means of pulsed magnetic fields [50, 51, 52]. However, neither group addressed the optimum strategy for achieving a compact focused cloud, nor the limiting features for the quality of their atom-optical elements. As well as achieving a compact cloud in space, it is also possible to use pulsed magnetic fields to reduce the momentum spread of an expanding cloud with appropriate magnetic impulses. This can be viewed as an implementation of δ-kick cooling, which has been demonstrated with atoms [53, 54], ions [55] and BECs [40, 41, 42].

It is also possible to load atoms into a magnetic trap, and transport the atoms whilst they are still trapped into a new position. Greiner *et al.*'s scheme involves an array of static coils, with the motion of the trapped atoms facilitated by time-dependent currents in neighboring coils in the chain [56]. There are some drawbacks to this scheme - a large number of coils and power supplies are required. Care must be taken to preserve the shape of the magnetic trap as it is transferred which necessitates a complex time sequence of currents to be maintained. Another scheme uses coils mounted on a motorised stage, so that they can be easily moved, thereby transporting the magnetically trapped atoms [57, 58, 59]. These experiments used a three dimensional quadrupole trap, which has a magnetic zero at its centre. For certain applications a trap with a finite minimum is required, and this year transport of atom packets in a train of Ioffe-Pritchard traps was demonstrated [60].

1.1.4 Light field interactions

As will be explained in Chapter 2, the atom-light interaction leads to two distinct forces that act on an atom. The dissipative scattering force arising from the absorption and spontaneous emission of light can lead to cooling; first proposed in 1975 [61, 62]. In 1985 Chu *et al.* demonstrated what is now called 'laser cooling' by cooling an atomic gas in 3-dimensions [63]. The addition of a magnetic field, creating a magneto-optical trap, allowed both the cooling and trapping of atoms [64]. Although an excellent method of collecting and trapping cold atoms, the incoherent and dissipative process is undesired in atom optics.

The second atom-light force is the optical dipole force which arises from the interaction between the atom's electric dipole moment and an inhomogeneous light-field. The coherent scattering by the absorption and stimulated emission of photons means the force is conservative. In Chapter 2, where the theory of dipole trapping is discussed in more detail, it will be shown that the sign of the detuning of the trapping laser's frequency from the atomic resonance frequency affects the type of trap formed. If the detuning is positive (blue-detuned) the atoms are attracted to regions of intensity minima, which has the advantage of minimising heating caused by scattering. If the detuning is negative (red-detuned) the atoms are attracted to regions of intensity maxima and unless the detuning is large, significant heating can occur.

The use of a dipole trap for atoms was first proposed in 1962 by Askar'yan [65] and the idea was developed further by Letokhov [66] and Ashkin [67, 68]. In 1978 Bjorkholm *et al.* focused an atomic beam co-propagating with a laser [69]. The first optical trap for atoms was demonstrated in 1986 by Chu *et al.* [70].

The dipole force can be used to perform atom optics (see ref. [15] for a review). For example, in 1992 Sleator *et al.* demonstrated focusing by reflecting a laser off a glass plate causing a standing wave to be set up, which resulted in an approximate parabolic potential at the anti-nodes of the wave [71]. An atom mirror can also be constructed from the evanescent wave of blue-detuned light subject to total internal reflection within a glass block [72, 73].

However, the dipole force is most often used in the context of guides to transport, or traps to store cold atoms. Laser guiding has been achieved both in free space [74, 75, 76, 77, 78], within Laguerre-Gaussian light beams [79] and also within optical fibers [80, 81, 82, 83]. Bose-Einstein condensates have also been transported from one chamber to another with an optical tweezer [84]. Further details of optical guiding experiments can be found in the reviews [85, 86].

The crudest example of a dipole trap is a tightly focused red-detuned laser beam which confines in all three spatial directions. An excellent review of the variations in dipole trap designs and operation can be found in ref. [87]. The problem of heating in red-detuned traps can be reduced by using far-off resonance optical traps [88]. At extreme detunings the traps can be viewed as Quasi-Electrostatic traps (QUESTs), where the atomic polarisability behaves as a static quantity. This trap for cold atoms was first demonstrated by Takekoshi *et al.* using a CO_2 laser and was shown to have negligible scattering [89, 90]. As the ground state dipole potential does not depend on the hyperfine states of atoms, different atomic species and states can be trapped simultaneously [91, 92]. One further advantage of using a CO_2 laser with its long wavelength ($\lambda_T = 10.6\ \mu m$) is that an optical lattice created from interfering multiple beams will have large lattice spacings. It is therefore possible to observe and manipulate individual sites [93, 94].

In the race to produce the first BEC, the optical trap was largely ignored in favour of magnetic traps. At that time the low collision rates resulting from a low initial phase-space density made optical traps unsuitable for evaporative cooling to quantum degeneracy [95]. Instead rf-evaporation out of magnetic traps was used [96]. Subsequent research groups followed the magnetic trap route, and it is only in recent years that optical traps have become popular again in the BEC community. In 2001 Barrett *et al.* produced the first all-optical BEC by evaporating ^{87}Rb atoms using a crossed CO_2 dipole trap [97]. Scaling laws for evaporation out of dipole traps were studied by O'Hara [98]. The very first ^{133}Cs BEC was obtained using dipole trap evaporation [99]. Recently a compressible crossed dipole trap was used to produce a ^{87}Rb BEC [100, 101] and an optical surface trap was used to create a ^{133}Cs BEC [102]

In general the optical dipole force is much weaker than the magnetic force discussed earlier, with typical trap depths on the order of 1 mK and 100 mK respectively. However there are a number of advantages, both fundamental and practical, of using optical rather than magnetic forces to manipulate and trap neutral atoms. The variety of atomic states and species available for trapping is much larger. For example, atoms can be trapped in their lowest internal state thus avoiding two body loss mechanisms and elements without a ground state magnetic moment can be trapped (eg. Ytterbium [103]). Furthermore, multiple spin states can be trapped simultaneously, an example of this is the spinor BEC experiment of Barrett *et al.* [97]. If no magnetic fields are present then Feshbach resonances can be used to tune the scattering length [104]. On a practical front, high magnetic field gradients require coils in close proximity to the vacuum chamber, thus reducing optical access for cooling beams. The high currents flowing in the coils may also require water cooling. Optical traps do suffer from disadvantages including: small capture volume; inefficient loading; the extra complication of another laser system; extra dangers from intense and far-infrared laser light.

Optical lattices

Periodic arrays of traps, called optical lattices, can be created by interfering multiple light fields [105, 106]. These crystals built from light have applications in simulating condensed matter systems and in quantum computing. In recent years, interest in optical lattices has been heightened by populating the lattices with BECs or degenerate Fermi gases. An exciting development is the reversible Mott insulator transition performed by Bloch *et al.* [107]. A BEC is placed into a 3D optical lattice with low enough trap depth to allow quantum tunneling between sites, thus allowing the phase coherence to be retained. By ramping up the laser intensity, the tunneling freezes out slowly enough to allow each site to be populated with exactly the same number of atoms per site. A number coherence has been created at the expense of destroying the phase coherence, as the atoms can no longer communicate through the potential barrier. The potential can now be lowered, resulting in the destruction of the number coherence but the rebirth of the phase coherence.

One extension to the experiment was to perform coherent spin-dependent transport of atoms [108]. In this case, an optical lattice was created that had a spin dependence; atoms in the lower hyperfine ground state experienced one potential, and atoms in the upper hyperfine ground state experienced another potential. By changing the polarisation of the lasers, it was possible to move the two potentials in opposite directions. By placing atoms in a quantum superposition of the ground and excited states, and then shifting the lattice sites, it was possible to coherently transport atoms.

Another recent experiment by Phillips *et al.* demonstrated patterned loading of BECs in optical lattices [109]. The experiment started with a BEC placed into an optical lattice. Then a second lattice, with lattice spacing an integer m times smaller than the original, is switch on. In the final stage the original lattice is switched off, leaving the second lattice populated at every m^{th} site.

1.2 Research aims and outline

The research presented in this thesis concentrates on the manipulation of cold atoms using magnetic and optical fields. There are two parallel topics of research. The motivation, aims and scope of each area are outlined below.

1.2.1 Atom guiding and focusing

Many cold atom experiments employ a double-chamber vacuum setup that is differentially pumped. The first collection chamber generally employs a relatively high pressure ($\sim 10^{-9}$ Torr) magneto-optical trap (MOT) to collect a large number of cold atoms. These atoms are then transported to a lower pressure 'science' chamber to allow for longer trap lifetimes. The act of moving the atoms between the two regions results in an undesired density decrease unless steps are taken to counteract the atomic cloud's ballistic expansion. One approach is to catch the atoms transported into the science chamber in a second MOT. However, an undesirable feature is the restriction placed on subsequent experiments by the laser beams and magnetic-field coils required to realise the second MOT. An alternative approach is to focus or guide the atoms such that they can be collected in a conservative trap. This would be ideal for remotely loading tight traps with relatively small depth, e.g. optical dipole traps [87], atom chips [31, 110, 111], miniature magnetic guides [112, 113, 114], and storage rings [115, 116]. Furthermore, a very similar procedure could be used in atom lithography [117] and a cold low-density atomic source for fountain clocks [11].

In comparison to an unfocused cloud, the density of the cloud can be increased by many orders of magnitude after magnetic focusing. To date, the studies of pulsed magnetic focusing have been analysed under the assumption that the magnetic lens potential is harmonic - this work addresses the validity of this approximation, and the effects of aberrations. Lens designs for 1D and 3D are presented that minimise aberrations due to the lens potential's departure from the perfect harmonic case. The timing calculations required to bring an atomic cloud to focus after either a single- or double-impulse are explained and the lens system is modelled in terms of $\mathcal{ABCD}$ matrices.

In addition, research presented in this thesis investigates a far-off resonance laser guide to radially confine a vertically launched atomic cloud. The optimisation of the guide parameters was studied, and an analysis of loss mechanisms are presented. However, the atoms remain largely unperturbed in the axial direction. The hybrid technique of combining radial confinement, via far-off resonance guiding, with an axially focusing magnetic lens is investigated.

1.2.2 Enhanced loading of optical lattices

When atoms are trapped within a 3D quasi-electrostatic optical lattice the long trap lifetimes, periodic structure, high trap frequencies and large lattice spacings make the system ideal to implement quantum information. The system satisfies the "DiVincenzo" criteria for creating a suitable quantum computer [118, 119].

One obstacle to overcome is the problem of a differential light-shift. For a CO_2 dipole trap the excited state has a ~ 2.6 times larger shift than the ground state. This has the undesired effect of turning the laser cooling mechanism into a heating mechanism in regions of high intensity. Thus loading is inhibited. Recently colleagues at Durham University have shown it is possible to engineer the light-shift by adding a second laser frequency [120]. The introduction of a Nd:YAG laser was shown to enhance the loading into a 1-Dimensional CO_2 lattice.

The second half of this thesis describes the design and construction of a 'second generation' experiment. The aim is to produce a face-centred cubic CO_2 lattice and load Rb atoms into it. Once complete the goal is to test a proposal that light-shift engineering can be performed with a diode laser operating close to the laser cooling frequency transition. Furthermore, it is planned to implement qubit rotations on lattice sites [121, 122] and ultimately produce entanglement between sites.

1.3 Thesis structure

Chronology and the immediate application of new material have been sacrificed to present the work in a methodical order: background → theory → experimental method → results and discussion → conclusions. The structure of the thesis is depicted in Figure 1.1. The research has two parallel areas of research (magnetic and optical potentials) and this is manifest in the thesis structure. Diversions from this structure, long proofs and supplementary information have been placed in the appendices. Special mention should be made of: common abbreviations (Appendix A); symbols and their meanings (Appendix B); values of fundamental constants (Appendix C); atomic structure of Rubidium (Appendix D). At the end of each chapter a summary of the key results is presented.

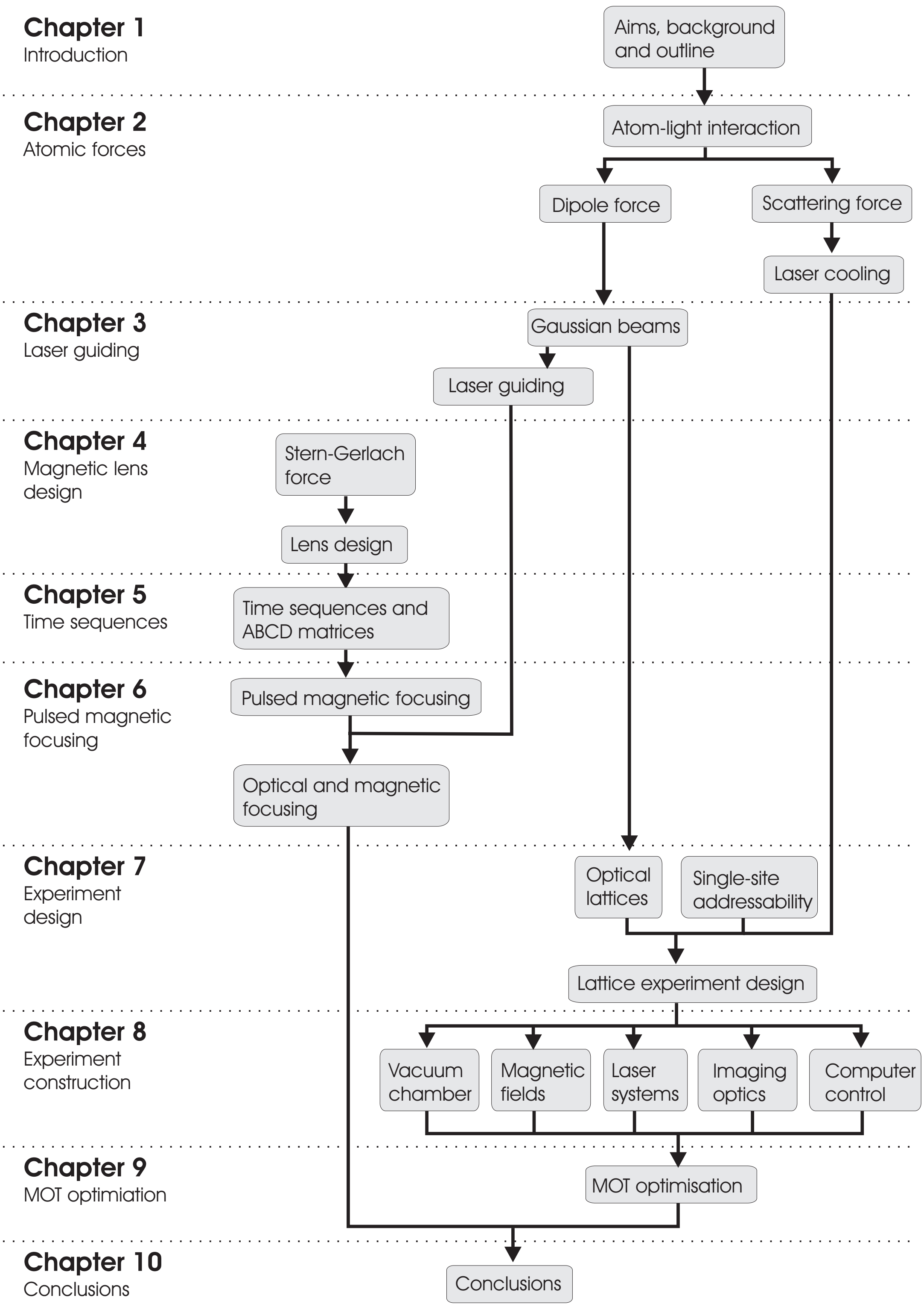

Figure 1.1: A schematic diagram of the thesis structure.

1.4 Publications

The work in this thesis has been partially covered in the following publications:

- *Single-impulse magnetic focusing of launched cold atoms*,
  M. J. Pritchard, A. S. Arnold, D. A. Smith and I. G. Hughes,
  J. Phys. B: At. Mol. Phys. **37**, pp. 4435-4450 (2004).

- *Double-impulse magnetic focusing of launched cold atoms*,
  A. S. Arnold, M. J. Pritchard, D. A. Smith and I. G. Hughes,
  New J. Phys. **8** 53 (2006).

- *Cool things to do with lasers*,
  I. G. Hughes and M. J. Pritchard,
  Accepted for publication in *Physics Education.*

- *Transport of launched cold atoms with a laser guide and pulsed magnetic fields*,
  M. J. Pritchard, A. S. Arnold, S. L. Cornish, D. W. Hallwood, C. V. S. Pleasant and I. G. Hughes,
  In preparation.

- *Experimental single-impulse magnetic focusing of launched cold atoms*,
  D. A. Smith, A. S. Arnold, M. J. Pritchard, and I. G. Hughes,
  In preparation.

Chapter 1 summary

- The research history of magnetic and optical manipulations of cold atoms has been briefly presented.
- The thesis aims have been stated.
- The thesis structure has been explained.
- Publications produced during the Ph.D have been listed.