

Chapter 1

Introduction

The laser trapping and cooling of atoms has been a rapidly growing field since its inception in the 1970s. A variety of optical trapping and cooling forces have been discovered and employed successfully on atomic gases. These technologies have made possible a host of advances, including more accurate atomic clocks, atom lithography, atomic interferometry, and the creation of quantum degenerate gases [1]. In addition, several precision measurements are being performed using these techniques, including the asymmetry of nuclear β -decay, the electric dipole moment of the electron, and parity non-conservation in electronic transitions of atoms.

The precision measurements listed above require large samples of rare atoms. The most sensitive measurement of parity non-conservation [2] required many grams of Cs per week, and 350 hrs of data collection. Such large quantities of radioactive elements are generally unavailable; production rates of 10^5 /s are typical [3]. Therefore, there is a need for efficient collection and manipulation of these atoms to make improved precision measurements possible.

The work presented here represents a series of advances that have implications for most of the topics mentioned above. The original motivation for these advances was to develop tools for making a precision measurement on radioactive alkali atoms. These advances therefore include an efficient technique for transferring atoms out of an initial magneto-optical trap (MOT) into a slow, bright atomic beam. They also include the efficient collection of radioactive Fr into a MOT. The majority of this work is dedicated to the description of a new type of laser trap that may prove useful for precision measurements. The properties of the trap are discussed, as well as the mechanisms developed to transfer atoms into it as efficiently as possible. Finally, cooling mechanisms in the trap are explored. While cooling may not be necessary for precision measurements, it is very important for achieving quantum degeneracy, and may make this trap useful for attaining Bose-Einstein Condensation using purely optical techniques.

1.1 Atomic Beams and the Development of Neutral Atom Traps

Since the beginning of modern atomic physics, effusive atomic beams have played a central role. The study of beams has led to the development of most of the tools in the lab used to produce this work, the first part of which (Chapter 2) is itself a useful advance in the technique of beam control.

In the 1920's, Stern and Gerlach first discovered the quantized nature of spin angular momentum by observing the deflection of a beam of Ag atoms [4, 5]. In the 1930s and 40s, I. I. Rabi developed the concept of nuclear magnetic resonance in beams of Na [6], laying the groundwork for the MASER and then the LASER, the principal tool of atomic physics as it is practiced today. In general, these beams were made by heating samples of Ag or Na in a container with a small aperture. The resulting increase in vapor pressure in the container caused the atoms to exit the aperture, forming a beam. Beams made this way were poorly collimated and moved very fast (on the order of 1000 m/s). However, they became the basis of seven generations of atomic time standards in Boulder, Colorado and around the world.

Forty years after Rabi's work, and with an interest in improving the time standard, Phillips and Metcalf successfully decelerated a beam of Na atoms using laser light and a magnetic field [7]. This technique, called the "Zeeman slower", is still used today. The key to the success of the technique is the application of a spatially varying magnetic field that tunes the atoms into resonance with the counter-propagating laser as they decelerate, in order to counteract the changing Doppler shift. Atoms leaving the oven with a high velocity and therefore a large positive Doppler shift absorb photons from a laser directed toward the beam and tuned near to the atomic resonance frequency. This laser exerted a "spontaneous scattering force" on the atoms. Each time the atom absorbs a photon from the laser beam, its momentum decreases by the amount of momentum carried by the photon, $\hbar k$. The photon is then reemitted in a random direction. Therefore, on average the atoms slow down as they move toward the laser beam until they are out of resonance with the laser. But by reducing the applied magnetic field, the atoms are shifted back into resonance with the lasers, absorb more photons, and are further slowed. Unfortunately, there is no cooling in the transverse direction, and in fact the spontaneous emission of photons in random directions gives rise to heating in the transverse dimensions. Thus as the longitudinal velocities approach the transverse velocities (≤ 15 m/s), the atoms diffuse randomly and densities are therefore limited. Another implementation of the slowed beam, such as the chirp-cooled beam [8], does not require magnetic fields. Instead, the frequency of the laser light is varied in time, in order to stay resonant with the atoms.

An important extension of the scattering force to three dimensions occurred when a so-called optical molasses was loaded with the chirp-cooled beam [9]. Optical molasses relies on the same spontaneous scattering force described above, but in three dimensions. Laser beams from six directions intersect at the end of the slowed beam, and their frequency is detuned several linewidths from resonance. When an atom in the molasses region moves toward one of the laser beams, it will be Doppler shifted into resonance with that beam and absorb photons from it until the atom slows down in that direction. The atom must then reradiate the photon in a random direction, which results in heating. The Doppler cooling temperature limit, or "Doppler Limit" T_D is then set by a balance between the molasses cooling and the heating that results from the spontaneously emitted photons. In general, this limit depends only on the natural

linewidth γ of the atomic transition [10]:

$$T_D = \frac{\hbar\gamma}{2k_B}$$

where \hbar is Planck's constant over 2π and k_B is Boltzmann's constant. A temperature consistent with the Doppler limit was initially observed in a cloud of Na atoms at 240 μK [9].

Several years later, Lett *et al.* [11] cooled Na to below the Doppler limit in an optical molasses, to 43 μK . No reasonable explanation of this surprising sub-Doppler cooling existed until two groups [12, 13] proposed a polarization gradient cooling mechanism. They explained that the counter-propagating, orthogonally-polarized molasses beams form a standing wave. In this case, the polarization of the standing wave changes every $\lambda/4$. When the polarization reverses, the direction of optical pumping and also the polarization-dependent light shifts of the atom change. An atom tends to be optically pumped into internal states with lower potentials as it travels through the standing wave. The time lag between traveling into the new polarization and optical pumping causes the atoms to be continuously pumped from deep potentials into shallower ones. Thus the atoms tend to move uphill more than down, and are therefore cooled in this so-called "Sisyphus" mechanism.

The first neutral atom trap to use the spontaneous scattering force was made in 1987 by Raab *et al.* [14]. To turn an optical molasses into a magneto-optical trap (MOT), the lasers must be circularly polarized and they must intersect in the center of a quadrupole magnetic field. This field is zero in the center of the trap, and increases in magnitude as atoms move away from this field zero. Now the scattering force can provide spatial confinement as well as cooling. As an example, consider what happens to an atom in one dimension as it moves to the left in the potential. The magnetic field in this dimension is pointed away from the center, and the laser polarization is then arranged so that σ_- comes from the left and σ_+ from the right. As the atom moves to the left, the magnetic field breaks the energy degeneracy of the atomic spin orientations. Thus $\Delta m = -1$ transitions shift to lower frequencies, into resonance with the red-detuned laser beam coming from the left, and further out of resonance with the σ_+ beam from the right. Therefore the atom is always pushed back to the trap center and spatially confined.

Later, it was shown that the MOT could capture atoms directly from a room-temperature atomic vapor instead of a precooled atomic beam[15]. A vapor-cell MOT is much simpler to construct than a beam-fed MOT. However, it has the limitation of a background pressure of atoms being trapped. Thermal background atoms limit the lifetime of the MOT and heat the sample [16, 17]. Therefore, when long lifetimes are required, a two-chambered MOT is constructed. In this system, atoms are pushed out of the MOT in the high-pressure chamber with a resonant laser beam, through a magnetic hexapole atom waveguide formed with six permanent magnets, and into a second MOT in a chamber of lower pressure[18]. In this way, the vapor cell MOT can be used in applications requiring very long lifetimes, such as Bose-Einstein condensation[19].

Meanwhile, the quest to create a brighter, better atomic beam continued. The

spontaneous scattering force techniques described above for three-dimensional confinement was employed to cool the two transverse dimensions. In this way, the atom funnel was developed [20]. Similar two-dimensional compression was demonstrated by other groups [21, 22, 23]. These systems often require a complicated apparatus or laser configuration.

In Chapter 2, a novel method of creating a cold atomic beam is presented. While making use of modern trapping techniques, the design is much simpler than that of other cold beam demonstrations. Dubbed a low velocity intense source, or LVIS, it is made by creating a small leak in a MOT through which atoms exit in a collimated beam. Its simple design and implementation make it an excellent source for cold atoms. In addition, it is a highly efficient source for an atomic beam, as the integrated flux in the beam can be up to 70% of the loading rate of the MOT.

After the publication of the first LVIS results in 1996 [24], it has been used as a source of atoms for several applications. An LVIS beam has been used to load a second MOT [25], with a transfer efficiency of $67 \pm 15\%$, limited only by beam divergence. Williamson *et al.* [26] transferred ^{39}K and ^{40}K a distance of 35 cm from a modified pyramidal trap [27] using an LVIS-like technique. Unfortunately, the transfer efficiency was limited to 6%, perhaps due to poor collimation in the pyramid configuration. In addition, atoms from the LVIS beam have been successfully guided in an optical fiber [28] and a magnetic waveguide [29].

1.2 Trapping Radioactive Elements

Chapter 3 describes the efficient transfer of radioactive ^{221}Fr atoms from a room-temperature vapor into a MOT. This represents a major advancement over the conventional vapor cell MOT technique described above. Typical vapor cell MOTs are inefficient for two major reasons. First, the probability of an individual atom in the vapor to be captured by the MOT is not optimized, in part because the volume of the vacuum chamber far exceeds the capture volume of the MOT (ie. the region of overlap of all 6 laser beams). Second, the alkali atoms tend to stick to and react with metal and glass surfaces, so that the majority of the atoms of interest in the chamber are adsorbed in a monolayer on the surface, and therefore cannot be trapped.

To circumvent the first problem, a redesigned vacuum chamber minimizes the chamber volume while maximizing the capture volume [30]. To solve the second, non-stick dryfilm coatings similar to those developed for optical pumping vapor cells are used to coat the trapping cell [31]. In addition, large, high-powered laser beams and optimized detunings improve the capture probability [32]. By using very large laser beams and high powers, along with a coated trapping cell almost completely illuminated with the trapping lasers, we demonstrated a ^{221}Fr trapping efficiency of over 50%. This represents a large improvement over previous radioactive trapping results. In addition, this experiment offers the advantage of a laboratory source to produce Fr [33] instead of a particle accelerator.

Other groups have continued to pursue trapping of radioactive atoms since the demonstration of the ^{221}Fr trap [34]. The Stony Brook collaboration has maintained an

active pursuit of spectroscopy in neutron-deficient isotopes of Fr (see for example Ref. [35]). Large samples of radioactive ^{82}Rb have been trapped using a technique similar to that described here, but with a trapping efficiency of only 0.3%. The poor trapping efficiency was largely due to poor coating performance, most likely caused by inductive heating of the foil to 800°C inside the cell, which damaged the dryfilm coatings. Using a Zeeman slower, 40,000 atoms of ^{21}Na [36] have been trapped in preparation for a β -decay asymmetry measurement.

1.3 Optical Dipole Traps

The optical dipole trap, another confinement technique developed in the 1980s, is based on an effect quite different from the spontaneous scattering force described above. While the scattering force acts in the direction of laser propagation, the dipole force acts in the direction of the gradient of the laser intensity. The optical dipole force was first observed in 1978 (See Ref. [37]), when researchers co-propagated a tightly-focused laser beam with an atomic beam. They observed that when the laser was tuned close to the atomic resonance frequency, the laser beam caused deflection and focusing of the atoms. Thus the light exerted a force on the atoms perpendicular to the direction of laser propagation!

The energy shift of atoms in a light field is often referred to as the AC Stark shift or the light shift, and the gradient of this energy shift gives the dipole force. The dipole force can be understood simply in terms of the atom electric polarizability. In free space, an atom in its ground state has no electric dipole moment. However, a static electric field induces a dipole moment in the atom, reducing its potential energy. Therefore a gradient in electric field draws the atom toward the region of space with higher field. The AC Stark shift arises in a similar fashion; the laser light is simply an electromagnetic field that reverses direction every few femtoseconds. If the laser frequency is below the atomic resonance, the dipole induced in the atom can “keep up”, or stay in phase with the light, and atoms are drawn to regions of highest intensity. If instead the light frequency is tuned above the atomic resonance, the dipole moment always opposes the electric field, and atoms are expelled from regions of highest intensity.

The dipole force was used to demonstrate the first optical trap for atoms in 1986 [38]. In this experiment, about 500 Na atoms were confined at the waist of a focused Gaussian laser beam. The laser beam contained about 220 mW, detuned about 650 GHz below the atomic resonance frequency and focused to a $10\ \mu\text{m}$ spot size. The trap was loaded from an optical molasses by rapidly alternating between the optical molasses and the optical dipole trap. The trap laser detuning Δ was much larger than the width of the transition, but not large enough to completely suppress the spontaneous scattering force.

Soon after this experiment, the MOT was developed and could trap many more atoms at much higher densities. Therefore dipole traps were generally abandoned until in 1993 when the far off resonance trap (FORT) was demonstrated [39]. This trap employed more power and larger detunings, and captured a few thousand atoms. The increased detunings allowed the much longer trap lifetimes than those of the original

dipole traps, in order to have strong dipole forces and simultaneously have low spontaneous scattering rates that cause negative effects. The dipole trapping force that actually does the trapping scales as Δ^{-1} , while the spontaneous photon scattering rate scales as Δ^{-2} . Spontaneous scattering, although many orders of magnitude lower in the FORT than the MOT, can still cause heating, decoherence, and scrambling of the internal states. Thus even if atoms are spin-polarized before they are stored in the dipole trap, the spontaneous scattering rate will tend to depolarize them [40].

Many other types of dipole traps have been developed that rely on large detunings and high powers. Blue-detuned light traps are also used. They have the advantage that atoms spend the majority of their time in the dark where they cannot absorb photons. However, these typically shallow traps tend to be difficult to construct and have large volumes and unusual heating effects.

Chapter 4 and Ref. [41] presents a novel kind of dipole trap called a circular FORT that takes advantage of an interesting aspect of the dipole force. When the dipole trapping beam is circularly polarized, the value of the light shift depends on the internal spin state of the atoms [42, 43]. Therefore, although we use small detunings of only a few nm, the spontaneous scattering of the circularly polarized light always returns the atoms to the same internal spin state. Although heating and decoherence still result, the atoms are not depolarized. Therefore this trap makes an excellent source of spin-polarized atoms for precision measurements.

Demonstration of the circularly polarized FORT, or “circular FORT,” first requires the efficient loading of a large atom sample. Although many groups have described their specific techniques for loading atoms into a dipole trap, no one has offered a detailed understanding of the many physical processes that govern the loading of the FORT. Therefore, Chapter 5 and Ref. [44] present a detailed study of the loading of the FORT as a function of the parameters of the MOT. A simple model is developed for the loading process and the loss processes unique to the FORT in the presence of the MOT light. Use of this model led to techniques which increased the number of atoms loaded into the FORT to 7×10^6 . Samples of this size are sufficient to consider precision measurements and novel dipole cooling schemes discussed below.

1.4 Cooling in Dipole Potentials

The spin states are non-degenerate in the circular FORT, much as they are in magnetic traps. Magnetic traps confine atoms using potentials arising from the interaction of the atomic magnetic moment with the magnetic field. Because they do not rely on light fields, spontaneous scattering does not occur, and trap heating can be limited to collisions with high temperature atoms in the vacuum chamber. In addition, two very powerful cooling schemes have been demonstrated in the trap. The first is forced evaporative cooling, in which the highest energy atoms of a thermal distribution are removed, leaving the cloud to return to thermal equilibrium at a lower temperature. This mechanism reduces the temperature rapidly, with minimal loss of atoms.

Because a magnetic trap relies on the Zeeman effect to produce confinement, different spin states of the atom have different dipole moments and therefore differ-

ing strengths of confinement. Using two of these spin states, a Sisyphus cooling was effectively demonstrated [45]. Atoms confined in a deeper potential were allowed to oscillate to their turning point, at which point they were transferred into the shallower state. After waiting a quarter oscillation period for the atoms to reach the bottom of the potential, they were transferred back to the deeper state. This powerful refrigeration technique cooled the atoms to nearly the recoil limit (ie. the temperature of an atom with the kinetic energy equivalent to 1 photon recoil). This mechanism is similar to the Sisyphus cooling described earlier; the biggest difference is that in this case, the potentials used for cooling are also used for confinement.

Both forced evaporation and this type of Sisyphus cooling are not feasible in traditional dipole traps. However, in the circular FORT the AC Stark shift splits the spin states, and both these cooling mechanisms become possible. In Chapter 6 the preliminary results of cooling in the circular FORT invoking the above methods is described. In this initial work, cooling from $280 \mu\text{K}$ to $40 \mu\text{K}$ is observed, due to one or both of the mechanisms described above. While substantial number loss accompanied this cooling, optimization of the cooling procedure should improve these initially promising results.