Advances in Laser Cooling Techniques

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A brief overview of laser cooling theory is given. Important techniques in laser cooling are then presented, including Zeeman slowing and optical molasses. Selected modern laser cooling schemes are discussed in latter sections, including the development of systems to cool single atoms and diatomic molecules.

I. INTRODUCTION

Since the 1970s, physicists have learned how to use lasers to cool atoms to temperatures close to absolute zero[1]. The work in the field has led to at least two Nobel prizes, one in 1997 for the development of laser cooling, and the second in 2001 for the create of Bose-Einstein condensates. Originally, the reason to cool atoms was to reduce the speed of their motion to allow for more precise measurements of atomic spectra and to improve the precision of atomic clocks. The first laser cooling experiments were carried out on ions trapped by electric fields and cooled by laser radiation. In comparison, it is more difficult to confine atoms at room temperature due to the smaller effect on neutral particles. Therefore, initial experiments slowed atoms in an atomic beam before confining them with a magnetic field (Zeeman cooling)[2]. Later on, Chu and colleagues [3] demonstrated a method known as optical molasses which cools atoms from all three dimensions to give very cold atomic vapor. In the following chapters, a brief overview of laser cooling basics is first given, and the theory behind laser cooling explained. Following this, a number of interesting experiments improving on older laser cooling techniques demonstrated more recently are discussed.

II. THEORY

A. Scattering Force

It was first suggested in the nineteenth century that radiation has momentum. It follows that when an object absorbs radiation, its momentum changes, and the force on the object equals the rate of change of momentum[4]. Therefore, the force equals the rate at which the light delivers momentum. Radiation of intensity I exerts a force on area A by:

$$F_{rad} = \frac{IA}{c} \tag{1}$$

Radiation forces have a dramatic effect on atoms because the peak absorption cross-section σ_{abs} is much greater than the physical size of the atom. Lasers produce collimated beams of light that can slow atoms in an atomic beam. A counter propagating laser beam exerts a force of $F = -\sigma_{abs}\frac{I}{/}c$ on an atom. Each absorbed photon gives the atom a kick in the direction opposite to its motion and spontaneously emitted photons go in all directions so that the scattering of many photons gives an average force that slows the atom.

B. Doppler Cooling

Laser cooling can be understood with simple arguments[5]. Consider an atom moving in the +x direction with velocity ν_x. Assuming that the atom interacts with a counter-propagating laser beam of frequency ν_L tuned to near resonance with one of the atomic transitions.

$$\nu_L = \nu_0 + \delta \tag{2}$$

Where ν_0 is the atomic transition frequency and the small detuning $\delta \ll \nu_0$. Since the atom is moving towards the laser source, the frequency seen by the atom will be up-shifted by the Doppler effect, resulting in the Doppler-shifted frequency:

$$\nu_L \simeq= \nu_0 + \delta + \frac{\nu_x}{c} \tag{3}$$

Hence, when $\delta = \frac{\nu_x}{c}$, the laser will be in resonance with those atoms moving in the +x direction. Every time the atom absorbs a photon, it goes into an excited state, then spontaneously emits another photon of the same frequency in a random direction. For each cycle this is repeated, there is a net change in momentum of the atom by the momentum of the photon $\frac{h}{\lambda}$ due to absorption. Since emission is in a random direction, the change in momentum due to emission averages to zero.

C. Zeeman Slowing

An early implementation of laser cooling was the use of a Zeeman slower to slow an atomic beam[2]. William Phillips (who shared the 1997 Nobel prize) and co-workers used the scheme showed in Fig.1. As atoms in the atom beam are slowed by the laser, the required detuning δ changes. Instead of changing the frequency of the laser to stay in resonance with the atoms (chirping), Phillips proposed the use of a magnetic field to change the energy level separation in the atoms. As the atoms propagate along the Zeeman slower, the magnetic field decreases. Hence, as the atoms absorb light and begin to slow down, their velocity changes, and hence their

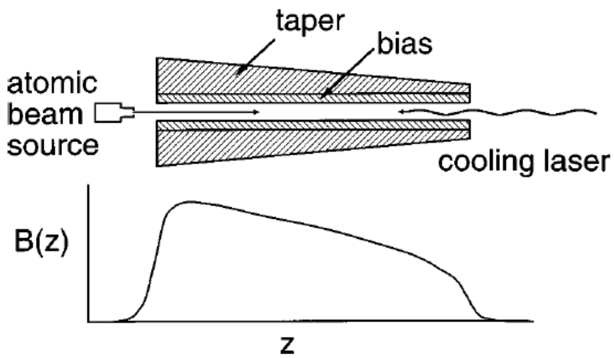

FIG. 1 Upper: Schematic representation of a Zeeman slower. Lower: Variation of the axial field with position.[2]

Doppler shift changes. This change is compensated by the change in Zeeman shift as the atoms move to a point where the field is weaker, which keeps them in resonance with the fixed-frequency laser. Eventually, all atoms are brought to a final velocity that depends on the details of the magnetic field and laser tuning. One advantage of the Zeeman cooling technique is the ease with which optical pumping problems are avoided. The atoms are always in a strong axial magnetic field, there is a well-defined axis of quantization that allows the use of selection rules for radiative transitions and avoid undesirable optical pumping.

D. Optical Molasses

Compared to an atomic beam where atoms are all moving in one direction and can be slowed by a single laser beam, atoms in a gas move in all directions. To reduce the temperature of atoms in a gas requires laser cooling in all three directions, by using three orthogonal standing waves.

The radiation forces from the laser beams balance each other for a stationary atom, while all other atoms will experience a radiation force from one of the 6 laser beams, each laser red detuned from the transition frequency. Just like in subsection II.A, we consider an atom moving only in the x-direction. We are concerned with the lasers propagating in the +x and x direction. Due to the Doppler shift of the atom, there will be an imbalance in the forces due to the two lasers. The laser which is propagating in the x direction is more strongly absorbed, which exerts a frictional, damping-like force:

$$F_{molasses} = -\alpha\nu \tag{4}$$

The analogy of a particle in a viscous fluid led the first ones to perform it [3] to call it the optical molasses technique. In their experimental setup shown in Fig.2, the authors hit the same spot in their vacuum chamber with red-detuned lasers from 6 directions. The 3 counter propagating pairs of lasers have zero net effect on stationary atoms, while slowly cooling atoms with low velocities in all 3 dimensions of space. The damping coefficient α can be shown to be:

$$\alpha = 4\hbar k^2 \frac{I}{I_{sat}} \frac{-2\delta/\Gamma}{[1+(2\delta/\Gamma)^2]^2} \tag{5}$$

Damping requires a positive value of α hence the detuning $\delta = \omega - \omega_0 < 0$, a red frequency detuning, as mentioned earlier. As shown in Fig.3, depending on the direction the atom is traveling ($+x$ or x), the force exerted on the atom is different and slows down the velocity of the atom for values of ν close to zero.

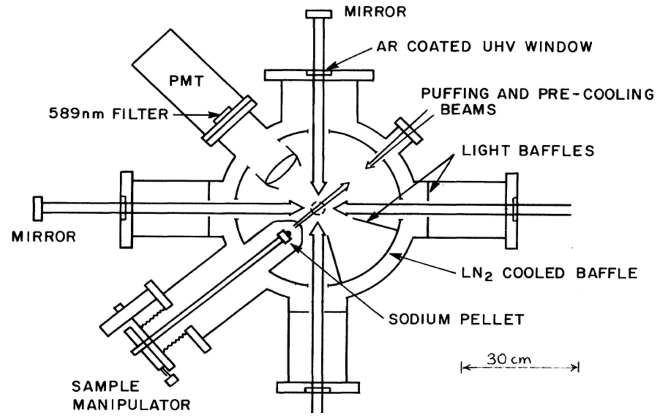

FIG. 2 Schematic of vacuum chamber and intersecting laser beams and atomic beam used by Chu and co-workers to cool trap Na atoms. The vertical confining beam is indicated by the dashed circle in the center.[3]

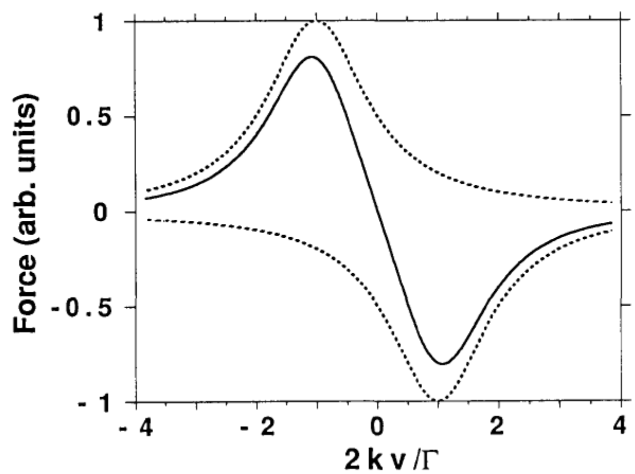

FIG. 3 Force versus velocity for $\delta = -\gamma/2$ and low intensity. The dashed curves are the individual forces due to the two counter propagating beams and the solid curve is the net force.[6]

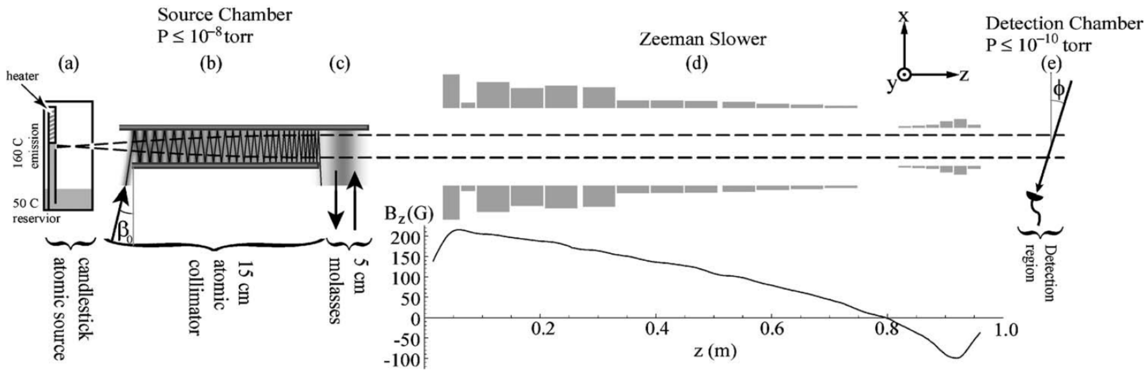

FIG. 4 An atom beam is produced using a candlestick atomic beam source (a) with a divergence angle of 100 mrad. The atoms then pass through 20 cm of transverse collimation (b) and cooling (c). They are then longitudinally decelerated and cooled by means of a 1 m long Zeeman slower (d), with z-axis magnetic field shown in the lower graph.[7]

III. RECENT EXPERIMENTS

IV. HIGH FLUX SOURCE OF COLD RUBIDIUM ATOMS

The authors Slowe et al. present in their 2005 paper[7] a high flux source of cold rubidium atoms exceeding 3×10^{12} atoms/s, a transverse temperature of 3mK and a longitudinal temperature of 90 mK. Their setup is shown in 4. In order to achieve this, they use multiple laser cooling techniques in their setup. First they use a 15 cm atomic collimator for transverse cooling. This is followed by 5 cm of 2D optical molasses. The atomic beam is then longitudinally slowed and cooled by means of a Zeeman slower, which allows for tuning of final atomic beam velocity.

The atomic beam produced by the candlestick has a 100 mrad divergence angle. If this beam is coupled into the Zeeman slower without the atomic collimator, the transverse velocity spread of the atoms will become comparable with the longitudinal velocity as the beam is decelerated. Thus, authors implement a two-stage transverse cooling setup. First, they put the atomic beam through 15 cm of transverse collimation by 2 pairs of near plane-parallel 15×2.5 cm mirrors. This is similar to the schematic shown in Fig.5 by Hoogerland et al. [8]. The laser beam is coupled into each set of mirrors at a small angle β_0, which allows for multiple reflections (50) along the entire path of the 15 cm mirrors. Compared to regular optical molasses discussed in Sec. II.D, the multiple reflections increases the interaction time between the laser and the atomic beam, leading to much more efficient atomic beam collimation. To further increase atom density, the atomic beam is then put through 5cm of 2-D optical molasses, with a red-detuned laser, as shown in Fig. 4(c). The authors note that while the 15 cm of collimation greatly increases atom flux, the laser beams in the 5 cm optical molasses region are chosen to be much closer to resonance, leading to increased beam flux.

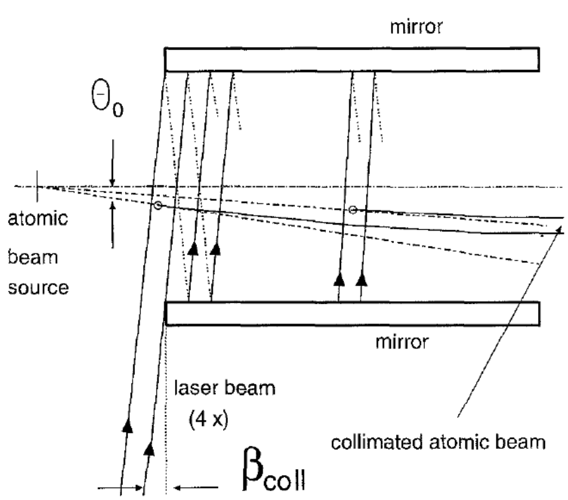

FIG. 5 Close-up schematic view of similar setup to Fig.4(b), implemented earlier in Ref. [8].

Finally, the atom beam is put into a Zeeman slower shown in Fig.4(d) used in the zero-crossing configuration. This slows the longitudinal velocity of the atoms from 300 to 40 m/s over the 1 m length of the Zeeman slower.

The three stage beam brightener introduced here uses only moderate laser power of 140 mW. The increase in flux and brightness is larger than possible in any simple one-stage transverse laser cooling scheme. They can easily be used for other atomic systems and applied to a large variety of experiments requiring collimated atomic beams.

V. CAVITY COOLING OF A SINGLE ATOM

While conventional methods to laser-cool atoms rely on repeated cycles of optical pumping and spontaneous emission of a photon by an atom, alternative methods have been proposed to cool single atoms by strongly coupling them to a high-finesse cavity. In this paper, Maunz et al. [9] demonstrate cavity cooling of single rubidium atoms stored in an intracavity dipole trap. The technique results in extended storage times and improved atom localization.

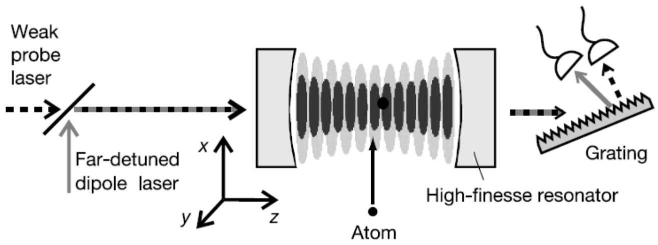

FIG. 6 Experimental set-up of [9]. The high-finesse cavity ($F = 4.4 \times 10^5$) is excited by a weak near-resonant probe field and a strong far-red detuned dipole field. 85Rb atoms are injected from below. Behind the cavity, the two light fields are separated by a grating. The dipole light is also used to stabilize the cavity length with a radio frequency sideband technique. It is generated by a grating- and current-stabilized diode laser with a linewidth of 20 kHz r.m.s.

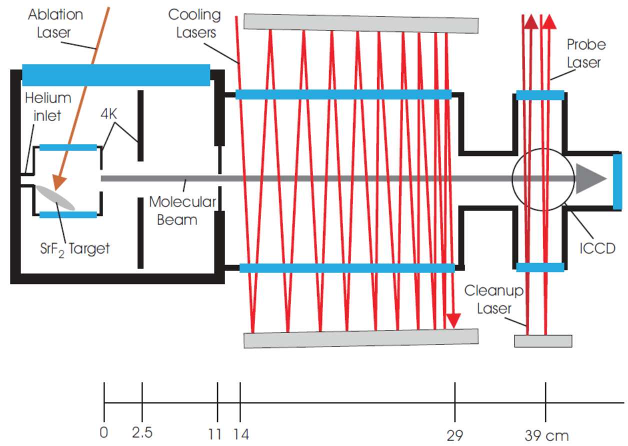

FIG. 7 Schematic of the experimental apparatus of[11].

The basic idea behind cavity cooling is simple. We start by considering a standing-wave optical cavity resonantly excited by a weak probe laser blue detuned from atomic resonance. Intracavity intensity is strongly affected by the atom. In a high finesse cavity, the intensity cannot drop instantaneously when an atom moves away from a node. Instead, the blue shift of the cavity frequency leads to an increase of the energy stored in the field, at the expense of the atoms kinetic energy. This additional energy (photons) escapes from the cavity, and is thus removed from the atom. Since the cooling process does not require atomic excitation, it follows that the lowest attainable temperature is no longer limited by atomic linewidth as with Doppler cooling, but is instead limited by the linewidth of the cavity.

In the experiment described here (Fig.6), a weak near-resonant probe laser is used to observe and cool the rubidium atoms. A strong far-detuned dipole laser serves to trap the atom. The detuning of the probe laser with respect to the cavity and atom, are chosen as a compromise between ideal detunings for detection and good cooling conditions, while also maintaining a very low excitation of the atom at any moment of the experiment. The result is that the presence of an atom at an antinode reduces the transmission of probe light through the cavity by a factor of 100. This allows the detection and manipulation of the atom with a high signal-to-noise ratio and a high bandwidth.

In contrast to free space laser-cooling techniques, the cooling force acts mainly by exciting the cavity part of the coupled atom-cavity system. Strong cooling forces can be achieved while keeping the atomic excitation low. The strength of the cooling force is estimated to exceed the force expected for free space Doppler cooling by 14 times. This technique could serve as a basis for cooling molecules or Bose Einstein condensates. Another application suggested by the authors is to cool the motion of an atom with a stored quantum bit.

VI. LASER COOLING OF A DIATOMIC MOLECULE

Molecules have a number of properties that make them advantageous for a wide range of applications[10]. The simplest molecules are vibrate, rotate, and may have a permanent electric dipole moment that enables them to interact over relatively long distances. This makes them useful for studying chemical reactions, simulation the behaviors of condensed-matter systems and testing fundamental symmetries. However, all this requires that the internal states of the molecules have to be controlled with a precision similar to that of atoms. For atoms, laser cooling techniques allow this to happen. With molecules, it has been more challenging and the authors of [11] report and experiment where they laser cool diatomic molecule strontium monofluoride(SrF). They have identified an optical cycling scheme in SrF such that laser cooling of this molecule requires only three lasers, and have successfully implemented the scheme.

As seen in Fig.7, the scheme used here is similar to the one mentioned earlier in Sec. IV and in [8]. The SrF atom beam is intersected at nearly 90^{circ}. The lasers reflect back and forth at a slight angle, so they intersect the SrF atom beam 75 times in the 15cm long cooling region. 10 cm from the end of the cooling region, laser-induced fluorescence (LIF) is imaged to obtain the spatial distribution of the molecular beam. They are shown in Fig.8, where the black line is without cooling lasers, blue line is with the cooling lasers blue detuned, and the red line is with the cooling lasers red detuned. We observe that for a red detuning, we observe significant narrowing of the molecular beam and enhancement of molecules with low transverse velocity (lower of Fig.8). For blue detuning (upper Fig.8), we observe a broadening of the molecular beam. These are the expected results for Doppler cooling and heating.

The results of this experiment have immediate implications for a number of future experiments such as improvement of statistical sensitivity of searches for electron electric dipole and nuclear anapole moments. In addition, the one-dimensional cooling is a step towards laser cooling of

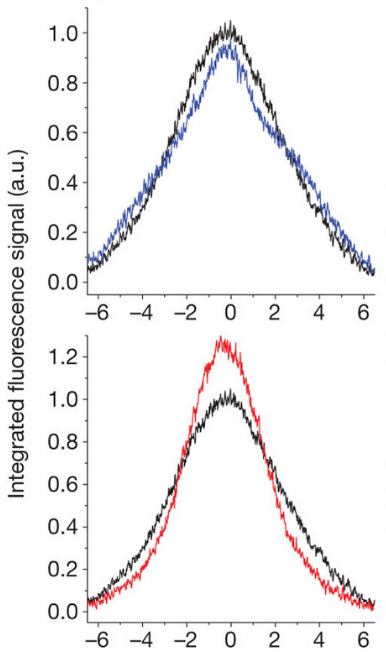

FIG. 8 Laser cooling of SrF from Ref.[11]. LIF in the probe region without cooling lasers in the interaction region (black), with cooling lasers and main pump laser red-detuned by $\delta = -1.5\Gamma$(red), and with cooling lasers and main pump laser blue-detuned by $\delta = +1.5\Gamma$(blue). $f = 46.4$ MHz, B=5 G, $\theta_B = 60^\circ$

molecules in three dimensions. The laser cooling techniques presented here are limited to those molecules that have closed electronic transitions with diagonal FCFs. However, because the set of diatomic molecules is so large, this subset contains a significant amount of molecules.

VII. CONCLUSION

This paper began by outlining the basics of laser cooling. Some modern techniques for laser cooling were then reviewed, but it is not an easy task to keep up with everything that has been done. Due to the practical applications of laser cooling, the field is large, and a lot of research has gone into the field to advance laser cooling techniques to its current state of the art. Its importance to science especially in physics research cannot be understated.

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