# LASER COOLING AND TRAPPING FOR THE MASSES

Photograph of cesium atoms trapped in a glass vapor-cell magneto-optical trap. The cell is a 6-sided cross with 2.5 cm diameter windows. The copper coils above and below the cell provide the inhomogeneous magnetic field. The trapped atoms are the bright bluish-white cloud at the center of the cell. They are excited to the 8S state to produce the blue fluorescence for the photograph.

**THERE HAVE BEEN DRAMATIC ADVANCES IN THE TECHNIQUES FOR** cooling and trapping neutral atoms using laser light. In particular, the use of inexpensive diode lasers and the vapor-cell trap have significantly reduced the complexity and cost of trapping atoms, which has opened the field to many additional researchers. Atomic densities of $10^{11}$ atoms/cm$^3$ have been obtained with temperatures of a small fraction of a millikelvin. In this article, we describe laser trapping techniques and discuss current applications of this technology, ranging from frequency and wavelength standards to basic physics research.

The primary force used in laser cooling and trapping is the recoil momentum transferred to an atom when photons scatter from it. This force is analogous to that applied to a bowling ball when it is bombarded by a stream of ping pong balls. The momentum kick that the atom receives from each scattered photon is small; a typical velocity change is about 1 cm/sec (room temperature gas atoms have typical velocities of a few hundred meters per second). However, by exciting a strong atomic transition, it is possible to scatter more than $10^7$ photons per second and produce accelerations on the order of $10^5$ m/sec$^2$ ($\sim 10^4 \bullet g$). The fundamental progress in this field has been in finding new ways to harness this acceleration so that it slows ("cools") the atoms in a sample to a particular velocity, usually near zero, and holds ("traps") them at a particular point in space.

## LASER COOLING

The cooling is achieved by using the Doppler effect to make the photon-scattering force depend on the velocity of the atom.[1] The basic principle is illustrated in Figure 1. If an atom is moving in a laser beam, it will see the laser frequency $\nu_{\text{laser}}$ shifted by $(V/c)\nu_{\text{laser}}$, where V is the component of the atom's velocity that is opposite to the direction of the laser beam. If the laser frequency is below the atomic resonance as a result of this Doppler shift, the atom will scatter photons at a higher rate if it is moving toward the laser beam (V positive) than if it is moving away (V negative). If we then consider the effect of sending laser beams from all six directions, the only remaining force is the velocity dependent part, which opposes the motion of the atom. This provides strong damping of any atomic motion and cools the atomic vapor. Chu *et al.* first used this configuration of laser fields to obtain very cold atomic samples, and gave it the descriptive name "optical molasses."[2]

A few years later, Lett *et al.*[3] found that, at certain laser frequencies, they could achieve atomic temperatures lower than could be explained by the Doppler cooling just described. This accidental discovery is now understood to arise from some very fortuitous atomic physics. As atoms move through the hills and valleys of potential energy produced by the standing-wave laser fields, the atoms tend to make transitions between states in such a way as to transfer their kinetic energy into that of the scattered photons very efficiently.[4]

## NEUTRAL ATOM TRAPPING

Although optical molasses can cool atoms, the atoms will still diffuse out of the region since there is no position dependence to the optical force. Position dependence can be introduced by using appropriately polarized laser beams and applying an inhomogeneous magnetic field. The magnetic field causes the atoms to be pushed to a particular point in space by regulating the rate at which an atom at a particular position scatters photons from the different beams. As well as holding the atoms, this greatly increases the atomic density since many atoms are pushed to the same point. This atom trap is referred to as the magneto-optical trap (MOT) or the Zeeman-shift optical trap (ZOT) in the literature.

Details of how the trapping works are somewhat complex for a real atom in three dimensions, so we will illustrate the basic principle using the simplified case shown in Figure 2. We consider an atom with a $J = 0$ ground state and a $J = 1$ excited state, illuminated by circularly polarized beams of light coming from the left and the right. Because of its polarization, the beam from the left can excite only transitions to the $m = +1$ state, while the beam from the right can excite only transitions to the $m = -1$ state. The magnetic field is zero in the middle, increases linearly in the positive x direction, and decreases linearly in the negative x direction. This field shifts the energy levels so that the $\Delta m = +1$ transition shifts to lower frequency as the atom moves to the left of the origin, while the $\Delta m = -1$ transition shifts to higher frequency. If the laser frequency is below the atomic transition frequencies and the atom is to the left of the origin, many photons are scattered from the $\sigma^+$ laser beam because it is close to resonance. The $\sigma^-$ laser beam from the right, however, is far from its $\Delta m = -1$ resonance and scatters few photons. The force from the scattered photons pushes the atom back to the zero of the magnetic field. If the atom

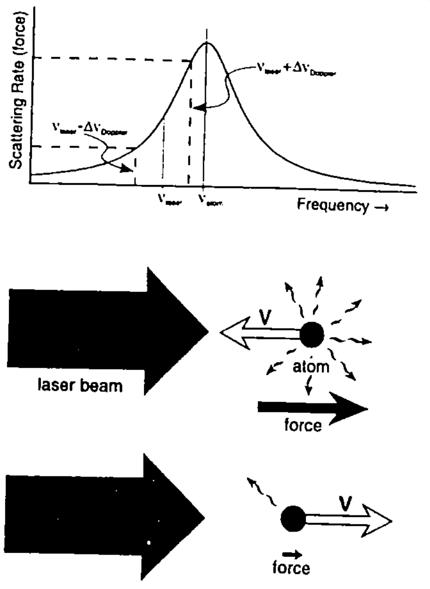

**Figure 1.** Velocity-dependent photon scattering force. The upper diagram shows the frequency dependence of the atomic excitation rate. The laser frequency $\nu_{\text{laser}}$ is tuned to the low frequency side of the atomic resonance. When an atom is moving toward the laser beam (middle of figure), it sees the laser frequency Doppler-shifted to higher frequency by the amount $\Delta\nu_{\text{Doppler}} = (V/c)\,\nu_{\text{laser}}$ and scatters many photons. When an atom is moving away from the laser beam (bottom), however, it sees the laser frequency Doppler-shifted to lower frequency and scatters very few photons. Thus, the laser photons exert a much larger force if the atom is moving toward the laser beam.

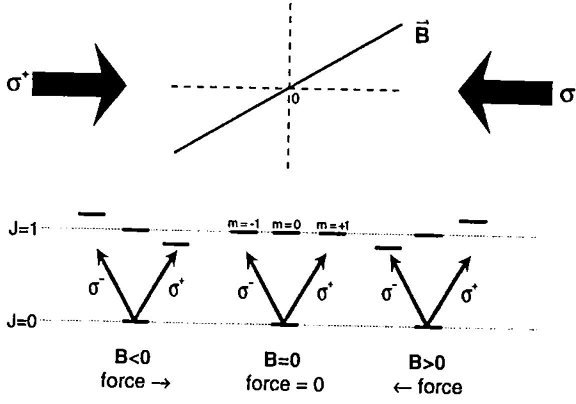

**Figure 2.** Magneto-optical trap (MOT) forces in one dimension for an atom with a $J = 0$ ground state and a $J = 1$ excited state. A magnetic field gradient of about 0.15 T/m (15 G/cm) is applied in a region of counterpropagating laser beams with circular polarizations of opposite helicity ($\sigma^+$ and $\sigma^-$). The upper diagram shows the laser beams and magnetic field and the lower diagrams show the atomic energy levels for negative magnetic field (left diagram, corresponding to an atom to the left of the origin), zero magnetic field (center diagram, atom at the origin), and positive magnetic field (right diagram, atom to the right of the origin). The magnetic field shifts the $\sigma^+$ transitions closer to resonance when the atom is to the left of the origin. When the atom is to the right of the origin, the $\sigma^-$ transitions are shifted closer to resonance. This causes a position-dependent force that pushes the atom toward the origin.

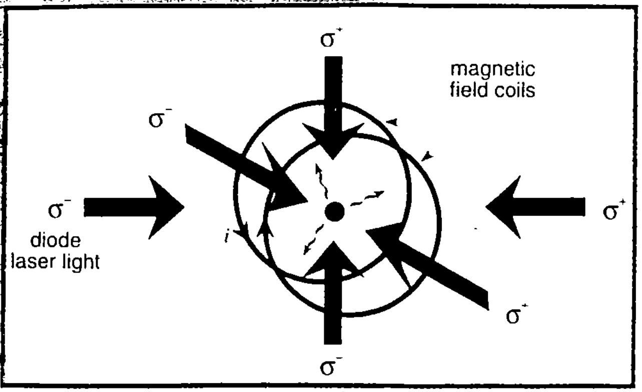

**Figure 3.** Schematic diagram of a three-dimensional MOT.

moves to the right of the origin, exactly the opposite happens, and again the atom is pushed toward the origin.

Although it is more complicated to extend the analysis from one to three dimensions, experimentally it is quite simple, as shown in Figure 3. As in optical molasses, laser beams illuminate the atom from all six directions. Two symmetric magnetic field coils with oppositely directed currents create a magnetic field that is zero in the center and changes linearly along the x, y, and z axes. If the circular polarizations of the lasers are set correctly, a linear restoring force is produced along each direction. Damping in the trap is provided by the cooling forces discussed above. It is convenient to characterize the trap's "depth" in terms of the maximum velocity that an atom can have and still be contained in the trap. This maximum velocity is typically a few times the velocity at which the Doppler shift equals the natural linewidth of the trapping transition ($V_{max} \approx 20$ m/sec).

### A Brief History

The experimental history of laser cooling and trapping began with laser cooling of trapped ions.[5] The first major neutral atom work was the cooling and slowing of atomic beams in one dimension by the groups of Hall[6] and Phillips,[7] who used laser light that propagated opposite to the atomic beam. The slowed atomic beams provided low velocity atoms that could then be further cooled using optical molasses. Chu, Ashkin, and co-workers then demonstrated the first optical trap by holding the molasses-cooled atoms at the focus of an intense laser beam.[8] The restoring force for this trap came from the interaction of the induced dipole moment of the atom with the light field, rather than the photon-scattering force discussed above. The scattering force has the obvious advantages that it can extend over a much larger distance, requires lower laser powers, and simultaneously cools the atoms. However, early attempts to use it for trapping were thwarted by the fact that the scattering force, by itself, cannot provide a confining potential in free space.[9] Pritchard *et al.* realized that this problem could be overcome by the use of inhomogeneous external fields to regulate the scattering force.[10] This quickly led to the demonstration of the MOT discussed above.[11] All of this work used sodium atoms, which started out in atomic beams that were slowed in 1-2 m long atomic beam machines. The slowing and cooling/trapping were accomplished using narrowband cw dye lasers.

This work demonstrated that it was possible to produce atomic samples with properties that were unprecedented. Densities on the order of $10^{11}$ atoms/cm$^3$ were obtained with temperatures of a small fraction of a millikelvin (V ≈ a few centimeters per second). Such gas samples provide large optical absorption without shifts and broadening due to the Doppler effect, since the atomic velocities are so low. A superior signal-to-noise ratio is achieved when probing atomic transitions because background noise due to nonresonant atoms is nearly eliminated. Also, problems caused by perturbations of optically excited levels due to atomic collisions (pressure shifts) are reduced for two reasons. First, the collision rate decreases as the atomic velocity decreases, and second, narrowband excitations can be detected at much lower densities (1/100) due to the absence of Doppler broadening. A final virtue of these samples is that the low velocities allow the interaction times between the atoms and electromagnetic fields to be nearly a second, rather than the fractions of a millisecond available in traditional atomic beams.

### Simpler Systems

While these experiments demonstrated tantalizing benefits, the size, cost, and complexity of the apparatus limited the potential applications. Recent simplifications in the technology have dramatically changed this situation. The two primary developments are the replacement of dye lasers by narrowband diode lasers (roughly a 100-fold reduction in cost, and even more in electrical power and size) and the vapor-cell MOT.

Near infrared diode lasers that can be tuned to the strong resonance lines of cesium and rubidium are readily available. Diode lasers have sufficient power since the intensities required for cooling and trapping are only a few milliwatts per square centimeter for these atoms. The typical linewidth (10 MHz or more) of inexpensive single-mode diode lasers is a problem. However, simple optical feedback schemes[12] reduce this linewidth to well below the natural linewidths of the relevant atomic transitions, which is the criterion necessary for trapping and cooling. Diode lasers have been used to slow beams of atomic cesium and rubidium, produce optical molasses, and optically trap these atoms in a MOT.[13] A variety of trapped-atom studies that were carried out with diode lasers revealed new information about very low temperature collisions and elucidated the photon-mediated interatomic repulsion that limited the density of trapped atoms.[14]

An atomic beam apparatus that included a 1 or 2 m long vacuum system was still required, however. This was subsequently eliminated by the invention of the vapor-cell trap,[15] which is simply a MOT that is established inside a small vapor cell. Rather than loading the trap from a slowed atomic beam, the atoms are captured directly from the low velocity tail of the Maxwell-Boltzmann distribution of a dilute room temperature vapor. Vapor-cell traps are now used routinely to produce very cold (as low as a few microkelvins) optically thick samples of cesium, rubidium, and sodium. The cells are constructed from glass or metal with glass windows. Fortunately, if one simply wants to obtain trapped atoms,

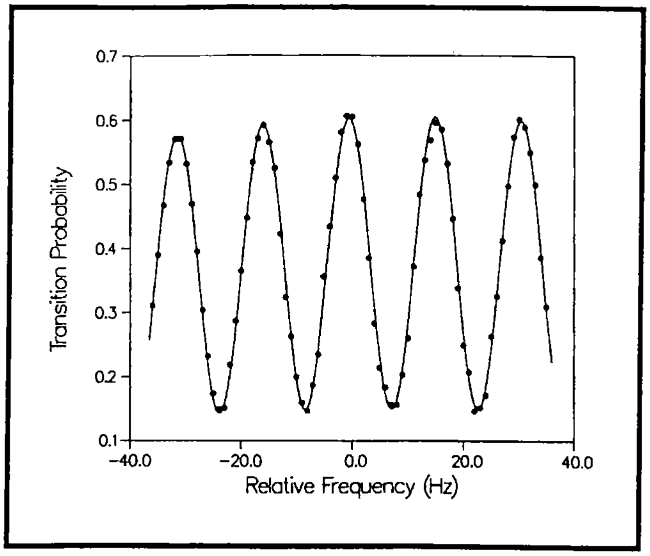

**Figure 4.** 9.2 GHz cesium clock transition spectrum (from Ref. 16) using atoms that were laser-cooled and trapped in a diode-laser vapor-cell trap. The oscillations arise from the use of the Ramsey separated oscillatory fields technique.

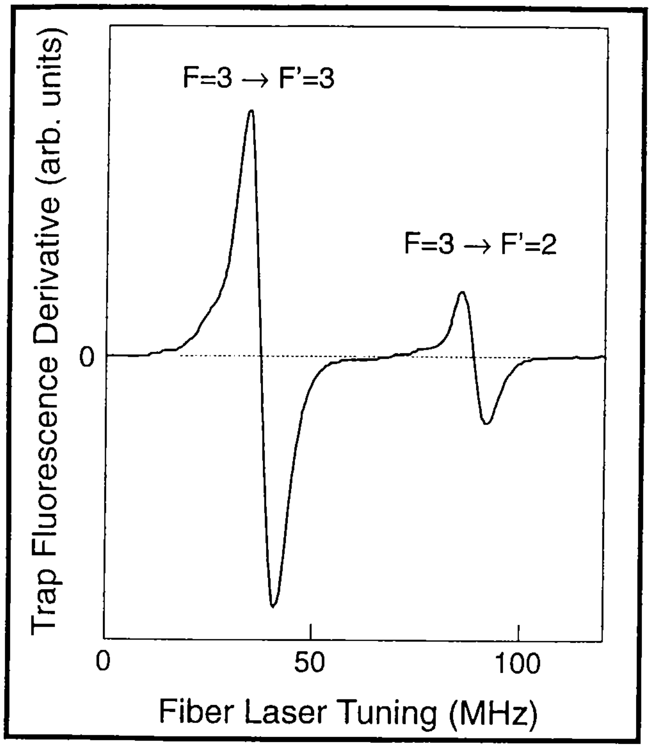

**Figure 5.** First derivative of the spectrum of the 1.529 μm $5P_{3/2}$, $F=3 \rightarrow 4D_{5/2}$, $F'=3$ and 2 transitions in rubidium atoms ($^{87}Rb$) confined in a diode-laser vapor-cell trap. The slight asymmetries on the low frequency sides of the lines are due to splitting of the F=3 hyperfine level caused by the trapping laser field.

the quality of the windows can be poor—a simple round flask is adequate. The pressure in the cell must be fairly low; typically $10^{-5}$ - $10^{-7}$ Pa ($\approx 10^{-7}$ - $10^{-9}$ Torr) is used. This is usually achieved by attaching a very small ion pump to remove the hydrogen and helium that diffuses through the walls, and limiting the pressure of the alkali metal by containing it in a small sidearm that is cooled or isolated by a valve.

## APPLICATIONS TO FREQUENCY AND WAVELENGTH STANDARDS

Diode lasers and vapor-cell traps allow trapped-atom samples to be obtained with a very compact, simple, and inexpensive apparatus, making them well suited for a variety of applications. Either or both of these technologies are now used in the development of improved frequency and wavelength standards, and are being employed in basic research in several areas of physics.

The low velocities of the atoms make them useful in improved cesium atomic frequency standards (clocks) that are based on a microwave transition in cesium. The resolution of this "clock" transition is limited by the interaction time between the atoms and the microwave field. In the traditional cesium clock, long atomic beam machines (anywhere from 5-0.5 m) are used; these yield linewidths in the range of 25-500 Hz. Using a diode-laser vapor-cell trap, linewidths as narrow as a few hertz are obtained in a cell only a few centimeters long. An example of a resonance observed in this manner is shown in Figure 4.[16] In addition to improving the resolution, the use of slow atoms improves the accuracy of an atomic clock, since most of the systematic shifts of the clock frequency are proportional to the velocity of the atoms. There are now several groups pursuing the development of laser trapped atomic clocks, both as research tools and commercial products, and investigating the performance limits of such devices.[17]

Wavelength standards for optical communication are another area where laser trapping has proven useful. For future developments in optical fiber communication systems, such as multiple wavelength channels and coherent detection, it is desirable to have a wavelength standard in the 1.5 μm spectral region with an absolute accuracy of about 1 MHz. Atomic and molecular references in this spectral region are few and difficult to probe; molecular absorptions are weak overtone or combination bands and there are no atomic absorption lines from the ground state. This lack of absorption features, of course, makes this region attractive for optical communications. To produce a 1.5 μm standard, high resolution spectroscopy of a transition between excited states of atomic rubidium is being carried out in one of our labs.[18] A diode-laser vapor-cell trap was constructed for rubidium atoms, and the 1.529 μm transition was probed in the trapped atomic sample using a tunable fiber laser. Figure 5 shows a spectrum obtained as the fiber laser's frequency was swept. To demonstrate a stable wavelength reference, the fiber laser's frequency was locked to one of the lines using an electronic feedback circuit.

A vapor-cell trap has several advantages over a simple room temperature vapor-cell wavelength reference. Due to the lack of Doppler broadening, the narrow linewidths necessary for an accurate standard are easily obtained. Also, as discussed above, a trap significantly reduces pressure shifts of the reference wavelength. Finally, the superior signal-to-noise ratio allows the required sensitivity to be obtained with weaker excitation of the atoms. This reduces light-induced shifts of the reference wavelength.

### APPLICATIONS TO BASIC PHYSICS

Laser traps are also being applied to problems in many areas of basic physics. An obvious application is precision atomic spectroscopy, since most of the requirements for this field are identical to those for wavelength and frequency standards. However, as the advantages of this technology become more apparent, it is being applied in many other types of experiments as well. Here we have space to discuss only two examples with which we are particularly familiar; however, other applications include quantum optics (cavity quantum electrodynamics), squeezed-light generation, and other coherence phenomena), atom interferometers, and studies of very cold atomic collisions.

Efforts are underway to use laser traps to collect and hold samples of rare shortlived radioactive isotopes. Experiments planned for these samples include precision studies of nuclear beta decay, searches for electric dipole moments of atoms, and the measurement of parity violation in isotopes of cesium.[19] Parity violation in atoms is produced by the weak (as opposed to "strong," "electromagnetic," or "gravitational") interactions between the electrons and quarks in an atom. These interactions are about $10^{11}$ times weaker than the electromagnetic interaction, but can be detected by observing a small difference in an atomic transition rate depending on whether the experiment is "right-handed" or "left-handed." The handedness of the experiment is defined by the directions of various applied fields. Because of the relatively large optical absorption and low collision-induced background, the signal-to-noise ratio that should be attainable with a trapped-atom sample is much larger than can be achieved in either traditional vapor cells or atomic beams. Furthermore, the comparison of different isotopes will provide an important test of the fundamental theory of elementary particle physics.

Another example is the quest to achieve the predicted, but never observed, Bose-Einstein condensation in a dilute vapor. The goal of this work is to produce an extremely cold sample of atoms in which traditional interactions are negligible (due to low density), but the atoms are separated by less than their de Broglie wavelengths. For these conditions, it is predicted that atoms with integral total spin ("bosons") should lose their individual identities and collectively condense into the lowest energy quantum state in the system. This macroscopic quantum state would be quite unlike any known form of matter. Although laser cooling and trapping have not yet achieved the extraordinarily low temperatures required ($< 0.1\ \mu K$), a cloud of trapped cesium atoms has been reduced to a temperature of $1.1\ \mu K$.[15] Furthermore, laser cooling and trapping have allowed one of our labs to carry out studies of very low energy interactions of atoms, which show how to overcome some particularly serious impediments to achieving Bose-Einstein condensation.[20] Several groups are pursuing different variations on the cooling and trapping techniques discussed here in an attempt to achieve Bose-Einstein condensation.

We are observing the rapid growth of an exciting new technology. It is currently applied to a range of research areas, from practical problems such as wavelength standards for optical communication to the study of the fundamental weak interaction between quarks and electrons. In the coming years, there will no doubt be many exciting new results based on this technology and a host of new applications.

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