Atomic Trapping and Cooling

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Optical Forces

The notion of optical forces goes back to Maxwell, but their modern implementation for laser cooling is most commonly described in terms of the momentum of light when it is absorbed by an atom making a discrete transition between states whose energy difference is ΔE. The magnitude of this momentum exchange is related to the energy through the relativistic formula $p = \Delta E/c = h\nu/c = \hbar k$ where $k \equiv 2\pi/\lambda$ and λ is the wavelength of the light. In order for the momentum exchange between the atom and the light field to be efficient, the light must drive a resonant transition between atomic states, and so must have the right frequency. This leads immediately to a model description that involves only two atomic states, one ground and one excited.

Both absorption and emission exchange nearly the same magnitude of momentum between the atoms and the light, so any net momentum exchange must arise from directionality. At low light intensity I the dominant return to the ground state is through spontaneous emission, and directional exchange is thus implemented because it occurs in random directions. Atoms can only undergo spontaneous emission from their excited states whose lifetime is $\tau \equiv 1/\gamma$, and even under the strongest excitation, they spend no more than 50% of the time in the excited state, so the maximum average rate of spontaneous emission from optically excited atoms is $\gamma/2$ and the maximum force is $\hbar k\gamma/2$. At high intensities the momentum exchange is limited by stimulated emission because the absorption and stimulated emission are both parallel to the laser beam. High intensity forces are usually produced in the presence of multiple beams so that absorbtion from one can be followed by stimulated emission into the other. The momentum difference between these is imparted to the atoms.

In the low intensity domain the spontaneous emission rate is $\gamma_p = (\gamma s/2)/(1+ s + \Delta^2)$. Here $s \equiv (3\lambda^3\tau)/(\pi hc)I$, and Δ is related to the detuning of the light ω_ℓ from exact atomic resonance ω_{atom} by $\Delta = 2(\omega_\ell - \omega_{atom})/\gamma \equiv 2\delta/\gamma$. Because spontaneous emission is in random directions its average vanishes so the direction of the force is the same as the direction of the light. This "radiative" force is usually written as $\vec{F} = \hbar\vec{k}\gamma_p$. The optical frequency is measured in the reference frame of the lab which is different from that of the atoms moving at velocity $\vec{v}$, and so the Doppler shift $\omega_D \equiv -\vec{k}\cdot\vec{v}$ must be included in the detuning δ. The negative sign arises because the frequency is increased when $\vec{k}$ and $\vec{v}$ are in opposite directions. In the atomic rest frame the optical frequency is $\omega_\ell - \vec{k}\cdot\vec{v}$.

The most common form of laser cooling uses counterpropagating beams of light tuned just below atomic resonance. The formula $\vec{F} = \hbar\vec{k}\gamma_p$ is applied for each of the two beams, but the force has opposite directions and the Doppler shifts are different. The result is a total force $\vec{F}_{tot} = -\beta\vec{v}$ which damps atomic motion in either direction. Here β is a constant that depends on the atomic

and laser parameters. The notion of this damping from the radiative force is readily extended to three dimensions, and such a cooling configuration is called "Optical Molasses".

A pure damping force would bring the atoms to rest and thus to the impossible temperature of $T = 0$. Therefore it is necessary to consider the discreteness of each momentum exchange near the cooling limit. The result is an ultimate low temperature of $T_D = \hbar\gamma/2k_B \sim 10^{-4}$K, where k_B is Boltzmann's constant and the subscript D refers to the Doppler shift dependence of the mechanism of cooling. Experiments have shown the inadequacy of the two-level atom model that leads to T_D, and in fact, both theory and experiment involving real atoms that have multiple energy levels show the ultimate low temperature obtainable by optical cooling in the presence of spontaneous emission is a few times $T_r = \hbar k^2/2Mk_B$ where M is the atomic mass and the subscript r refers to recoil. At $T_r \sim$ few μK the atomic deBroglie wavelength is comparable to λ, and this has important consequences for further cooling.

When atoms interact with nearly-resonant light, they not only absorb its energy and momentum, but they are also subject to shifts of their energy levels given by $\Delta E_{LS} = \hbar\left\{\sqrt{\Omega^2 + \delta^2} - \delta\right\}/2$ where the Rabi frequency Ω characterizes the strength of interaction between the atoms and the light such that $\Omega^2 = s\gamma^2/2$. In the limit of $\delta \gg \Omega$ that characterizes many low intensity experiments, $\Delta E_{LS} \approx \Omega^2/4\delta$ is proportional to the light intensity and is therefore called the light shift. This light shift can result in forces on atoms when the light intensity varies in space, such as between the nodes and anti-nodes of a standing wave, because the spatial energy dependence can be viewed as a potential. In some sense, it derives from multiple sequences of absorption and stimulated emission, and is therefore conservative and cannot be used for cooling, just as is the case for any force derived from a potential. Such interactions are labelled the "dipole force" in analogy to the static case, because the light induces an atomic dipole moment, and the atom is in an inhomogeneous field.

Thus optical forces on atoms arise from absorption followed by either spontaneous or stimulated emission, and in general, both processes take place. Atoms can be confined or steered by the dipole force, and cooled by the radiative force, thereby providing physicists with enormously powerful and flexible tools for controlling atomic motion.

Confinement - Light Beams and Magnetic Fields

The sign of the the light shift depends on the detuning. For $\delta < 0$, called "red" detuning, the energy of ground state atoms is lower in more intense light and thus atoms in an inhomogeneous light field are attracted to regions of high intensity. The region near the focus of a single laser beam therefore provides a radial attraction for atoms via the dipole force. If the focus is sufficiently sharp, meaning that the light intensity decreases strongly in either longitudinal direction moving away from the focus, this dipole force can exceed the radiative force that tends to expel the atoms from the focal region longitudinally, especially if the detuning is large enough. Thus a single focussed laser beam

having sufficiently large Ω and δ can confine atoms to a quite small region of space. Changing the position of the focus by steering the beam allows atoms to be manipulated as if they were held by tweezers. Such "optical tweezers" have been used on single atoms and on Bose-Einstein condensates, as well as on macroscopic objects.

By contrast, ground state atoms are repelled from the region of high light intensity if the detuning is "blue", $\delta > 0$. Atomic mirrors have been made by focussing a blue detuned laser beam into a sheet of light with cylindrical optics, and a trap has been made with an array of such sheets of light. Atomic mirrors have also been made using the very thin film of light produced by a blue detuned evanescent wave near the surface of a flat piece of glass illuminated from the inside with a beam of light near the critical angle. Finally, blue detuned Laguerre-Gaussian beams with a hollow center have been used to confine atoms in two dimensions and thus guide their motion along the path of the light beam. Two orthogonal, separated sheets of light can cap such an elongated region making a quasi one dimensional trap.

Many new phenomena appear in multiple laser beams because there can be absorption from one beam and stimulated emission into the other. Optical molasses described above is achieved in counterpropagating beams having $\delta \sim \gamma$ and $s \sim 1$ so that spontaneous emission is more likely than stimulated emission. Under these conditions, an atomic sample is cooled. By contrast, in the parameter range $\delta \gg \gamma$ and $s \gg 1$ satisfying $\delta \gg \Omega$, the dominant interaction is the dipole force. In a standing wave, this dipole force oscillates in space on the wavelength scale thereby forming a periodic potential, and atoms are said to be subject to an optical lattice. (Optical crystal is an inappropriate name except under conditions where all the sites can be filled with exactly one atom.) Atomic motion in such a periodic potential is subject to the well-known conditions described by the Bloch theorem and Bloch wave functions. By careful choices of the mean kinetic energy (temperature) and well depth of the lattice, very many phenomena of condensed matter can studied.

Most atoms have a non-zero magnetic moment in their ground state, and hence can be confined by an inhomogeneous magnetic field. The simplest imaginable case uses a pair of coaxial coils carrying opposite currents to form a quadrupole field. (A single coil cannot work because a local field maximum cannot exist.) The B field at their geometric center is zero, but is non-zero everywhere else in space. Thus atoms whose magnetic moments $\vec{\mu}$ are properly oriented are attracted to the field zero, and can be confined there if their kinetic energy is less than $\vec{\mu} \cdot \vec{B}_{max}$ where $\vec{B}_{max}$ is the smallest magnetic field in the vicinity of the coils that constitutes a local maximum. Such magnetic trapping of atoms is free from the disturbing effects of light beams, and can therefore confine atoms with far less disturbance than optical traps. Magnetic traps are widely used for the containment of ultra-cold samples of gas, and particularly Bose-Einstein condensates.

Perhaps the most widely used atomic confinement method is the magneto-optical trap (MOT). It exploits the selection rules associated with the polarization of light and the magnetic sublevels of atoms by making the absorption of

light from multiple beams depends upon atomic position in an inhomogeneous magnetic field. The field and light beams are carefully arranged so that atoms not in the center of the trap preferentially absorb light from beams that tend to push them back toward the trap center through the radiative force. The MOT has an extremely large velocity capture range and depth, much larger than either pure optical or magnetic traps.

A much more important property, however, is that the force in a MOT is velocity dependent through the Doppler shift, similar to the force in optical molasses. Both magnetic and optical traps are conservative, that is, atoms entering from one side will readily pass through them and escape from the other side. They can be loaded only by applying them to an already cooled sample of atoms, or by applying a cooling force to atoms travelling in them. By contrast, a MOT tends to slow atoms traversing it so that they cannot escape, and therefore it can capture atoms without auxiliary cooling. Moreover, their capture range can be chosen by the laser and magnetic parameters, and can be changed after a sample is captured to enable further cooling and/or compression. Finally, the magnetic field configuration is the same as that of the quadrupole magnetic trap, so that a MOT can be converted to a magnetic trap simply by shutting off the laser beams, thereby transferring a captured sample from the MOT into a dark and cold purely magnetic trap.

Applications

Although laser cooling has first been discussed in relation with high-resolution atomic spectroscopy, today it is used in many areas of atomic physics. One of the most prominent applications is the research of atomic collisions, where the researchers have been able to study atomic interactions at very low energies. This has led to photoassociation spectroscopy, where during the interaction between two ultra-cold atoms a photon is absorbed and the total system is bound in a transient molecular state. Since the translational energy in the initial state is very low, this offers a novel way of studying molecular states with very high resolution. One of the results of these studies is the measurement of the scattering length in the ground state, which can be measured for with unprecedented resolution. This information is of crucial importance for the achievement of Bose-Einstein condensation is such systems.

For sufficient low energy and high densities atomic gases can make a transition to a new state, the so-called Bose-Einstein condensation. Although this has been predicted already in 1925 by S.N. Bose and A. Einstein, its experimental realization in dilute atomic gases was first realized in 1995 using laser cooling and trapping in combination with evaporative cooling. If the atomic gas makes a transition to a condensate, all atoms are in an identical state and have to be described by one macroscopic wavefunction. The coherence properties of such a condensate can be exploited for many novel experiments, like superfluidity, quantized vortices, parametric down-conversion, collapsing condensates and matter-wave interferometry.

The study of Bose-Einstein condensation forms a bridge between the research

in atomic physics on laser cooled atoms and many other fields in physics, like low-temperature physics, condensed matter physics and statistical physics. For example, loading a Bose-Einstein condensate in an optical lattice make it possible to study in this atomic system the quantum phase-transition between a superfluid and Mott insulator state. In analogy with electron conduction in condensed matter, the conduction of atoms in an optical lattice can be tuned by increasing or decreasing the optical potential for the atoms, leading to an "conduction" state, where the atoms are distributed over the lattice in a random way, or an "insulator" state, where the atoms are evenly distributed over the lattice sites, thus creating an integer filling of all sites. It is shown, that this transition can be crossed many times without loosing the coherence of the atoms in the superfluid state.

See also: enter cross-references to othere encyclopedia entries here.

Bibliography

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