Pat Burchat 02/15/07

Physics 41N

Mechanics: Insights, Applications and Advances

Lecture 6: Laser Cooling of Atoms

The 1997 Nobel Prize in Physics was awarded to Professor Steven Chu of Stanford University (now Director of the Lawrence Berkeley National Laboratory), Professor Claude Cohen-Tannoudji of Collège de France and École Normale Supérieure, Paris, and Dr. William D. Phillips, National Institute of Standards and Technology, Gaithersburg, Maryland. The prize was awarded to these three scientists for the development of methods to cool and trap atoms with laser light. The subject of the 1997 Nobel Prize in Physics offers an opportunity for us to consider a technique that combines elements of quantum mechanics and special relativity, with principles from classical mechanics. In this lecture, we will discuss the cooling of atoms with lasers.

What do we mean by the "cooling" of atoms? Normally, atoms in a gas move with a speed that is related to their temperature. For example, at room temperature, the atoms and molecules in air move at an average speed of about 4000 km/hour. The atoms can be slowed down by lowering their temperature. At normal atmospheric pressure, gases will condense and turn into a liquid and then a solid as they are cooled. If the gas is cooled in a vacuum, it will remain a gas, and the individual properties of the atoms (rather than the properties of atoms in liquids or solids) can be studied. So "cooling" atoms can be interpreted as "slowing them down." Many techniques that are used to control the velocity (or momentum) of a particle rely on the particle being electrically charged. For example, in particle accelerators, beams of charged particles are manipulated with electric and magnetic fields. In laser cooling, electrically neutral atoms are slowed down.

Normally, we think of laser beams as heating something, not cooling it. Today, we'll see how laser beams can be used to first slow down atoms and then trap them. To understand the technique, we will first digress to introduce a few concepts from special relativity and quantum mechanics. I will use some examples from astronomy (which have nothing to do with laser cooling!) to illustrate these new concepts.

1 Photons and the Doppler Shift

Let's start with two descriptions of light:

1. Light is an ocillating electromagnetic wave. We denote the frequency of oscillation with the Greek letter ν (pronounced *nu*).

2. Light consists of particles, which we call photons. Each photon corresponds to a packet (or quantum) of energy. The amount of energy E in each packet is related to the frequency ν by the formula

$$E = h\nu,$$

   where $h = 6.63 \times 10^{-34}$ J·s is called Planck's constant and is one of the fundamental constants of nature.[1]

For visible light, we perceive different frequencies ν as different colors. To understand the cooling of atoms with lasers, we will use both the particle and the wave description of light.

First, what's special about laser light? Laser light has a special property called "coherence". Whereas the photons in light from most sources (such as the sun or an incandescent light bulb) have a spectrum of frequencies, and a variety of directions and phases, the individual photons in a laser beam all have the same frequency, are in phase with each other, and are travelling in the same direction. Different types of lasers can be used to provide different frequencies of light.

Light of any frequency travels at speed $c = 3.0 \times 10^8$ m/s in vacuum, and (usually) at lower speeds in other media. As with any wave, the product of the frequency ν and the wavelength λ (pronounced *lambda*) is equal to the speed of the wave:

$$c = \lambda\nu.$$

Another property that light shares with other waves is the Doppler shift in frequency perceived when the source and observer are moving relative to each other. You are probably already familiar with the Doppler shift for sound. Sound is a pressure wave. We perceive the frequency of a sound wave as pitch. If the source of the sound is moving towards you, you will perceive a pitch that is higher than if the source were stationary; similarly, if the

[1] The momentum carried by a photon is related to its energy by the following formula: $p = E/c$.

source is moving away from you, you will perceive a lower pitch. An example is the changing pitch of a train's whistle as it passes you. The shift in pitch is called the Doppler shift. An observer will also perceive a Doppler shift in the frequency of light if the source of light is moving relative to the observer. When the direction of propagation of the light is the same as the direction of the relative motion of the source and observer, the shift in frequency is given by[2]

$$\Delta\nu = \nu - \nu_o = \nu_o \frac{v}{c}.$$

In this equation, ν_o is the frequency observed when the source is at rest relative to the observer, and ν is the frequency observed when the source is moving towards the observer with velocity v. If the source is moving away from the observer, replace v by $-v$.

The Doppler shift for light is used by astronomers to determine the speed at which different objects in the universe are moving with respect to us. Since the universe is expanding, other galaxies are moving away from ours.[3]

---

[2]This equation is true only when v/c is much less than 1. If a source of light is moving relative to an observer with speed v, the frequency seen by the observer is

$$\nu = \nu_o \frac{1 + v/c}{\sqrt{1 - v^2/c^2}}$$

where c is the speed of light. This equation reduces to the simpler one in the text when v/c is much less than 1.

[3]It turns out that some of our closest neighbor galaxies are moving toward us and therefore are "blue-shifted" rather than "red-shifted". Most of these blue-shifted galaxies are in the cluster of galaxies containing our Milky Way Galaxy; this cluster is called the "Local Group". There is a subtlety here that is worth mentioning. The redshift I have just described is due to objects moving *through* space and the formula for this redshift is given by the theory of special relativity. This movement through space itself is usually due to the motion caused by the gravitational attraction between two massive objects, such as galaxies. However, for galaxies that are very far away, the redshift is primarily due to the expansion of space itself rather than motion of the galaxies through space. The expansion of space stretches the wavelength λ of light, decreasing its frequence ν, and thereby causing a redshift. Note that this is not really analogous to a classical Doppler shift and that the expansion of space is not included in the theory of special relativity. However, the equations describing the shift in frequency due to the expansion of space are the same as those describing the special-relativistic Doppler shift for relatively small expansions of space (e.g., for nearby galaxies). For very distant galaxies, for which space has expanded by a large amount between the time the light was emitted and when we detect it, we must use the equations of general relativity and account for the entire content of the universe, its geometry (curved or flat), etc., in order to interpret the redshift.

Therefore, the frequency of light emitted by the galaxies is shifted downwards. Within the visible spectrum, light that we perceive as red has a lower frequency than light that we perceive as blue. Hence the light that we observe from other sources in the universe is shifted towards the red end of the visible spectrum and is called the “red shift”. Evidence from many observations of red-shifts shows that all distant objects are moving away from us, and that there is a direct relationship between the speed of the object and its distance from Earth – the more distant the object, the higher the redshift. The linear behavior of the relationship, deduced from measurements of the red shift of objects and independent measurements of their distance, is the primary evidence for the expansion of the universe.[4] We’ll come back to the red shift below after we’ve discussed some quantum effects in atoms that are necessary ingredients for understanding the laser cooling of atoms.

2 Absorption of Energy by Atoms

Most physical systems, including atoms, absorb energy particularly well at certain resonant frequencies. Before discussing atoms, let’s consider a very simple physical system: a pendulum consisting of a weight at the end of a string. If you gently swing a weight at the end of a string (say, your keys at the end of a key chain), you will tend to swing the weight at a particular frequency that is the natural frequency of oscillation for the pendulum. In the second lecture in this course we used dimensional analysis to show that the frequency depends on the length of the pendulum and the acceleration due to gravity g, but does not depend on the mass of the weight. Try swinging a key chain at different frequencies. You will find that it is almost impossible to pump any significant amount of energy into the system if you swing the key chain at a frequency higher or lower than the natural oscillation frequency. However, if you choose the natural frequency, energy is transferred from your moving hand to the keys very effectively.

Atoms absorb electromagnetic energy at very particular frequencies. Since electromagnetic energy can be viewed as particles called photons each having

[4]The exact behavior of the relationship is not necessarily linear at large distances. See the discussion in the previous footnote. In fact, precise measurements published in 1998 of the behavior of the redshift for very distant galaxies show that today and in the “recent” past (couple of billion years), the universe has been expanding at an ever-increasing rate rather than slowing down! We may discuss this further in a later lecture.

energy $E = h\nu$, we can also say that atoms absorb photons with particular energies or frequencies. In the lowest energy state, the constituents of the atom (the nucleus and the orbiting electrons) are arranged so that the total energy in the system is minimal. This is called the ground state of the atom. By absorbing a photon, the atom can move into a higher energy state, which corresponds to a different arrangement of the electrons around the nucleus. Each type of atom (*i.e.,* each element) has its own unique set of possible energy levels. An atom can be in a state corresponding to one of these energy levels, but can never be between energy levels. This is analogous to the energy levels possible for a ball on a staircase. The energy level is determined by which step the ball is resting on. In order to move to a higher energy level (a higher step on the staircase), there is a minimum amount of energy that the ball must be given. Likewise, there is a very particular spectrum of photon energies that each type of atom can absorb or emit. Photons of the wrong energy (or frequency) will have no effect on an atom.

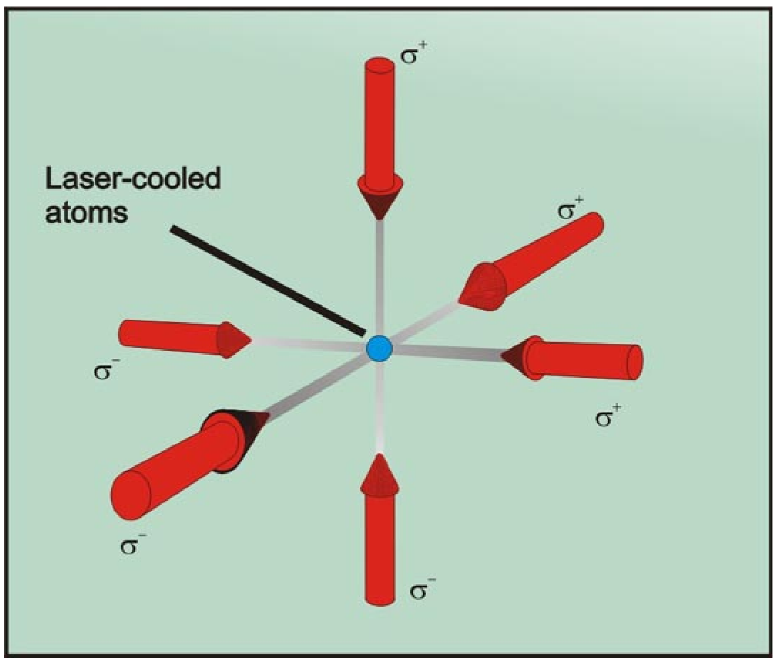
If you make a graph of the number of photons emitted by a particular type of atom plotted against the energy of the photon, you will get a series of vertical lines. Therefore, the energy spectrum is often referred to as spectral "lines" of emission or absorption.[5] Also, if you take light emitted by an atom and spread it out with a prism or diffraction grating, you will see a series of lines, rather than a continuous spectrum.

In the previous section, I mentioned that astronomers use the Doppler shift to determine how fast other objects in the universe are receding from us. They measure the shift in the frequency of light towards the red end of the spectrum. But how do they know what the original frequency of the light was? How can they tell that we are observing a shifted frequency? The measurement of red shifts depends on the fact that each type of atom has a characteristic spectrum of electromagnetic radiation that it emits and absorbs. Most objects in the universe contain Hydrogen. The spectrum of Hydrogen is well known. Therefore, astronomers can look for a pattern of spacing between spectral lines that matches the spacing for Hydrogen and measure the red shift.

[5] If light with a continuous spectrum passes through a cloud of gas, for example, then there will be dark lines in the otherwise continuous spectrum due to absorption (and re-emission in random directions) of these particular frequencies by the gas. Therefore, these absorption lines reflect the frequencies that are characteristic of the gas, not the object emitting the continuous spectrum of light.

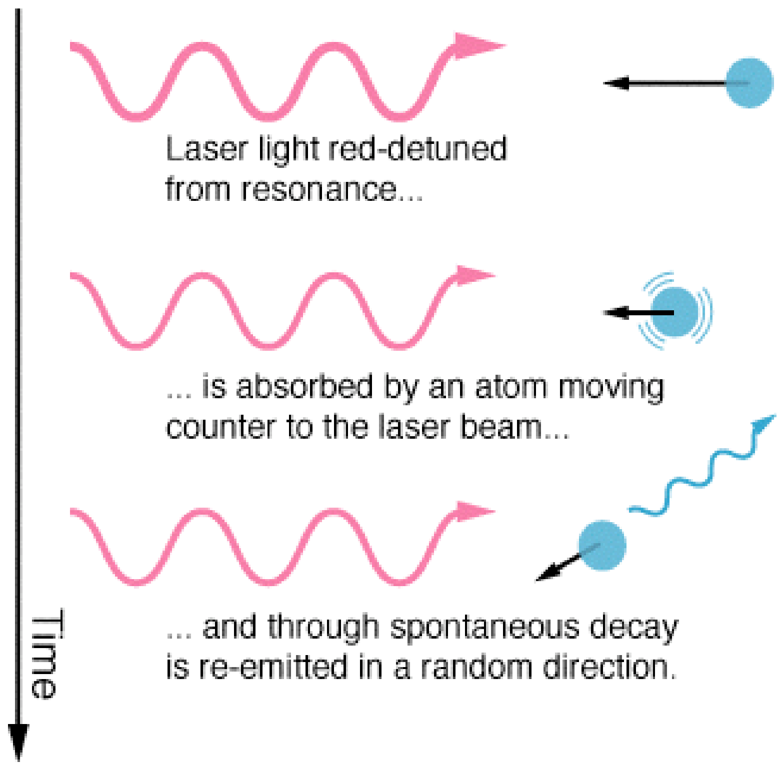
3 Cooling Atoms with Lasers

In the laser cooling of atoms, six laser beams are used to cool a sample of atoms located in the region where the six beams cross. The six laser beams consist of three orthogonal pairs; the beams in each pair are pointing straight at each other as illustrated in the sketch below.



How do these lasers cool atoms? First consider just one incident beam. If the energy (or frequency) of the photons in the laser beam corresponds to the difference between the ground state and an excited state of the atom, then the atom can absorb the photon. Once it has absorbed the photon, the atom is in an excited state. It will soon drop back into its ground state, emitting a photon of the same energy that it absorbed, but in a *random* direction.

What happens to the momentum of the atom during this process? When the atom absorbs the photon, the atom will experience a change in momentum; the momentum of the atom will increase in the direction of the laser beam. When the atom emits a photon, it will again experience a change in momentum; the atom will recoil in a direction opposite the direction of the emitted photon. If an atom repeatedly absorbs photons from a laser beam, emitting a photon in a random direction after each absorption, the atom will

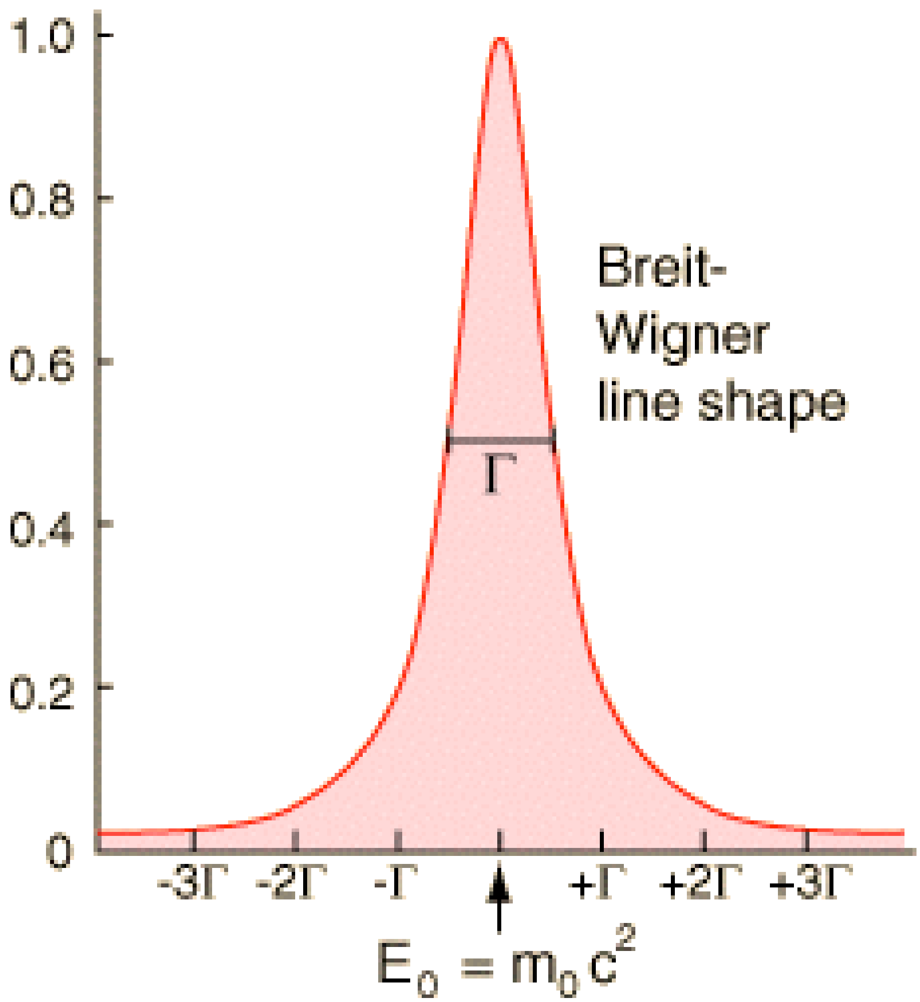

Laser light red-detuned
from resonance...
... is absorbed by an atom moving
counter to the laser beam...
... and through spontaneous decay
is re-emitted in a random direction.
Time

experience a net change in momentum in the direction of the laser beam due to the absorption of photons. Since the emitted photons come out in all directions, the average change in momentum due to the emitted photons will be zero.

The process just described could be used to slow down atoms that are travelling toward the laser beam. But in a gas, atoms are moving in all directions. Won't the above process also speed up atoms that are travelling away from the laser beam? How can we use the photons in a laser beam to slow down but not speed up atoms? We need a way to control whether or not an atom will absorb a photon, depending on whether the atom is moving opposite to or in the direction of the laser beam. But wait a minute – won't the Doppler shift do what we want? Atoms absorb photons of a precise energy (or frequency, as measured in the atom's frame of reference). What if we deliberately choose a frequency that is too *low* for a stopped atom to absorb? Atoms moving in a direction *opposite* to the photons in the laser beam will "see" a higher frequency. If the frequency is chosen correctly, the Doppler-shifted frequency will be exactly that which can be absorbed by an atom moving towards the laser and the atom can be slowed down. Atoms moving in the *same* direction as the photons in the laser beam will "see" a lower frequency and will not absorb the photons. Therefore, if we use a pair of lasers pointing in opposite directions, one laser slows down atoms moving in one direction while the other laser slows atoms moving in the opposite direction. Three pairs of orthogonal lasers can be used to slow the atoms in three-dimensions.

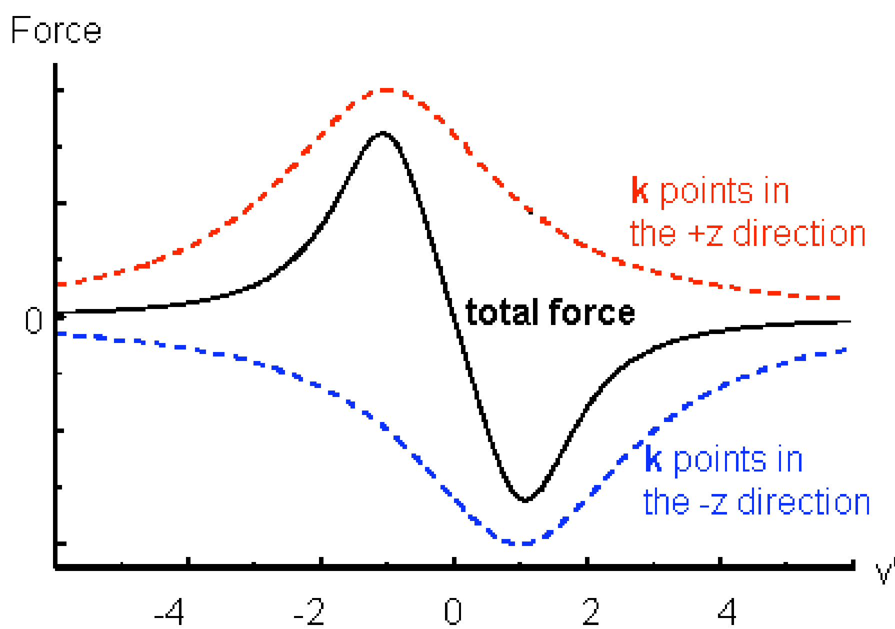
If you think about the above argument carefully, you will detect what might appear to be a problem with the technique. If an atom can absorb photons of only a very precisely defined frequency, isn't it true that only atoms with a very precisely defined speed can absorb the Doppler-shifted photons? To see the resolution to this problem, we must consider one more aspect of the absorption and emission of light by atoms. It turns out that an atom can actually absorb or emit photons with frequencies within a narrow range of the central frequency. In other words, atomic spectral emission and absorption "lines" are not infinitely thin lines; they have a natural width. The curve describing the probability that the atom will emit or absorb a photon of a particular frequency has a characteristic shape, shown in the figure below. The curve is characterized by a width, which is usually denoted by the capital Greek letter gamma: Γ.

We can now see that although it is true that atoms with just the right


1.0
0.8
0.6
0.4
0.2
0
Breit-
Wigner
line shape
Γ
-3Γ
-2Γ
-Γ
+Γ
+2Γ
+3Γ
$E_0 = m_0 c^2$

speed have the highest probability of absorbing photons, atoms with other speeds will also absorb photons, albeit at a lower rate.

The net effect of all the impulses that the atom gets from absorbing and emitting photons is a force always directed opposite to the direction of motion of the atom. In the figure below, the force is plotted as a function of the velocity of the atom, v, for the case of two lasers directed at each other. (We'll discuss what's actually plotted on the horizontal axis in a minute.) Note that the force is negative when v is positive and vice versa. In other words, the force always drives the speed towards zero. In the central region, the force depends linearly on speed with a negative slope. This is exactly the same dependence of force on speed that applies to motion in a viscous fluid. Steven Chu and his colleagues gave the name "optical molasses" to this laser configuration.



The above figure corresponds to the case when the laser is tuned to a freqency that is lower than the central value of the atomic absorption peak by exactly half the natural width Γ of the peak. It is this laser frequency that gives the maximum slope and hence the maximum "viscosity" near zero velocity. The horizontal axis on the plot of force is the dimensionless quantity $2\pi\Delta\nu/\Gamma = 2\pi(\nu_{laser}/\Gamma)(v/c)$.

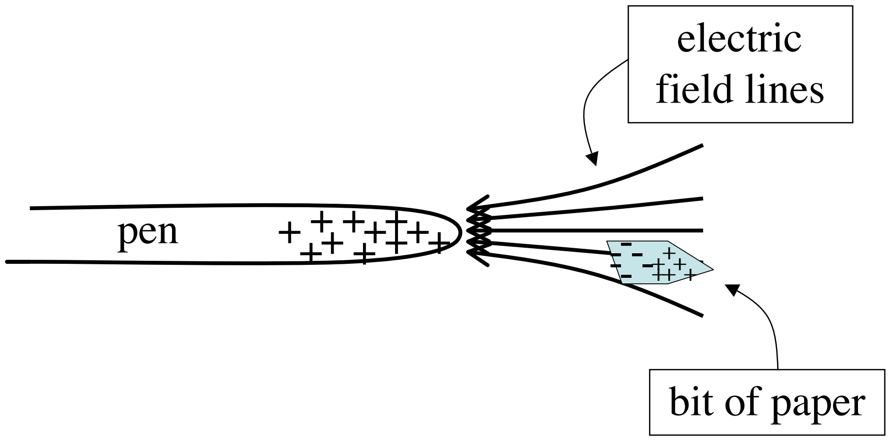
It was predicted that the technique just described would allow scientists to cool atoms to a temperature of a few hundred microKelvin (μK). However, when the velocity distribution of laser-cooled atoms was actually measured, it was found that the temperature was a few tens of μK. It was soon realized that the situation was more complicated than orignally thought — at very low speeds other cooling mechanisms were setting in that eventually allowed cooling to temperatures of a few μK. These mechanisms are beyond the scope of this lecture and are discussed in the second reading listed at the end of these notes.

4 Trapping Atoms with Lasers

The method just described cools and traps atoms – each atom behaves as if it were held within a viscous fluid that resists its motion. The frequency of the laser used for cooling is selected to be just below the resonant frequency of the atom. We will now very briefly discuss another way in which lasers can be used to trap electrically neutral particles such as atoms. The frequency of the laser used for trapping is selected to be well away from (and lower than) the resonant frequency of the atom.

To understand how this laser trapping of atoms works, we should first understand how you can get tiny (electrically neutral) pieces of paper to stick to a pen that you have rubbed against your hair. By rubbing the pen against your hair, you are building up charge on the pen. Therefore, there are electric field lines near the end of the pen, as shown in the sketch below.

The field lines are densest near the pen, indicating that the electric field is highest at this point. If you bring an (electrically-neutral) bit of paper near the pen, the electrons in the part of the paper closest to the pen feel a stronger force than those furthest from the pen. Suppose the pen has a buildup of positive charge. Then the charge in the paper will be redistributed so that there is a net negative charge at the end closest to the pen, and a net positive charge at the other end. The negative charge will be attracted to the rod while the positive charge will be repelled. But the negative charge is in a higher-field region; therefore, the attraction will overcome the repulsion, and the paper will be drawn to the pen. Convince yourself that the paper will be attracted to the pen even if there is a net buildup of negative charge on the pen. The conclusion is that (polarizable) electrically neutral objects will always be pulled into the region where the electric fields are strongest.



Hence, neutral particles can be trapped by an electric field that has a local maximum.

It turns out that no system of fixed charges can produce an electric field with a local maximum. However, a focused laser beam can produce an alternating electric field with a local maximum. As long as the electric field is not changing too quickly, the electric charge in the atom will continuously rearrange itself and the atom will be attracted to the local maximum of the electric field at the focal point of the laser beam. This technique can be used to trap atoms and also to trap macroscopic electrically-neutral objects.

5 Uses for Laser Cooling and Trapping

Here are a few examples that are discussed in more detail in the papers listed in the next section:

1. Steven Chu's group has made an atomic fountain in which cooled atoms are launched upwards into a chamber in which they are slowed by gravity. This gives scientists the opportunity to observe and make measurements on the atom for longer periods of time, allowing more precise measurements of properties of the atoms. It is believed that this technique will make it possible to build atomic clocks with a hundredfold greater precision than currently possible.

2. Laser cooling and trapping techniques form the basis for the discovery of Bose-Einstein condensation in atomic gases. Cornell, Ketterle and Wieman won the Noble prize in 2001 for this accomplishment. See Reference 5.

3. Steven Chu's group attached tiny spheres to each end of a strand of DNA, trapped each sphere at the focal point of a laser, and used these "optical tweezers" to stretch, drag and manipulate the DNA molecule. This technique is now widely used in biophysics for manipulating biological "stuff".

6 Further Reading

1. *Cooling and Trapping Atoms,* by W.D. Phillips and H.J. Metcalf, Scientific American, March 1987, p. 50.

2. *New Mechanisms for Laser Cooling,* by C.N. Cohen-Tannoudji and W.D. Phillips, Physics Today, October 1990, p. 33.

3. *Laser Trapping of Neutral Particles,* by S. Chu, Scientific American, February 1992, p. 71.

4. *Experimenters Cool Helium below Single-Photon Recoil Limit in Three Dimensions,* by. G.B. Lubkin, Physics Today, January 1996, p. 22.

5. *Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor,* M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, E.A. Cornell, Science, July 14, 1995, p. 198. (Also see p.152 and p.182 for perspectives.)

6. *Electromagnetic Trapping of Cold Atoms*, Balykin, Minogin and Letokhov, Reports on Progress in Physics, Volume 63, Number 9, September 2000.