School Physics Project 1999

Hewlett Packard Telementoring Programme

LASER COOLING
&
ATOM TRAPPING

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Introduction

The need for greater accuracy and precision in spectroscopic measurements has urged the developments of methods to eliminate certain problems. One of these problems involves Doppler smearing, when the spectral lines recorded are broad and diffused due to the random motion and wide range of velocities of the atoms, instead of being fine and distinct.

To solve this problem, many schemes have been devised, but the most amazing one makes use of lasers. It is commonly thought that lasers only heat things up; this misconception is developed because people more often come across industrial lasers, which are used for cutting and melting. Medical lasers have the main purpose of burning tissue. However, recent studies have shown that lasers do have a cooling effect.

In 1619, Johannes Kepler observed that comets entering our solar system had their tails pointing away from the sun rather than trailing along the path of the comet. He speculated that the light from the sun exerts a force on the loose particles of the comet to push them away. Nichols, Hull and Lebedev proved the existence of radiation pressure with an experiment in which light produced a torque on a suspended pivoted mirror. Later, Otto R. Frisch showed in 1933 that light from a sodium could deflect a beam of sodium atoms by a detectable amount. This was just the beginning of how radiation pressure could be useful.

The use of this light pressure force in laser cooling has come to be known as the scattering, or spontaneous, force and this was the first way the atoms were cooled. Another force, the dipole force, was discovered later and the net sum of the two forces is called the radiation force. The dipole force is due to the electric field generated by the laser beams and acting on induced dipoles.

Other than theses two forces, other mechanisms have been developed to cool atoms to even lower temperatures. Polarization gradients and optical pumping are used in these mechanisms.

These cooling and trapping mechanisms have lead to a vast array of applications that enable us to further improve existing technologies.

1. Cooling

The basic idea of using radiation pressure of laser light involves colliding many photons, of momentum $\boldsymbol{p = (hf)/c}$**,** with atoms to slow them down.

For each collision, a photon would transfer its momentum to an atom, causing the latter to change velocity. The photon, being energy, is fully absorbed by the atom, so all of its momentum and energy is transferred. However, the atom can only absorb photons of certain discrete frequencies, because absorption of light by atoms causes the atom to be excited, the electrons move from one of the higher energy level to another. According to the laws of quantum mechanics and the quantization of the energy of the electron, electrons are only allowed to have certain energies. The energy of a photon is related to its frequency by the equation $\boldsymbol{E = hf}$ where $\boldsymbol{E}$ is the energy of the photon and these energies must match the energy difference between the quantum states of the atom.

After, a few femtoseconds (10^{15}s), the atom spontaneously emits a photon due to instability and would decay to its original state, usually the ground state. The emitted photon, which may not be of the same frequency of the one absorbed, but usually is, is in an arbitrary direction. Just as absorbing a photon gives the atom a 'kick' emitting a photon causes the atom to recoil. As emission has no preferred direction, there is a low probability that the photon emitted is in the same direction as that of the first photon, thus the atom is more likely to slow down. The final velocity is its initial velocity subtracting the recoil due to absorbing the photon and adding the recoil due to emitting the other photon. Mathematically it is this: $\boldsymbol{v_f = v_i - v_{RA} + v_{RE}}$

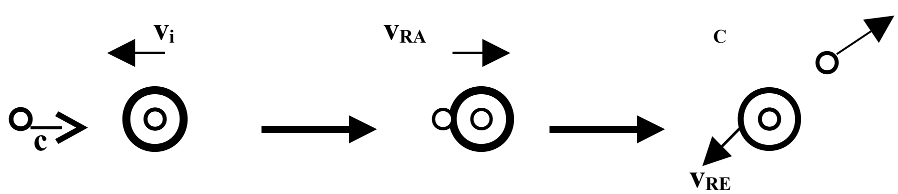


figure 1: 3 consecutive stages of an atom-photon collision

The reason why laser light is used instead of light from a conventional household lamp is because the laser light is a lot more intense, i.e. there are more photons radiated by the source per unit time, and coherent, i.e. the light waves have the same frequency and are in phase, while the latter is not. To cool the atom in three dimensions, the first theory put forward was Doppler cooling.

a. Doppler Cooling

Two laser beams are needed to cool an atom even in one dimension. If an atom moves towards the right and is met by a photon travelling leftwards, they would collide and the atom would experience an acceleration towards the left. After several collisions, the atom would eventually move leftwards and causing the atom to speed up. This is not wanted, as heating occurs. Another laser shooting photons in the opposite direction is needed to push the atom back and cancel the pressure force of the first beam.

By extending this from one dimension to two dimensions, four lasers are needed to prevent the atom from gaining speed upwards or downwards. In three dimensions, six laser beams can be used to further minimize motion forward and backwards. Theodor Hänsch and Arthur Schawlow proposed this in 1975.

Unfortunately, another complication arises due to the atom's speed — the Doppler effect. If an atom moves towards the light source, the wave fronts of the light get compressed with respect to time, so the atom experiences each wave at a faster rate then a stationary atom would. Consequently, the laser frequency has to be reduced, for approaching atoms, such that the photons appear to be resonant and can interact with the atom. Following each atom-photon collision, the atom slows down. Its speed being slower than before would have its Doppler shift altered; the light frequency is red shifted. Again the laser has to be detuned, but to higher frequencies to allow the atom to continue to absorb photons. This technique is called frequency chirping. If the atom moves away from one laser source, a counterpropagating laser would handle it. For the other directions, the rest of the six lasers would suffice. V.S.Letokov demonstrated this process in 1980.

This was not a very convenient technique as at that period, only the tunable dye laser could provide for frequency chirping and the range, though wide, is only limited. Another technique to deal with the changing Doppler shifting is to tune the energy levels of the atom instead of tuning the frequency of the laser. This makes use of the Zeeman effect, that the energy levels of an atom, under the influence of a magnetic field, are altered; some rise, others fall.

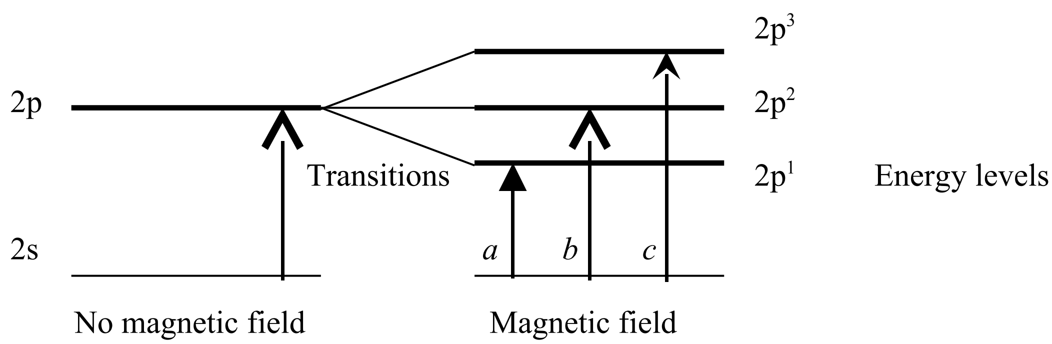


Figure 2: an ideal Zeeman effect

Consider and assuming the energy level of an electron in the $2p^1$ orbital and due to its involvement in the atom-photon interaction, its atomic transition is *a*. As the atom moves along the path with increasing magnetic field strength, the atom would have to absorb photons with lower and lower frequencies. This effect can counter the changing Doppler shift, which requires the photon frequency to rise. If the magnetic field is tailored correctly, the Zeeman effect cancels out this effect of the changing Doppler shift such that the photon frequency can remain constant. Zeeman compensation has led to cheaper cooling techniques being developed. Scientists can now use inexpensive diode lasers, having the size of a grain of salt, each, on caesium atoms.

There exists a limit for Doppler cooling due to the recoils the atom receives when absorbing and emitting photons. The atom absorbs photons at an arbitrary rate and emits them also in random directions. This random recoils has led to fluctuations in the motion of the atom, known as quantum heating, which causes the atom to speed up. When the rate of heating and the Doppler-cooling rate balance, equilibrium is the Doppler limit. However, it was soon that this limit could be broken.

b. Polarization Gradient Cooling

As opposed to the two quantum states theory, of conceptual two-level atoms, predicted by Doppler cooling it has been experimentally verified that the atoms now have multiple sub states within each quantum state.

The first evidence of loopholes in the theory of Doppler cooling came about when Steven Chu's group, at Stanford University, found that the atoms they used were too massive to attain the low temperatures thay they have reached, at the experimental conditions. William D. Phillips at the National Institute of Science and Technology NIST, Gaithersburg, USA developed an efficient method of measuring temperature, called the time-of-flight method, to confirm the temperatures. Atoms are allowed to fall out of a trap and are detected by a probe laser below. The duration of falling a particular distance is measured and the temperature derived.

With Phillips new technique, it became apparent that the Doppler limit was broken. Later, Claude N. Cohen-Tannoujdi's group at the École Normale de Supréme and P. Ungar of the Stanford group came up with similar theories to explain the phenomenon in 1990.

- Sisyphus Cooling

Many types of polarization gradient cooling schemes have been developed but the first one, discovered by Phillips, is Sisyphus cooling. This is in analogy to Sisyphus in Greek mythology, who was condemned to role a stone uphill only to have it role down at the summit, causing him to repeat the procedure endlessly. There is a slight difference in the case of the atoms, that they only role 'upwards', losing energy.

To simplify matters, a situation in one dimension shall be elaborated. When two counterpropagating beams of circularly polarized light waves interfere, they form a pattern, where at every one-eighth of a wavelength, the light field is circularly polarized, with opposite helicities, or spins, alternately. The pattern is a type of standing wave. The transitions between these polarizations, called polarization gradients, are smooth.

It has been explained earlier that when an atom absorbs a photon, it transfers its linear momentum and its energy, the former to the atom and the latter to a valence electron. If the photon also has a spin, as in the case of circularly polarized light, it can also transfer this to the electron. Electrons are confined to move about in orbitals of an atom; each orbital can only contain two electrons each with opposite spin 6½, for counterbalancing. For an atom with a half-filled orbital, optical pumping can cause the electron in that orbital to flip between each form: spin + ½ or – ½. Absorbing a photon of helicity, or spin, = +1 can pump atoms from the $g_{-½}$ state to the $e_{+½}$ state. It would then decay to the $g_{+½}$ state. The converse is also true.

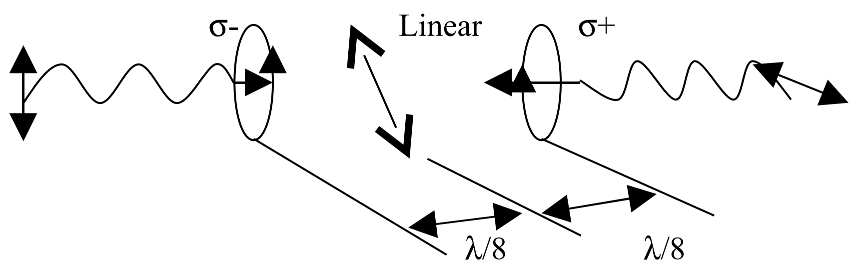


Figure 3: schematic diagram of the interference pattern used in Sisyohus cooling

With circularly polarized light used in the standing wave of the counterpropagating lasers, atoms are optically pumped at certain positions in space. At the locations where there is purely circularly polarized light, it is most likely that the atom is optically pumped accordingly. The potential energy of the atom would vary with respect to its position in the light field. The resulting variation of the energy looks like a sine wave with respect to displacement. For an atom in the other sub state, the energy changes are opposite; the curves are a reflection of each other. Energy fluctuations are because of the change in stability of the atom.

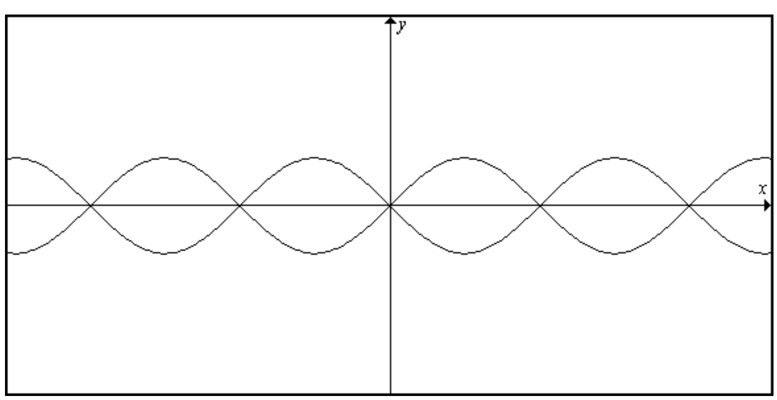


Figure 4: fluctuation of the energy of the atom in its 2 sub states with respect to space

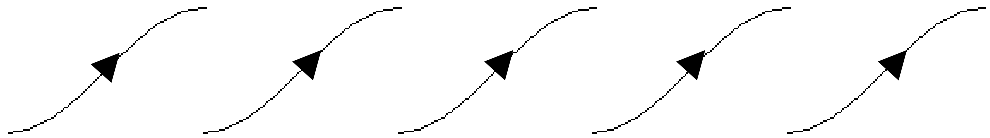


Figure 5: energy changes of an atom during Sisyphus cooling

Optical pumping takes time to occur and scientists have adjusted the duration such that when the atom has travelled one-eight of the optical wavelength, optical pumping then occurs and the photon is absorbed. This is desired because when the atom, in one sub state, has a maximum energy, it would then be pumped to the other state, which has its minimum. The energy of the atom would then begin to rise again after that. The rise in potential energy is from the loss in kinetic energy of the atom. When the atom is pumped and spontaneous emission has occurred, the new photon radiated is of a higher frequency than that absorbed. In other words, the kinetic energy of the atom is converted to its potential energy then finally to light energy. This process can be repeated until the atom comes to a stop.

Similar to Doppler cooling, this has a limit too. This time it is the recoil limit, due to the recoil of at least one photon. This is derived because even if the atom can come to a stop with Sisyphus cooling, it will inevitably absorb a photon and receive a recoil.

- Velocity Selective Coherent Population Trapping VSCPT

To get atoms to obtain temperatures below the recoil limit, scientists had to prevent the atoms from absorbing anymore photons once they are slow enough. For the atom, having two quantum states, it is pumped such that these two states influence each other in a special way. The probability amplitudes of the atom to absorb photons in each state interfere destructively such that it is impossible for the atoms to absorb photons at these states. The group at École Normale Supriéure have made the process of coherent population trapping velocity selective so that only atoms sufficiently slow enough, below the recoil limit, are pumped into this state called the 'dark state'. In the dark state, the atom, overall, has a velocity of zero, but it consists of two quantum states each with velocities of equal magnitudes, but opposite directions. It has a 50-50 chance of being in each state, having either of the velocities. Thus even the recoil limit has been broken.

These cooling schemes have only managed to slow the motion of the atoms down, but have not confined them. To truly hold these atoms in fixed positions, traps have been developed.

2. Atom Trapping

The need for ever slower atoms that do not run away, so that sufficient time is provided to study them, has led to inventions of a myriad of atomic traps. Different methods have been devised to trap atoms with the help of magnetic, electric and light fields.

a. Electric Traps

Scientists make use of the fact that atoms contain a cloud of electrons around their nuclei, which can be distorted, to come up with the concept of this trap. In an electric field with a positively and negatively charged region, dipoles would be induced in atoms. For a homogeneous field, the atoms would just attract each other with no particular direction, but in a trap, it is desired that the atoms concentrate at a region. A field with a local minimum/maximum is used because each of these dipoles can experience a net force from an inhomogeneous field: they get attracted towards higher intensity field.

So the theory of the electric field has been defined, but there is one problem: scientists have not been able to create a pure electric with a local maximum. Luckily, it is known that light is of electromagnetic waves and can set up an electric field. It can also be focussed and thus produce a local maximum. Therefore light, or optical, traps has been invented.

b. Optical Dipole Force Traps

Even though a light field oscillates, as long at the oscillation frequency is lower than that of the natural oscillation of the atomic dipole, the dipoles will be induced in the atoms on time such that the effect is similar to a static electric field. In this case the atoms would be attracted to the local maximum, but if the frequency of the field is higher than that of the atomic dipole, the induction of the dipole would lag behind as the field oscillates. At some moments, the dipoles would be aligned such that like charges face each other and repulsive forces are generated. This leads to repulsion from high intensity field. The attractive and repulsive forces are used in different types of optical traps.

The first type utilises a Gaussian beam which has a local maximum was devised by Vladilen S. Letokov; its workings have already been explained. The other type of optical dipole force trap uses the standing light wave that has a frequency blue shifted from the atomic resonance. The atoms are then repelled from regions where there are oscillations to the nodes where there are none. The atoms are then held there by the repulsive forces.

With special arrays of laser beams, it as been possible to produce optical lattices, in which the atoms are arranged into a regular three-dimensional pattern. These lattices can help in the cooling process because the atoms, held, temporarily, in fixed, regular positions, are easier to cool than atoms in a big mess.

In both cases, the laser frequency is detuned, above or below, far from resonance so as to reduce the scattering force, which can ‘kick’ the atoms out of position.

c. Magnetic Traps

Focussing less on light, traps mainly using magnetic field were developed. Just as the electric trap was proposed for atoms due to its functionality on ions, the magnetic trap was invented for neutral bodies. However, the first magnetic trap, the Paul trap, by Wolfgang Paul, worked on neutrons. The magnetic trap was later, after 1983, extended to include atoms.

One restriction of magnetic traps is that the atoms used have to be paramagnetic, i.e. have a permanent magnetic dipole. This happens when the nuclear spin and the electron spins do not cancel each other, overall, such that the atom has a net spin. A further requirement in such traps is that by changing the spin of one electron of the atom, the atom's net spin and thus its magnetic dipole would change. This flipping is carried out with optical pumping.

The magnetic field used in the traps is inhomogeneous with a local minimum or maximum, but it is usually a minimum. Whether the pole of the high intensity is north or south depends on the optical pumping and whether the scientists want attraction or repulsion from high intensity field. The forces exerted by this field are similar to those of the electric field. The magnetic trap works by attracting/repelling the atoms to the centre of the trap.

d. The Magneto Optical Trap MOT

The magneto-optical trap, or MOT in short, is the innovative incorporation of many of the concepts involved in cooling and trapping. It was the first, which allowed continuous loading of atoms during cooling. Constructed in 1987 by David E.Pritchard and Steven Chu of AT&T Bell Laboratories, the MOT, basically, consists of a couple of solenoids and laser sources producing three orthogonal pairs of counterpropagating laser beams. The solenoids generate magnetic dipoles facing each other such that a magnetic field is set up with a local minimum at the centre, where the neutral point coincides.

With a pre-cooling laser added on, pre-cooling can be carried out to reduce the velocity of an atomic beam, in one dimension, with the help of the magnetic field acting as the Zeeman slower.

Once the atoms are close to the centre, the pre-cooling laser shuts off and the six other lasers are activated. Sisyphus cooling and later VSCPT takes place. Meanwhile, optical trapping occurs. Later, the magnetic field strength is increased for magnetic trapping.

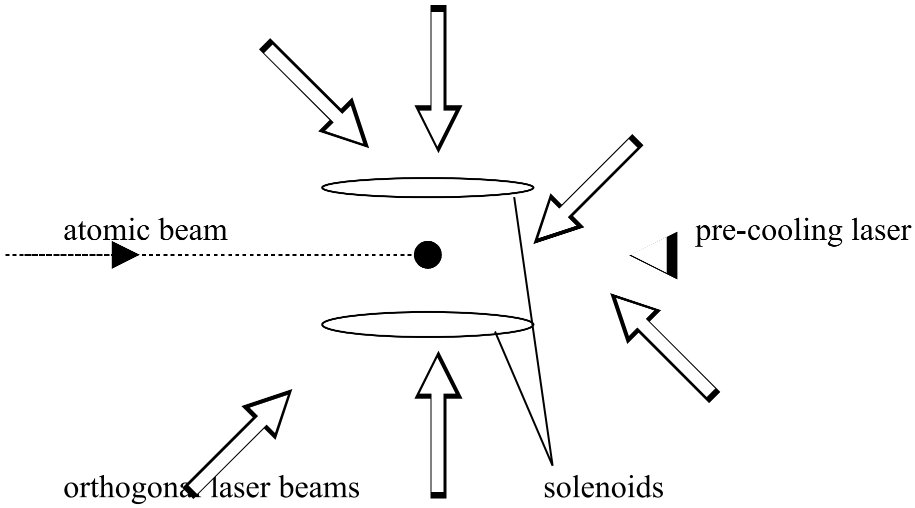


Figure 6: schematics of an MOT

With the processes completed, a cooled trapped sample of atoms has been produced and can be transferred elsewhere. The atoms can be used in some applications or they can be further studied.

These are the few different methods employed to trap cold atoms and among these the MOT is the most popular. Uses of the products and other functions of the techniques involved thus far are explained in the later section.

3. Applications

While laser cooling and atom trapping was developing, other technologies followed suite and when scientists discovered the importance of the former, more sprouted. The following is a brief description of just a few of them.

a. Ultrahigh Spectroscopy

With the success of laser cooling and atom trapping, its original objective is handled effectively; Doppler broadening is greatly reduced with spectral lines being more distinct. The range of velocities of the atoms is greatly reduced, so that the range of Doppler shifts is also reduced. With the atoms moving slower, more time is provided in measuring their features and precision is improved.

Not only can the internal structure of the atom be studied more carefully, the measurement of time through atomic clocks can also be made more accurate.

b. The Atomic fountain

The atomic fountain, first demonstrated by Chu when at Stanford University, shoots a slow beam of atoms, which can be obtained from an MOT, at speeds of about 2.0 ms^{-1} upwards and allows them to fall freely under gravity. The trajectory is a parabola and at the top of it, the atoms have close to zero velocity. At such a low speed, high resolustion spectroscopic measurements can be carried out on it.

There, Ramsey spectroscopy can carried out by exposing the atoms to two pulses of microwaves. The frequency of the microwaves measured can be used as information in atomic clocks, to increase their accuracy, because the velocities of the atoms are more uniform.

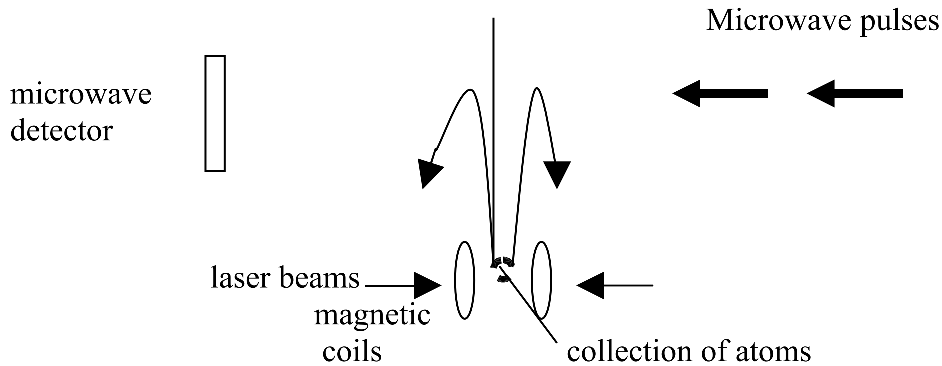


Figure 7: schematics of an atomic fountain

c. Optical Tweezers

The concept of how the optical tweezers work is very similar to that used in the optical trap. Here, the dipole force is also utilized, but rather than just on atoms; it has been extended to include macroscopic objects such as polystyrene spheres and cells.

Using a Gaussian beam of laser light, a field with a local maximum is set up. This can definitely attract atoms to that region; now it can even attract the molecules, which are made up of these atoms and also the organelles, which consists of these molecules. When such a beam is shone onto a specimen, it 'grabs' hold of it and when the beam is moved about, it follows.

Such optical tweezers have been tested on the organelles of bacteria and DNA molecules, among others to investigate compliance and elasticity.

d. Ultracold Collisions

One study of the cooled atoms is their bonding. Usually, molecular bonding occurs at high speeds, but scientists have been able to form a molecular state between pairs of atoms by having them collide slowly and aiding this with pulses of light. The light would excite the atoms and cause a weak molecular bond to form. The molecule is much larger than typical ones, but is very unstable and decays quickly. The nature of molecular bonding can be studied more carefully and with spectroscopic methods, the lifetime of the atoms in such systems can be measured.

e. The Bose-Einstein Condensate BEC

A Bose-Einstein condensate is a state of matter that occurs when atoms are cooled to the microkelvin scale. According to Bose statistics, such atoms have the quantum energy level and would begin to superimpose onto one another's position forming a 'super atom' of indistinguishable atoms.

This condensate, postulated by Satyendra Nath Bose and Albert Einstein in the 1920s, finally, first observed by Eric Cornell and Carl Wiemann on June 5, 1995, is prominent only for temperatures of about 50 billionths above absolute zero. To obtain atoms this cold, a evaporative cooling is used where a sample of cooled atoms is kept in a magnetic trap with magnetic field strength reducing at a certain rate such that the more energetic atoms escape, leaving the even cooler atoms behind. The result is a sample with less atoms but a sufficiently low temperature.

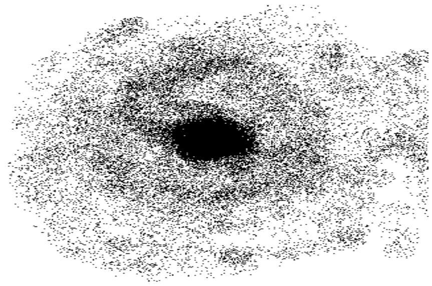


Figure 8: a Bose-Einstein condensate; the black region represents it

f. Atom Lasers

Just as photons in optical lasers are in the same quantum state, an atom laser would have atoms all with the same quantum energy level. However, this is the only requirement of an atom laser, it need not be collimated. The atoms for such a laser are obtained from a Bose-Einstein condensate, as all the atoms there are in the same, lowest, ground state. To make the laser, a beam of such atoms have to be produced.

The first atom laser was invented by David Ketterlie of the Massachusetts Institute of Technology MIT who released the atoms of a BEC from the magnetic trap, through optical pumping to eliminate the influence of the trap, and allowed the atoms to fall under gravity. The beam of atoms forms the laser, but it was quite divergent then.

g. Atom Optics

The success of Laser Cooling and Atom Trapping has brought about numerous developments, not excluding the field of Atom Optics. Laser cooling was just the beginning that atoms could be manipulated using light. In atom optics, atoms, at reasonably low temperatures, have their de Broglie's wavelengths sufficiently long to treat them as waves, instead of particles. Scientists can now do to atoms what they have been doing to light. Just as light can be reflected and diffracted, so can atoms, in atom optics. When light is refracted through a lens, it is focussed; similarly, atomic beams can also be concentrated to a fine point.

- Atomic Interferometry

The study of waves involves measuring their amplitudes, phase and, particularly, their frequency. Interferometers are used for the measurement of these frequencies; however, at the moment, most of them are used on light waves. There are many interferometers, but generally it works by taking a wave, splitting it into two, passing each through different paths and recombining them eventually such that an interference pattern is formed. The phase difference between the waves show up in the pattern and scientists can deduce what has happened to the waves. This can be used to measure the wavelength of the wave used and also the environment in which the wave travelled in. One usage of atomic interferometers of the latter application is to measure the acceleration due to gravity. The first atom interferometer was constructed only in 1991.

- Atom Optical Lithography

Lithography, a technique of creating shapes on a piece of metal, has always involved etching. With the advent of the atom laser and the dipole force, situations would soon change. Scientists are now able to lay atoms onto a substrate instead of scraping off material from it.

The atom laser shoots a beam of atoms, all in the same quantum state, onto the substrate. As it can be focussed to a fine point, microcircuits can be placed in position and nanomachines can be structured.

A mass productive technique involves the optical dipole force. Atom waves can be diffracted, just as light can. Matter and optical gratings can be used for diffraction; the optical standing wave is employed here with the atoms repelled from the antinodes. If atoms were heading towards a standing wave, they would be repelled towards the nodes and thus deflected. With a two dimensional standing light wave formed with four waves interfering, the atoms would fall to the substrate in dots.

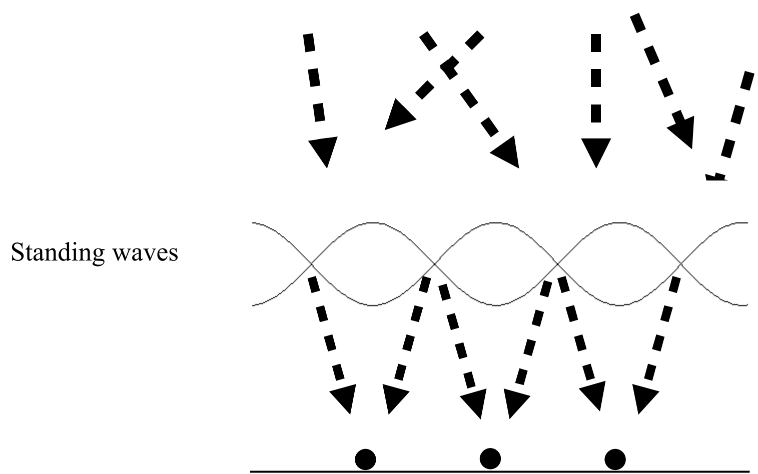


Figure 9: schematics of atom optical lithography

- The Atomic Trampoline

The atomic trampoline, sometimes called the atom mirror because it reflects atoms from a surface, is another illustration that light can change the motion of atoms. Evanescent waves, formed at the air to glass boundary when total internal reflection occurs as, are used to provide for the radiation pressure, which deflects the atoms. Such waves propagate from the glass surface and have their intensity decrease exponentially with time. Atoms can bounce of a surface without touching the matter there, thus avoiding any undesired effects. One particular use of this is in an atom pipe.

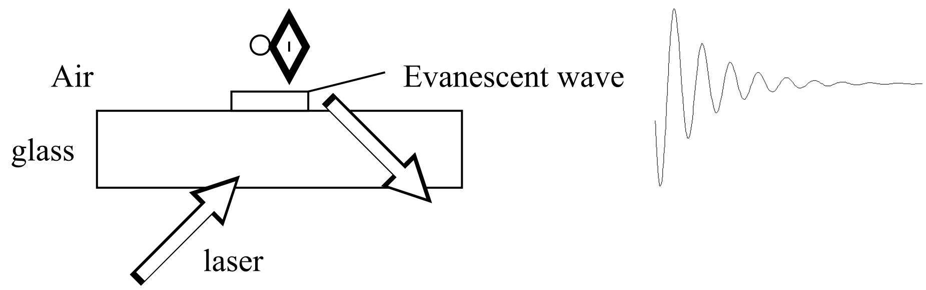


Figure 10: an atomic trampoline

- **Atom Pipes**

Fibre optics is used to transmit light through wires, while an atom pipe does that with atoms. It is a cable with a hollow in the middle and a transparent material around. The outer layer around the cable functions like optic fibre, allowing light to transmit through. The light is not to carry information but to totally internally reflect at the inner glass to air boundary so as to provide the evanescent waves. To the atom, the surface of the hollow in the pipe appears to be coated with a highly 'reflective' material. The atoms passing through the pipe would then behave as light passing through fibre optics, being confined within it. This is the type of atom pipe that uses evanescent waves.

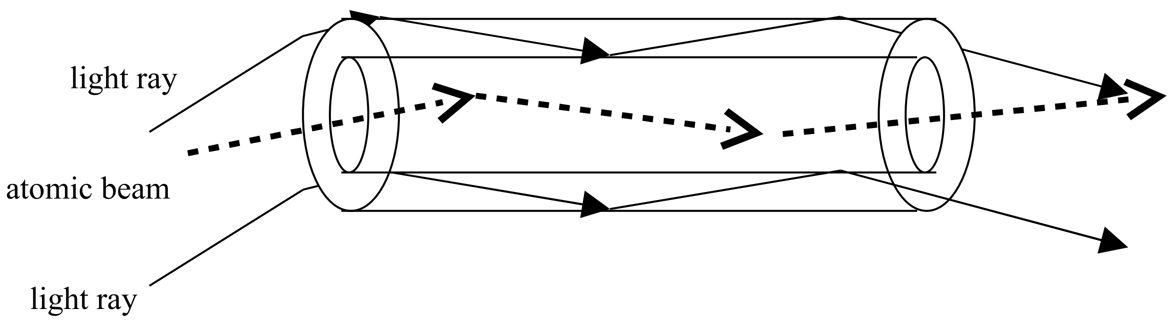
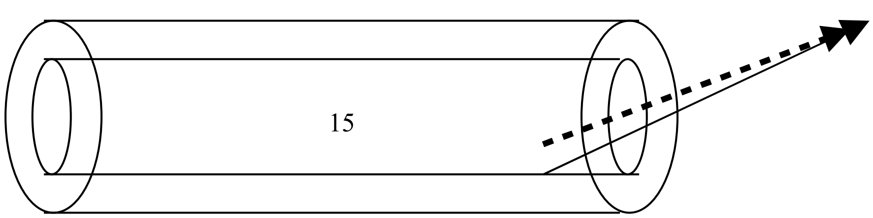


Figure 11: one type of atom pipe

Another type makes use of the optical dipole force. The structure of the pipe is about the same. By shining light through the hollow of the pipe, a light field is set up with high intensity at where the light beam travels. The atoms would then pass through the hollow of the pipe and be guided by the light beams as they are attracted to high intensity field. As, in general, the high intensity field accumulates at the centre of the hollow; the atoms tend to stay at the centre of the pipe. This facilitates the transportation of atoms through the pipes.



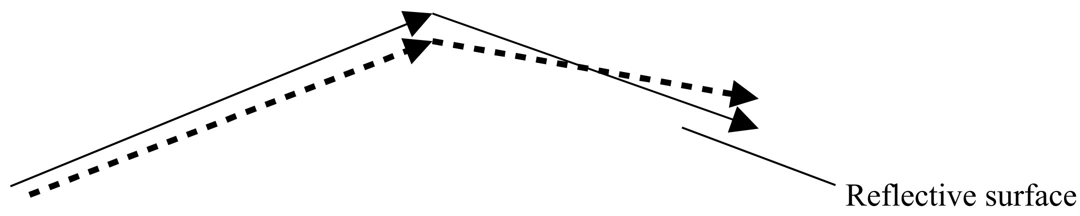


Figure 12: another type of atom pipe

Conclusion

With modernization, the technology is developing rapidly and these have outstanding consequences on science, especially quantum physics. As scientific infrastructure is rapidly improving newer and better techniques are being devised. Scientists have achieved temperatures few billionths above absolute zero, an accuracy that could not be even dreamt off during the 1960's. Significant progress in the laser technology enhances the cooling and trapping methods. The trapping procedures have become so efficient that a huge portion of the ultraslow atoms can be isolated.