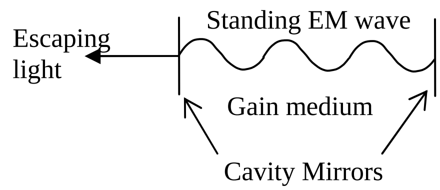
Atomic Physics
PHYS 210- Spring 2006

Atomic physics is a sub-field of physics that focuses on properties of individual atoms and systems with relatively weak interactions between atoms. Since atoms can be accurately described using only basic quantum mechanics they can be studied with high precision. Atoms can also be easily manipulated using lasers and various other electromagnetic fields. Atomic physics has many different research directions, such as precision measurements and tests of fundamental physics laws, cooling and trapping of atoms, development of atomic clocks, accelerometers, magnetometers, etc. Atomic physicists use a wide range of experimental techniques and often combine theoretical and experimental work.

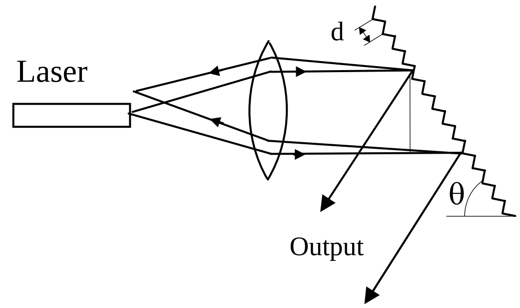
Lasers

Atomic physics is closely related to laser physics. Lasers were first developed by atomic physicists and today almost all atomic experiments use a laser. Lasers operation is based on the fact that photons are bosons and prefer to occupy the same quantum state. A laser typically consists of a resonance cavity formed by two mirrors and a gain medium. The resonance cavity has a discrete set of electromagnetic field modes, similar to a discrete set of standing waves on a string. The gain medium contains atoms in an excited state. In the absence of a cavity the atoms decay to the ground state by emitting photons in a random direction. But inside the cavity the probability of emission into any particular electromagnetic mode is proportional to $N^{1/2}$ where N is the number of photons already present in that electromagnetic mode. Therefore, the atoms will have a larger probability to decay by emitting a photon into an electromagnetic mode that already has a large number of photons, a process knows as stimulated emission. Under ideal conditions one mode of radiation will win over all other modes and all radiation emitted by atoms will collapse into a single electromagnetic mode.



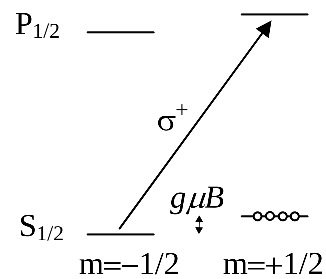
The gain medium does not necessarily have to consist of atoms, it can also be a semiconductor which emits photons by recombination of electron-hole pairs. The electron-hole pairs are created by flowing an electric current through a p-n junction diode. Semiconductor lasers gradually replace other types of lasers because of their simplicity, low cost and small size. The frequency emitted by a semiconductor laser depends on the band gap in the semiconductor material, which can be adjusted by varying its chemical composition. The frequency also has a weak dependence on temperature and the driving electric current. Semiconductor lasers typically emit light into several adjacent electromagnetic modes. Electron-hole pairs that recombine near a node of one of the standing waves will not be stimulated to emit into that particular mode and are more likely to emit into an adjacent mode that does not have an intensity node at their position. A common technique to select a single wavelength is to use external feedback, which sends light of a particular wavelength back into the laser. This increases the number of photons present in the desired electromagnetic mode and makes the probability of emission into this mode higher than into any other mode.

One way to setup external feedback is to use a diffraction grating. A diffraction grating consists of a series of equally spaced parallel steps. Each step is scattering the laser light in all directions. The waves interfere constructively in the directions where the path difference between successive steps is equal to a multiple of the wavelength of light λ. This interference condition can be written as $2\,d\cos(\theta) = \lambda$. Therefore the direction of the reflected beam depends on the wavelength of light. By tilting the grating and changing the angle θ one can send the light of the desired wavelength back into the laser. This allows one to select a single laser mode in a semiconductor laser.



Optical pumping

The term optical pumping refers to redistribution of atoms between different quantum states using light. Consider a simple atom, such as Rb, which has a single valence electron outside of a closed shell and has energy levels similar to a hydrogen atom. The ground state is an $S_{1/2}$ state with total angular momentum J = 1/2 and the first excited state is $P_{1/2}$, also with J = 1/2. In a magnetic field these states split into m = 1/2 and m = –1/2 levels. Suppose that the atom is illuminated with right-circularly polarized light (denoted by σ^+) parallel to the magnetic field. Since each photon carries one unit of angular momentum, only transitions from $m = -1/2$ ground state to the m = 1/2 excited state will conserve the total angular momentum. The atoms typically quickly decay from the $P_{1/2}$ back to the ground state. They can decay to either of the two ground states by emitting a photon of appropriate polarizaton. If they decay to $m = -1/2$ they will be excited again, but if they decay to m = 1/2 ground state, they will remain there, unable to absorb a photon. After several optical pumping cycles all atoms will accumulate in m = 1/2 ground state. This also means that the electron spins of all atoms will point along the magnetic field, the atoms will be spin-polarized. When the atoms are fully polarized they can not absorb light and the amount of light transmitted through the cell increases.



Magnetic resonance

One way to probe the polarization of the atoms is to apply an electromagnetic field that can induce transitions between m = 1/2 and m = –1/2 levels of the ground state. The energy difference between these levels in a magnetic field B is given by $g\mu B$, where μ is the magnetic moment of the electron and g = 2 is the “Dirac g factor”, which is a quantum-mechanical correction to the classical energy of a magnetic dipole in the magnetic field. To induce a transition between the m = 1/2 and m = –1/2 levels one has to apply an oscillating magnetic field whose frequency times the Plank constant h is equal to the energy difference between the two atomic states. If the oscillating field is tuned to the resonance, it will transfer some atoms from the m = 1/2 state to m = –1/2 state and they will be able to absorb photons, decreasing the transmission of the light. Therefore, by looking at the transmission of the laser through the cell one can find the magnetic resonance frequency.

There are several ways to observe the resonance. One of the simplest is to modulate up and down the RF frequency of the oscillating electromagnetic field around a center frequency. If the center frequency is exactly equal to the resonance frequency, one will only observe a signal at the second harmonic of the modulation frequency, because the transmission through the cell will go down whether the RF frequency is shifted up or down from the resonance. On the other hand, if the center frequency is shifted away from the resonance frequency, the signal will have the first harmonic of the modulation frequency, because shifting the RF frequency one way increases the transmission and shifting it the other way decreases the transmission. Using a lock-in amplifier and a feedback loop it is possible to lock the RF frequency to the atomic resonance frequency and build a simple magnetometer.