Spontaneous Emission

Spontaneous emission is an energy conversion process in which an excited electron or molecule decays to an available lower energy level and in the process gives off a photon. This process occurs naturally and does not involve interaction of other photons. The average time for decay by spontaneous emission is called the spontaneous emission lifetime. For some excited energy levels this spontaneous decay occurs on average within nanoseconds while in other materials it occurs within a few seconds . As with absorption, this process can occur in isolated atoms, ionic compounds, molecules, and other types of materials, and it can occur in solids, liquids, and gases. Energy is conserved when the electron decays to the lower level, and that energy must go somewhere. The energy may be converted to heat, mechanical vibrations, or electromagnetic photons. If it is converted to photons, the process is called spontaneous emission, and the energy of the photon produced is equal to the energy dierence between the electron energy levels involved. The emitted photon may have any direction, phase, and electromagnetic polarization.

There are many ways in which an electron can be excited to a higher energy level. Spontaneous emission processes may be classified based on the source of energy which excites the electrons, and these classes are listed in Table below. If the initial source of energy for spontaneous emission is supplied optically, the process is called photoluminescence. Glow in the dark materials emit light by this process. If the initial form of energy is supplied by a chemical reaction, the process is called chemiluminescence. Glow sticks produce spontaneous emission by chemiluminescence. If the initial form of energy is supplied by a voltage, the process is called electroluminescence. LEDs emit light by electroluminescence. If the initial form of energy is caused by sound waves, the process is called sonoluminescence. If the initial form of energy is due to accelerated electrons hitting a target, this process is called cathodoluminescence. If spontaneous emission occurs in a living organism, such a firefly, the process is called bioluminescence. At temperatures above absolute zero, some electrons in atoms are thermally excited to energy levels above the ground state. These electrons decay and emit a photon by spontaneous emission. Any object at a temperature above absolute zero naturally emits photons by spontaneous emission, and this process is called blackbody radiation. In 1900, Max Planck derived a formula for the energy density per unit bandwidth of a blackbody radiator by making the assumption that only discrete energies are allowed [10, p. 453]. His work agreed with known experimental data, and it is one of the fundamental ideas of quantum mechanics.

Photons emitted by a blackbody radiator have a relatively wide range of wavelengths, and this bandwidth depends on temperature. Figure 7.1.17.1.1 plots the energy density per unit bandwidth for blackbody radiators as a function of wavelength at temperatures 3000, 4000,

and 5000 K. Room temperature corresponds to around 300 K. Visible photons have wavelengths between 400 nm $<\lambda<<\lambda<$ 650 nm. From the figure, we can see that black body radiators at higher temperatures emit both more photons and have a larger fraction of photons emitted fall in the visible range.
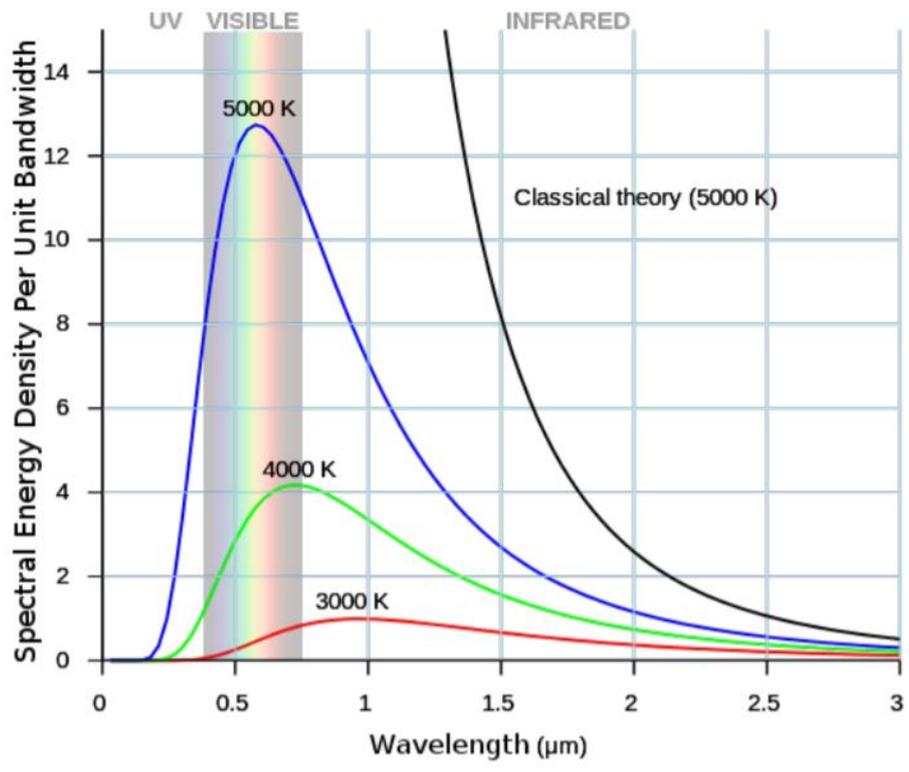

Figure 1: Spectral energy density of a blackbody radiator.

Stimulated Emission

Stimulated emission is the process in which an excited electron or molecule interacts with a photon, decays to an available lower energy level, and in the process gives o a photon. As with the other processes, this process can occur in isolated atoms, ionic compounds, organic molecules, and other types of materials, and it can occur in solids, liquids, and gases. If an incoming photon, with energy equal to the difference between allowed energy levels, interacts with an electron in an excited state, stimulated emission can occur. The energy of the excited electron will be converted to the energy of a photon. The stimulated photon will have the same frequency, direction, phase, and electromagnetic polarization as the incoming photon which initiated the process.
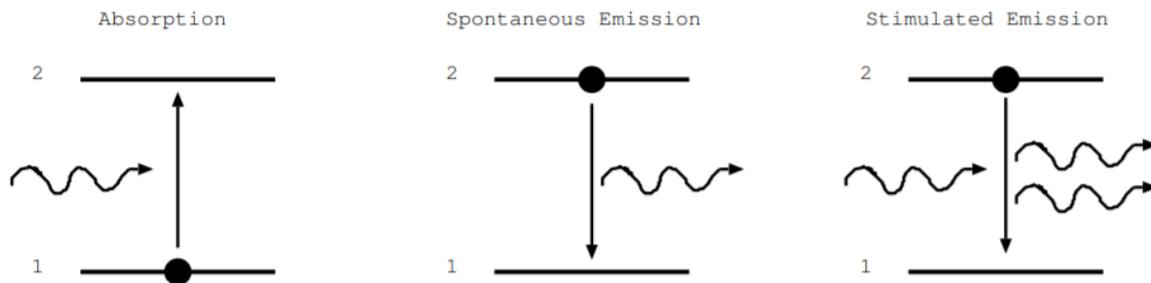
Figure 2: Energy level diagrams illustrating absorption, spontaneous emission, and stimulated emission.

The processes of absorption, spontaneous emission, and stimulated emission are illustrated by energy level diagrams in Fig. 2. Energy is on the vertical axis, and nothing is plotted on the horizontal axis. Only two energy levels are shown, so this diagram illustrates only a small fraction of possible energy levels of a material. The lower energy level is labeled 1. It may represent, for example, the highest occupied energy level of an electron in an isolated atom, or it may represent the valence band of a semiconductor. The higher energy level is labeled 2, and it may represent the lowest unoccupied energy level of an electron in an isolated atom or the conduction band of a semiconductor. The dot represents an electron occupying the energy level at the start of the process. The squiggly arrows represent a photon absorbed or emitted by the process. The vertical arrow shows how the internal energy of the electron changes in the process. During absorption, an electron takes energy from an incoming photon, and the internal energy of the electron increases. During spontaneous emission, the internal energy of an electron decreases, and a photon is emitted. Stimulated emission occurs when a photon, with energy equal to the energy gap of the levels, interacts with the electron. In the process, the electron decays to the lower energy level, and a photon is produced with the same frequency, direction, phase, and electromagnetic polarization as the original photon. The figures do not illustrate a change in position of the electrons. Instead, they illustrate a change in energy and internal momentum.

The descriptions of the processes above involve changes in energy levels of an electron. However, absorption, spontaneous emission, and stimulated emission can instead involve vibrational energy states of molecules. For example, a photon may be absorbed by a molecule, and the energy may cause the molecule to go from one allowed vibrational state to another with higher internal energy. Similarly, this molecule may spontaneously decay from the higher energy state to a lower energy state emitting a photon by spontaneous emission or by stimulated emission. An example involving molecular vibration states is a carbon dioxide laser. This laser produces infrared light by stimulated emission at $\lambda=10.6\mu m\lambda=10.6\mu m$, and the stimulated emission occurs between allowed vibrational energy levels of the CO2 molecule. However, to simplify the discussion in this text, we will assume that electron energy levels are involved. This assumption is true in most, but not all, energy conversion devices.

Population inversion

 The redistribution of atomic energy levels that takes place in a system so that laser action can occur. Normally, a system of atoms is in temperature equilibrium and there are always more atoms in low energy states than in higher ones. Although absorption and emission of energy is a continuous process, the statistical distribution (population) of atoms in the various energy states is constant. When this distribution is disturbed by pumping energy into the system, a population inversion will take place in which more atoms will exist in the higher energy states than in the lower. By considering the factors that affect the rate of absorption, spontaneous emission, and stimulated emission, we can see some similarities and differences in the processes. As absorption occurs, the population of electrons in the upper energy level increases, and the population of the lower energy level decreases. As both spontaneous and stimulated emission occurs, the population of the upper energy level decreases, and the population of the lower energy level increases. Both the rate of absorption and the rate of stimulated emission depend on both the population of electrons in an energy level and the energy of incoming photons while the rate of spontaneous emission does not depend on the energy of incoming photons.

Level 3, E_3, N_3

R (fast, radiationless transition)

Level 2, E_2, N_2

P (pump transition)

L (slow, laser transition)

Level 1 (ground state), E_1, N_1