Name: ______________________________________ Date: ________________________

Quantum Applications: Lasers

Learning goals
After completing this activity, you will be able to …

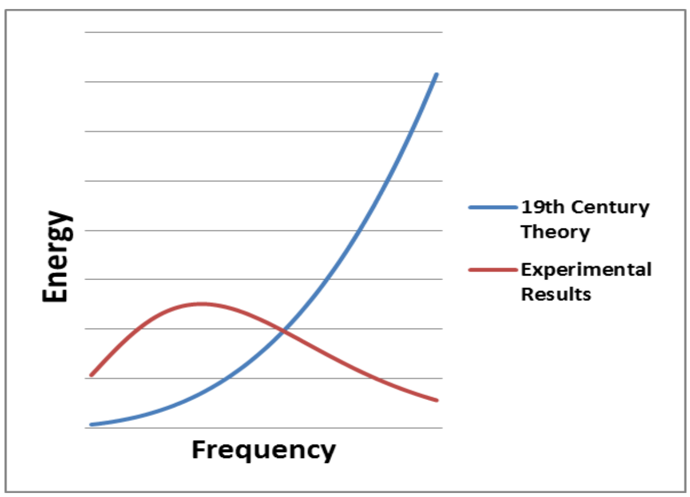
- Explain the phenomenon of stimulated emission.
- Describe how a laser works.

Vocabulary: coherent light, electromagnetic wave, gain medium, laser, photon, Planck hypothesis, spontaneous emission, stimulated emission, thermal equilibrium, thermal radiation,

Thermal radiation
Molecules are constantly moving in random directions, and the temperature of a material is proportional to the average energy of this motion. Because molecules contain charged particles, their movement changes the electric and magnetic fields within and around the material.

As James Maxwell showed in the mid-19th century, an **electromagnetic wave** can be generated when electric and magnetic fields are altered. If a material gets hot enough, the random motion of its molecules are so energetic that they create electromagnetic waves with enough energy that we can see them as light. This is why hot metal can glow red. Incandescent light bulbs work for the same reason: electric current raises the temperature of an extremely thin piece of metal, causing it to become "white hot" and give off light. The energy produced in the above fashion is called **thermal radiation**.

If an object is absorbing as much energy from its environment as it is giving out, and if it is not being affected by its environment in any other way, it is said to be in **thermodynamic equilibrium**. Light waves have many different shapes because they can spiral through space in different ways. For an object to be in thermodynamic equilibrium, its light waves have to have a specific kind of shape. The higher the light's frequency, the easier it was for it to have the right shape.



At the end of the 19th century, scientists were perplexed because the light given off by hot objects in thermal equilibrium did not match what Maxwell's theory of light predicted. Maxwell's theory, which was widely accepted, predicted that such an object should always give off more energy at higher frequencies than at lower frequencies because there were more light waves at higher frequency that had the right shape. But this did not match experiments, which showed there was a specific frequency (based on the temperature) after which the amount of energy decreased as the frequency increased. One serious problem with their theory was that it required the object to give off an infinite amount of energy every second.

Max Planck's work resolved this conflict. He presented the **Planck hypothesis**, which states all energy is absorbed or emitted in packets, called quanta. For light, such a packet is called a **photon**. Photons with higher frequencies have more energy. This means that it is harder for the motion of molecules in an object to produce a high-frequency photon than it is for them to produce a low-frequency photon because high-frequency photons require a great deal of energy to be concentrated in a single wave.

This leads to a balance between high-frequency light and low-frequency light. There are more ways for a high-frequency photon to be produced, and each one of them has more energy than a low-frequency photon, but high-frequency photons become harder and harder to generate as the energy needed for each one increases.

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1. Why does raising the temperature of an object cause it to produce more energetic radiation?

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2. Give two examples of appliances that work by heating an object, causing it to radiate.

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Stimulated emission

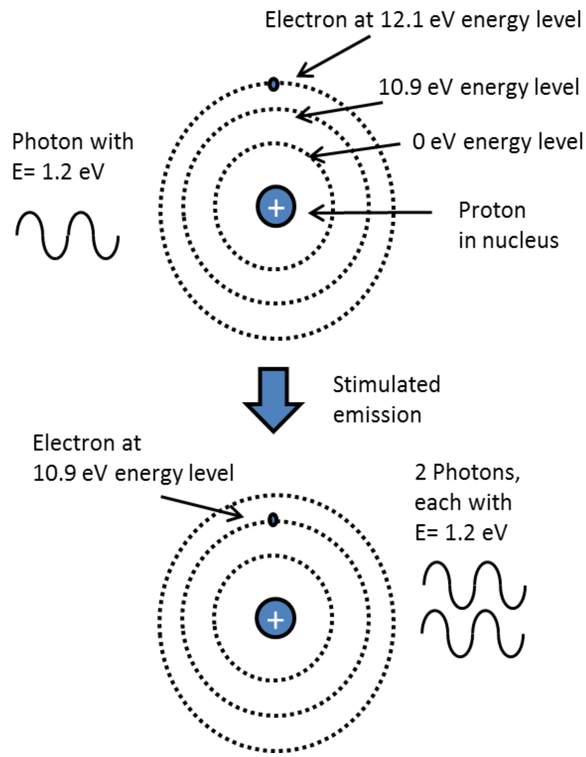
Electrons bound to atoms are at different energy levels. If a photon with just the right amount of energy strikes an atom, the atom can absorb the photon and one of its electrons will switch to a higher energy. Scientists say the electron is *excited* when it is at a higher state than normal. Conversely, an atom with an excited electron can emit a photon of light, and the electron will move to a lower energy state. This occurs randomly and is known as **spontaneous emission**. (You can investigate these phenomena in the *Bohr Model of Hydrogen* Gizmo™.)

In 1916, Einstein discovered something quite strange about absorption and emission of electrons. Based on the work of previous physicists, Einstein knew what percentage of atoms in an object should have electrons at a given energy level. When Einstein combined this information with Planck's theory describing how many photons exist with each energy for an object in thermodynamic equilibrium, he found that the number of atoms absorbing photons of a particular energy was greater than the number of atoms undergoing spontaneous emission.

This seemed impossible. If the number of photons being absorbed were greater than the number being emitted, the balance between excited electrons and non-excited electrons could not be maintained. Soon there would no longer be any electrons at the lower energy levels, making further absorption impossible.

Einstein made a brilliant deduction. When a photon interacts with an atom *that already has an excited electron*, it can cause the atom to emit a photon. That is to say a photon of just the right energy can cause an excited electron to move *down* to a lower energy level as easily as it can cause an unexcited electron to move up. In both cases the photon's energy needs to match the gap in energy between the two electron energy levels.

This phenomenon, in which one photon can induce the emission of another, is called **stimulated emission**. The diagram to the right shows an atom having an electron at an energy level of 12.1 eV before interacting with a photon having an energy of 1.2 eV. This causes the electron to drop to a lower energy level and emit a photon equal to the energy of the original photon. One photon hits the atom, but two exit.



This resolves the problem Einstein found because these extra emissions make up for the discrepancy between photons absorbed and photons emitted through spontaneous emission.

1. What happens when an electron drops from one energy level to another? _______________

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2. How does stimulated emission differ from spontaneous emission?

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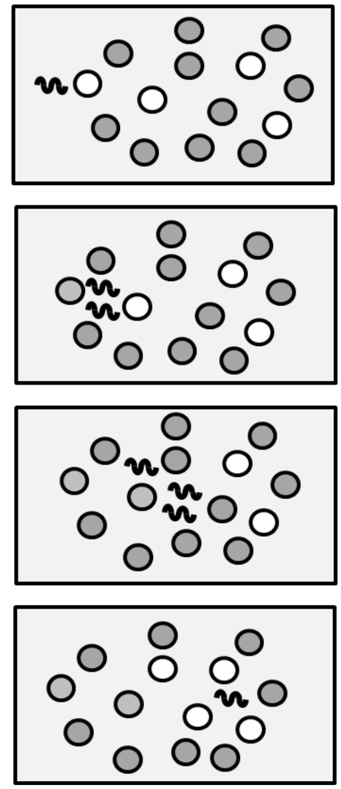
Chain reactions through stimulated emission

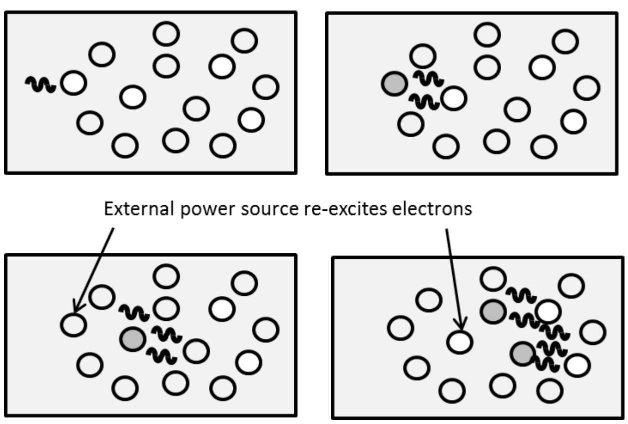
Stimulated emission is different from spontaneous emission in one key way. Spontaneous emission generates a photon with a random phase going in a random direction. When one photon causes an atom to emit another through stimulated emission, the second photon is like a copy of the first. It not only has the same energy, but it moves in the same direction with the same phase. It is as though the atom has allowed the original photon to clone itself.

This means that stimulated emission can create a kind of chain reaction. One photon gives rise to two, each with the same phase and direction, and these strike other atoms, generating two more photons. At that point all four have the same phase and direction. These hit other atoms, doubling to 8 and so on.

In most settings, there are very few atoms with excited electrons compared to those without excited electrons. The figure at right shows how this prevents chain reactions of the sort described above because stimulated emission can only occur when a photon interacts with an atom having an excited electron (the unshaded circles in the figure). Atoms with no excited electrons (the shaded circles) act as blockers, absorbing photons rather than duplicating them.



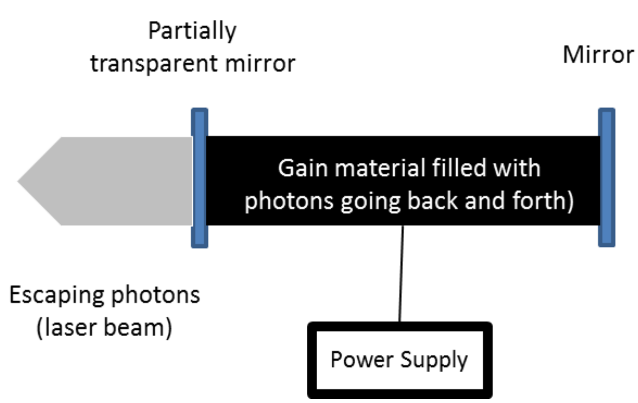
However, if energy is pumped into a system it can cause more and more electrons to be excited. If the system absorbs enough energy, almost all the atoms will have excited electrons, and it is possible for a single photon to create many copies of itself, all with the same phase. When two waves have the same phase, their strength combines. Thus, stimulated emission can allow a single photon to give rise to an extremely powerful pulse comprising a multitude of photons. A figure showing this can be found at left.



Engineers use the term "gain" to refer to the amplification of an input signal by a system. A substance that can support the type of chain reaction described above is called a **gain medium** because its particles can amplify photons by making extra copies through stimulated emission. Many different materials can work as gain media when attached to an external power source, including gases, liquid dyes, specially constructed crystals, and more exotic substances.

Look again at the image above and to the left. Imagine the photons reaching the right edge and being reflected back through, re-duplicating as they hit the re-excited atoms. More and more photons would be generated as the gain material's amplification would compound. This is exactly how a **laser** works!

A laser (Light Amplification by Stimulated Emission of Radiation) uses mirrors to send light back and forth through a gain medium. One of the mirrors allows some light (about 1%) of the light to escape. This is the laser beam seen coming from the laser. The rest of the light builds upon itself until it reaches a maximum energy level determined by the specifics of the construction.



In addition to allowing the light energy to build up inside the laser, the mirrors have a second role. Light waves bouncing back and forth between the mirrors are similar to sound waves moving back and forth between the ends of a flute or clarinet. An instrument can only play certain notes because those are the only pitches whose sound waves can build up inside them . Sound waves of other frequencies die out because they destructively interfere with themselves after reflecting off the ends. Similarly, only certain wavelengths of light can survive the back-and-forth trips between the mirrors without dying out from interference. (You can investigate the effect of interference with the *Ripple Tank* Gizmo.)

Thus, a laser can make use of both the particle and wave properties of light to form a powerful beam of nearly monochromatic light. The strength of the light comes from the generated light waves having the same phase so they do not destructively interfere with each other. Careful selection of gain medium and mirror locations can severely limit the frequencies of generated light that can survive interference when reflected back and forth in the chamber. This way, most of the lasers' energy goes into producing energy of the desired frequency.

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1. The mirrors inside a laser server what two purposes? ________________________________

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2. How does a laser make use of both the wave and particle properties of light?

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