LASER Fundamentals

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I. Introduction

This course will provide you with valuable information about surgical options for patients to correct their vision. The lecturers in this course will provide clinical details as well as some basic science about the procedures.

Optics is a fundamental part of refractive surgery. In particular, I will be guiding you through the topics of lasers, higher order aberrations/wavefront correction, and the optics of intraocular lenses. Hopefully, the discussions that we have about these topics will give you additional insights about refractive surgery that you can bring to your patients.

We will begin with the fundamentals of lasers. Lasers, of course, are one of the primary tools used in refractive surgery.

II. Review of Energy Level Diagrams

A. Classical energy of an atom

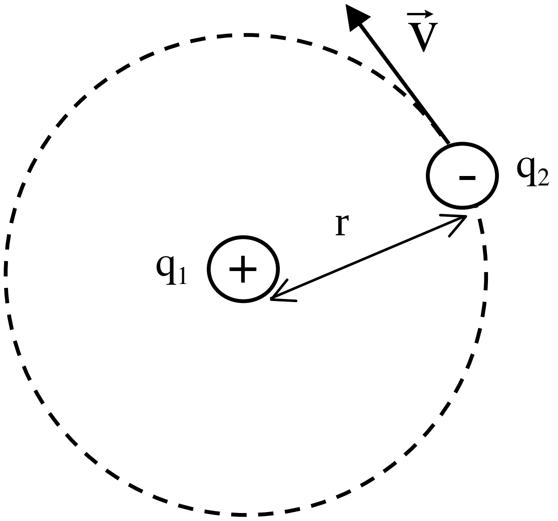
Recall from basic physics that the total mechanical energy of a system is calculated by:

Total Energy = (Kinetic Energy) + (Potential Energy)

or

$$E = \underset{\frac{1}{2}mv^2}{\underset{\nearrow}{KE}} + \underset{\text{Depends on separation of objects}}{\underset{\nwarrow}{PE}}$$

Classical picture of atom:



q_1 = charge of nucleus

q_2 = charge of electron

In this case the speed (and therefore the kinetic energy) depends on the orbital distance with:

v (and thus KE) *decreasing* as r increases

$$v = \sqrt{\frac{kq_1q_2}{mr}}$$

Also, the potential energy depends on the orbital distance with:

PE *increasing* as r increases

It can be shown that the total energy in this case is given by:

$$E = \frac{kq_1q_2}{2r}$$

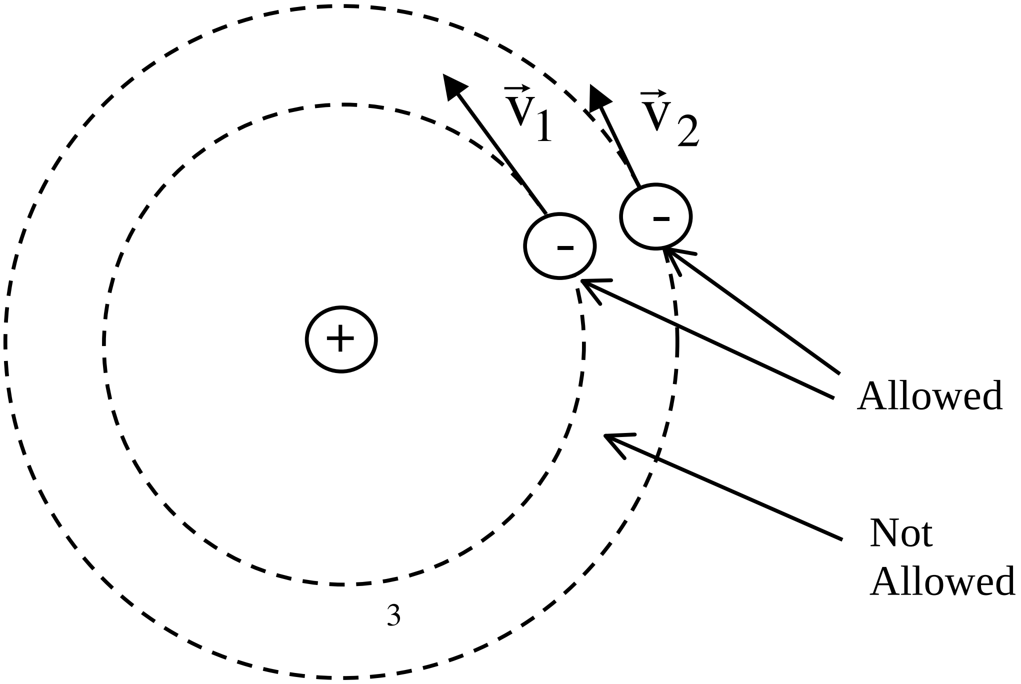
Notice that r can take on *any* values from 0 to ∞. Here k is a constant given by $k \approx 9 \times 10^9\ \mathrm{Nm^2/C^2}$.

Question: What happens to the total energy of the atom as r increases? (Hint: What are the signs of q_1 and q_2?)

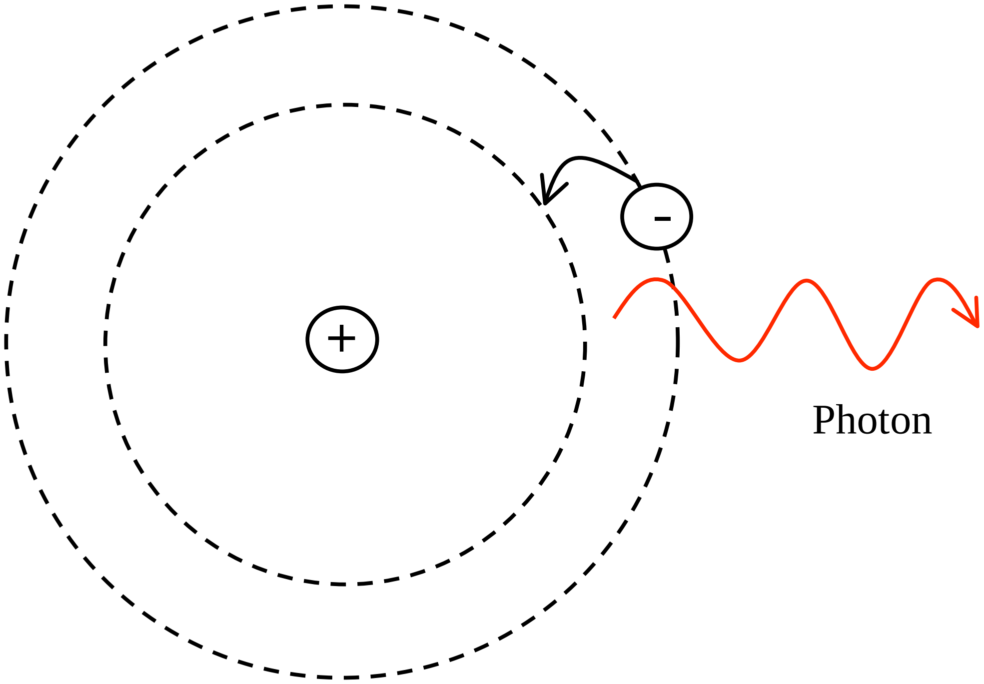
A. increases
B. decreases
C. stays the same

B. Quantum mechanical energy of an atom

In order to explain the observed spectra produced by atoms in the early 20th century, it was found that the orbital distance can only take on certain, *discrete* values! (Bohr Model)



Electrons in a higher energy orbit will “jump” down to a lower energy orbit (either spontaneously or through an outside push). Often times (but not always), the energy lost in this jump is emitted in the form of a photon.



The energy of the emitted photon (in Joules) is equal to the difference in energy of the upper and lower orbits ($E = E_2 - E_1$) and is related to the frequency of the photon by:

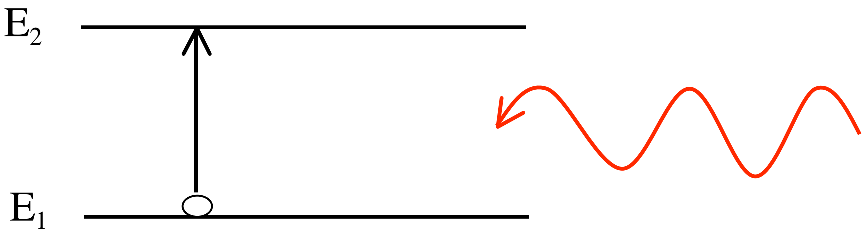
$$\mathbf{E = hf}$$

where h is Planck’s constant ($h = 6.626 \times 10^{-34}$ m^2 kg / s) and f is the frequency (in Hz). Using the fact that the frequency and wavelength (λ, in meters) are related to the speed of light by $c = \lambda f$ we can also relate the wavelength and the photon energy by:

$$\mathbf{E = hc/\lambda}$$

Question: Do red or blue wavelengths have higher energy? The reverse process is also possible with an electron in a lower energy orbit absorbing a photon (of the appropriate frequency) and jumping up to a higher energy orbit.

Rather than drawing atoms with electrons orbiting them, we often just draw "energy level diagrams" with horizontal lines at various heights corresponding to allowed electron energies.



III. Spontaneous Emission

All atoms (or molecules) ultimately "want" to get back to their ground state (the state of lowest energy). When an atom is in an excited state, it will sooner or later emit a photon and jump down to a lower energy state (unless it gives off the energy through other means first, like by colliding with another atom). This process of an isolated atom emitting a photon and dropping to a lower energy state is called "spontaneous emission".

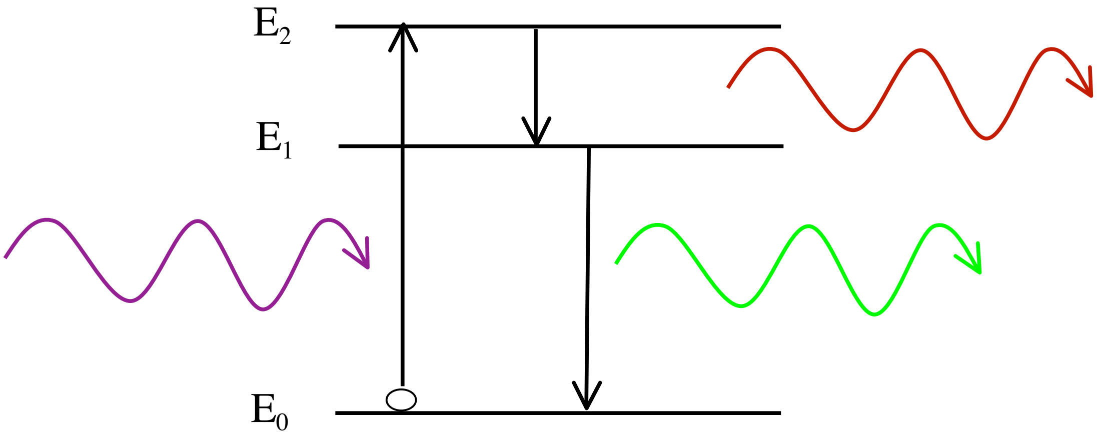
The average time that the atom will remain in a particular excited state is a characteristic of the atom and is called the "lifetime" (τ) of that state. Typical excited state lifetimes are around 10 nanoseconds ($\tau \sim 10^{-8}$ s) or shorter.

Key feature of spontaneous emission – the emitted photon is given off in a random direction compared to the incident photon.

Special cases:

a. Fluorescence

In this case, the atom has at least two excited states. A high energy photon excites the atom which then spontaneously emits two photons of lower energy thus giving off a different color light than what it was exposed to.

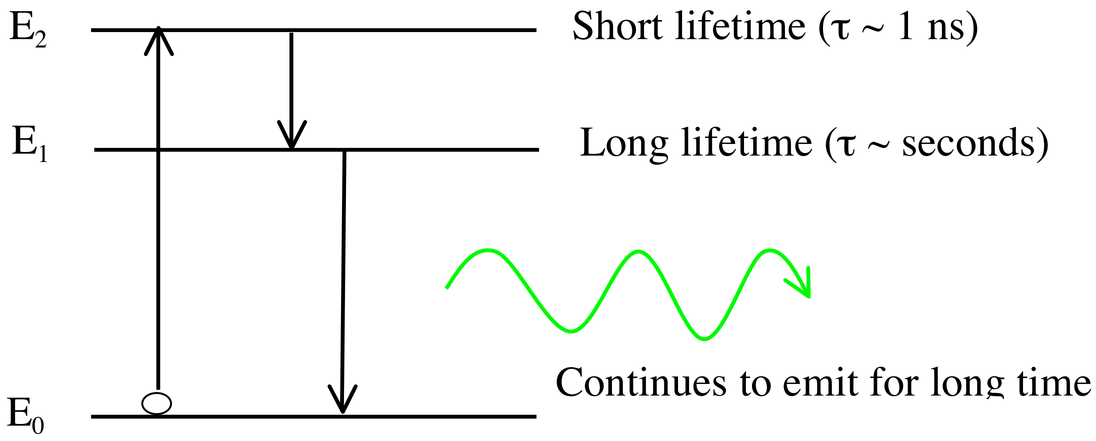


Example:

Sodium florescein – dye commonly used in contact lens evaluations. Excited at 365-470 nm (UV-violet) and fluoresces at 522 nm (green) and 1711 nm (IR).

b. Phosphorescence

In this case, one of the excited states of the atom has a much longer lifetime than the others ("metastable"). Lifetimes might be as long as milliseconds to hours! These materials will continue to emit light via spontaneous emission for a long time after the exciting light is turned off.



Examples – any material that “glows in the dark” after being in the light.

Practice with spontaneous emission

Go to the Physics Education Technology website:

http://phet.colorado.edu

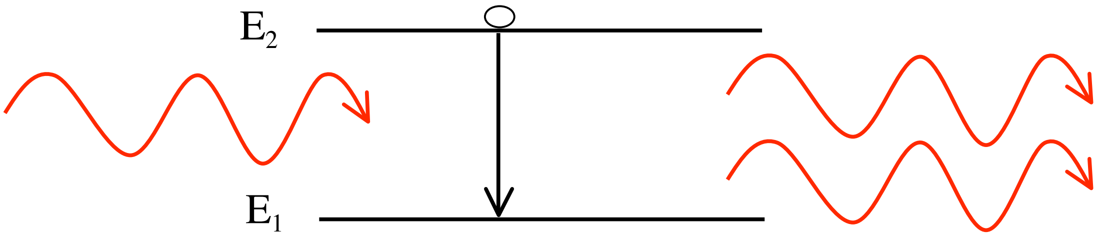
Click on “Play with sims” ⇒ “Physics” ⇒ “Light & Radiation” ⇒ “Lasers”. This is a java based program and has trouble opening sometimes so you may need to close it and open it again. Be patient.

The program opens showing a single atom in a container with a light source at one end. You can adjust the wavelength of the source, the irradiance of the source, and the energy level diagram of the atom. Let’s play with this to gain some experience.

IV. Stimulated Emission

As described above, when at atom is in the ground state it can be made to jump to an excited state by absorbing a photon of just the right frequency (called the "resonance frequency" for the ground and excited states). The reverse process can also happen.

A photon incident on an atom in an excited state will make the electron oscillate with the frequency of the photon. If the photon frequency is equal to the resonance frequency, the electron will be *forced* to jump back down to the ground state and emit a *second* photon.



This process is referred to as "stimulated emission" since the atom is being stimulated to emit before it is able to do so on its own via spontaneous emission.

Key feature of stimulated emission – the emitted photon is ***identical*** *to the incident photon. So, the two photons travel together in the same direction and are in-phase!*

LASER –
Light **A**mplification by **S**timulated **E**mission of **R**adiation

Practice with stimulated emission

Go back to the computer program we were playing with earlier. Adjust the source and energy level properties so that photons are incident on the atom while it is already in the excited state. Observe the photons that are emitted by the atom.

V. LASER Fundamentals

Requirements to make a laser:

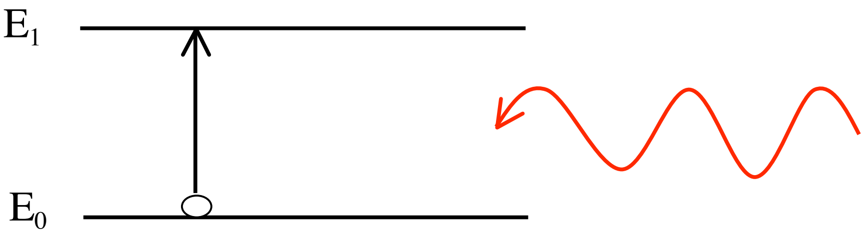
1. Establish a situation where the laser medium (atoms) provides "gain" – more photons being emitted than absorbed by the atoms.

2. Provide a means of sending the photons produced by the gain back and forth through the medium (atoms). This provides "amplification" – an exponential increase in the amount of light being produced.

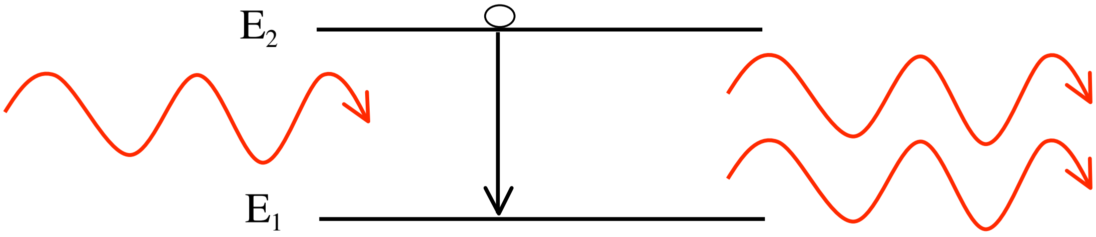
a. How can we achieve gain?

Consider a group of basic, two-level atoms as shown.

Question: Which of the two processes exhibit gain?



Absorption: If a photon is incident on an atom in the ground state, the photon will be absorbed.



Stimulated Emission: If a photon is incident on an atom in the excited state, the atom will drop to the ground state and emit a second photon.

To achieve gain, the medium must have more stimulated emission events than absorption events.

Question: What state should the atoms be in if we want stimulated emission to dominate?

Under normal circumstances, the number of atoms in a given energy level is found to be given by

$$N \propto e^{-E/kT}$$

where $k = 1.381 \times 10^{-23}$ J/K is “Boltzmann’s constant” and T is the temperature of the atoms in Kelvin.

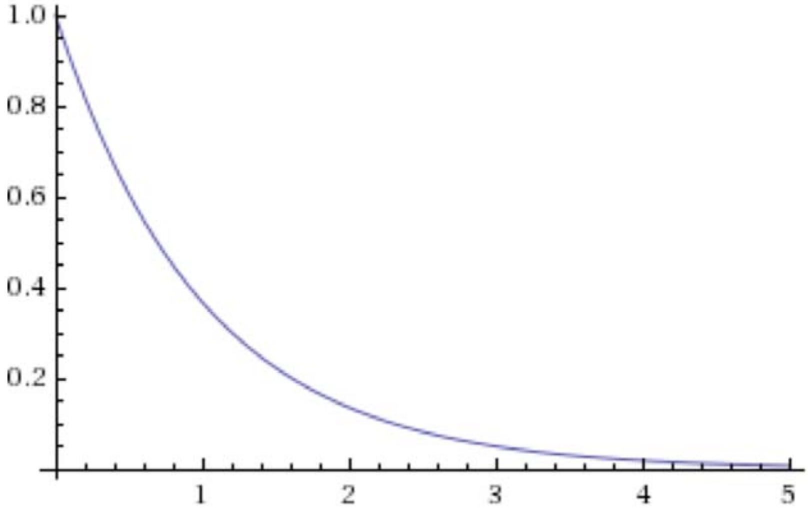
At room temperature (293 K) kT is 4×10^{-21} Joules.

If we consider two states with energies E_1 and E_2 where $E_2 > E_1$, the ratio of the number of atoms in these states is

$$N_2/N_1 = e^{-(E_2 - E_1)/kT}$$

A 632.8 nm transition has E_2-$E_1 = 3 \times 10^{-19}$ joules. So N2/N1 is $e^{-75} = 2 \times 10^{-33} \approx 0$, all atoms in the ground state!

Question: What is the largest value that N_2/N_1 can be and at what temperature does that occur? (below is a plot of e^{-x})

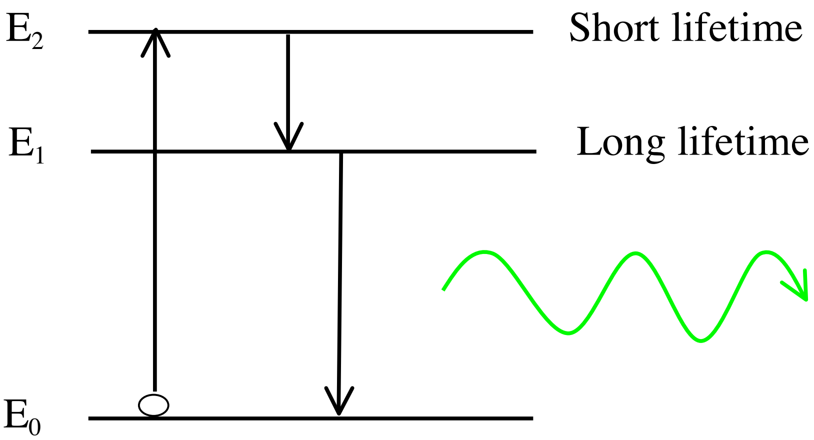


Notice: Higher energy states have smaller populations! This means that at equilibrium, there will be equal absorption of photons and emission of photons – no amplification of light!

b. The trick to achieve gain is called “population inversion.” Where we have more atoms in the excited state than in the ground state. How do we generate a population inversion?

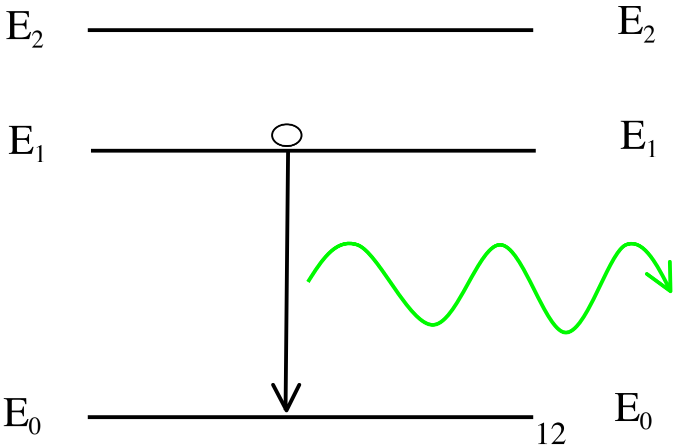
Use a 3 (or more) level atom with a metastable state – phosphorescence!

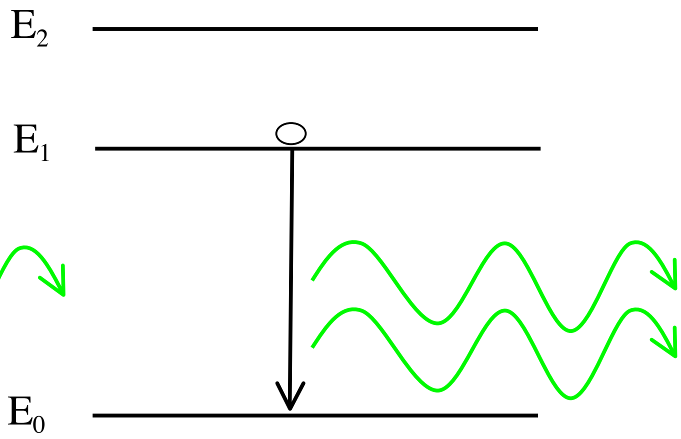
Consider a group of 3-level atoms as shown.



If we supply energy causing the atoms to jump ("pumping") to the second excited state (E_2), the atoms will quickly drop down to the first excited state (E_1) and build up due to the long lifetime. If we continue pumping, we can get more and more atoms in the first excited state until there are a greater number of atoms in this excited state than in the ground state.

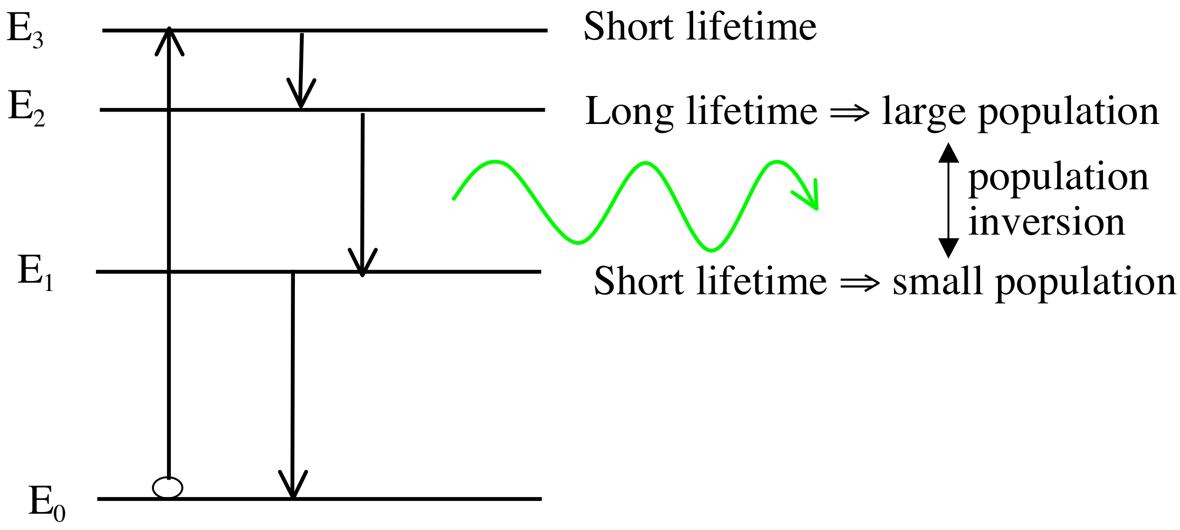
Suppose one of these excited atoms emits a photon. If that photon interacts with another excited atom (which most are), it will emit two photons via stimulated emission.





It is this process of multiplying the number of photons that travel in the same direction with the same phase that is at the heart of what makes any laser work!

This process is even more efficient with 4-level atoms.



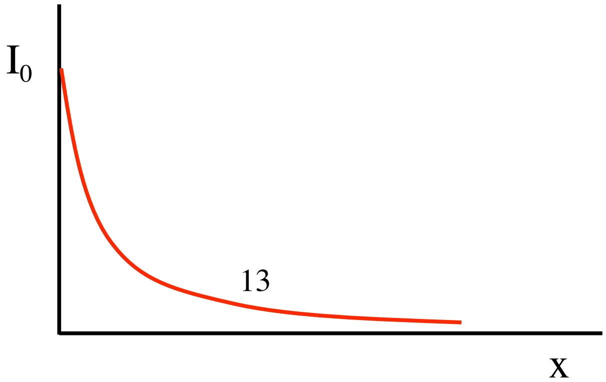
In general we find that the irradiance increases (or decreases) exponentially with distance traveled through the material:

$$I = I_0 e^{\alpha x}$$

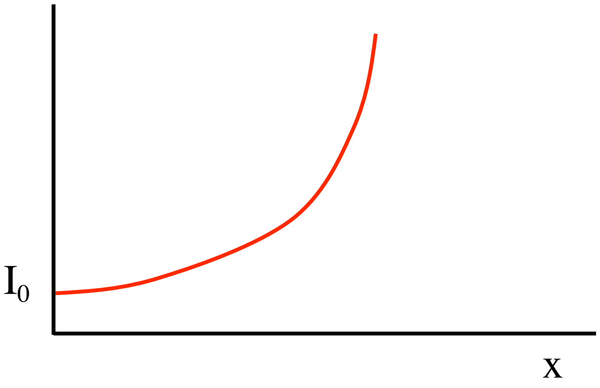
where I_0 is the incident irradiance, x is the distance light travels through the material, and

$$\alpha \propto (N_2 - N_1)$$

Notice that if $N_2 < N_1$ then α is negative and there is an exponential decrease in irradiance (and α is the “coefficient of absorption”).



If $N_2>N_1$ then α is positive and there is an exponential increase in irradiance (and α is the "coefficient of gain").



Question: Suppose we set up a situation where $\alpha x = 2$ so $I = I_0e^2 = 7.39I_0$. If the coefficient of gain doubles while keeping the propagation distance the same, what happens to the irradiance as it propagates through the sample?

A. does not change
B. doubles
C. increases by factor of $e = 2.72$
D. increases by factor of $e^2 = 7.39$
E. increases by factor of $e^4 = 54.6$

c. How do we provide a means of continuing to send the stimulated light through the atoms?

Mirrors! We form an "optical cavity" by placing mirrors on either end of our group of atoms. These mirrors trap some of the stimulated photons and force them to travel back and forth through the atoms. This process is called "feedback".

If we continue to pump energy into the atoms as the stimulated photons are being confined to the optical cavity, the irradiance will continue to grow inside the cavity. We can form the laser beam by making one of the mirrors partially transparent (~95-98% reflective) so that some of the photons can escape.

Practice making a LASER

Go back to the computer program we were playing with earlier. Add mirrors on either side of the atoms and see if you can make the laser operate.

VI. Lasers for Refractive Surgery

Lasers have two primary purposes in refractive surgery:

1. Corneal reshaping to correct refractive error
2. Cutting the corneal flap in LASIK

Each of these uses a different type of laser. We will consider each of these in turn.

1. Corneal reshaping (LASIK, PRK)

Typical laser type - Excimer, operating at 193 nm wavelength (UV), 10 nanosecond pulse duration

(How fast is 10 nanoseconds? There are the same number of 10’s of nanoseconds in one second as the number of seconds in 3 years!)

Why this type of laser? The UV operating wavelength!

The cornea has a large absorption coefficient at this wavelength ⇒ focused UV laser beams can ablate (remove material from) the cornea.

Excimer is short for "excited state dimer". In these systems, the molecules used as the lasing medium are short lived and only exist as molecules in an excited state. Rather than jum p to a ground state, the molecule dissociates into its constituent atoms. Example: ArF. Since there is no ground state, a population inversion exists as soon as the molecules are formed.

2. Cutting corneal flap in LASIK

Typical laser type - Nd:glass, operating in near-IR (around 1060 nm), 100 femtosecond pulse duration

(How fast is 100 femtoseconds? There are the same number of 100's of femtoseconds in one second as the number of seconds in 300,000 years!)

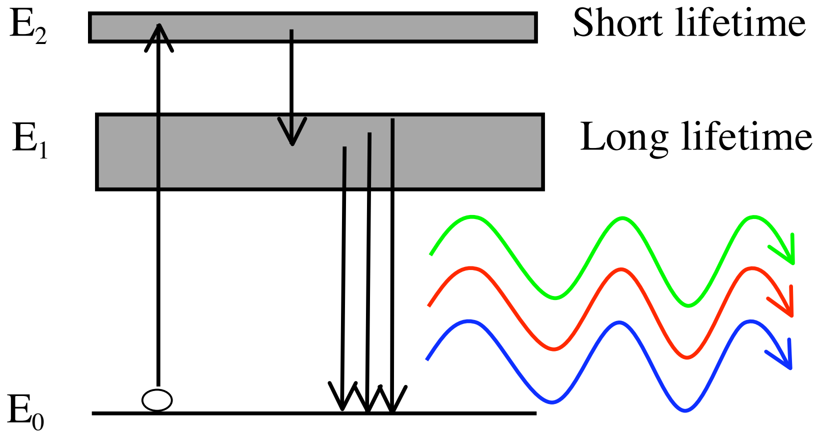
Why this type of laser? The femtosecond pulses!

The cornea does not have a significant absorption at this wavelength. However, focused pulses this short in duration can have high enough energy densities within a very small volume to cause Laser Induced Optical Breakdown (LIOB) of the corneal tissue at the focal spot of the laser. This breakdown is caused by the generation of a small volume of plasma (separation of the electrons from the atoms of the material) accompanied by cavitation (vapor) bubbles and a shock wave.

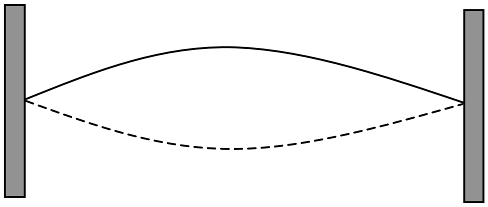
LIOB provides a means to damage the cornea in a controlled way in order to produce a "cut".

How are femtosecond laser pulses produced? Through a process called “mode-locking”.

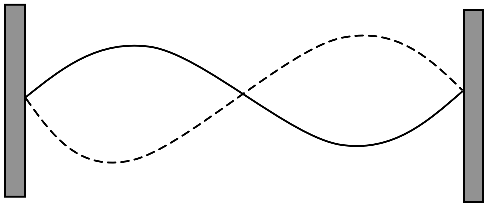
In lasers that utilize solids (typically crystals) for their lasing medium, the energy levels can be very broad. This leads to a large number of wavelengths that are emitted simultaneously.



Within the laser cavity, only certain discrete wavelengths are allowed. These particular waves produce standing waves within the cavity. Each of these standing wave patterns is called a “mode”. Because the cavity is so long compared to the wavelengths, there are many, many discrete wavelengths that will satisfy this requirement.



mode order 1



mode order 2

If many of these waves are present simultaneously, they will constructively interfere over a very short region of space. Everywhere else the waves will tend to cancel. This region of constructive interference can behave like a very short pulse ⇒ femtoseconds!

An instructive movie showing this effect can be found at

http://ecen4843.okstate.edu/Readings/Other%20Resources/movie1.mov

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