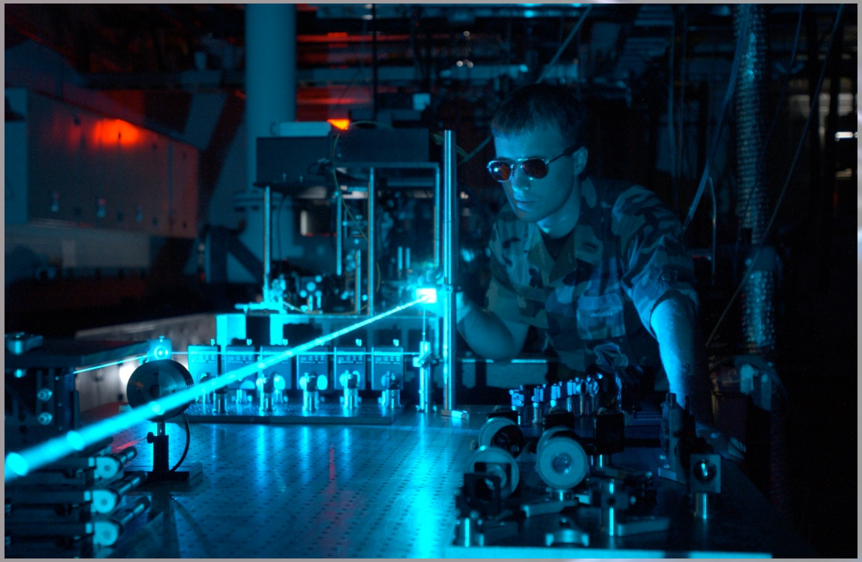
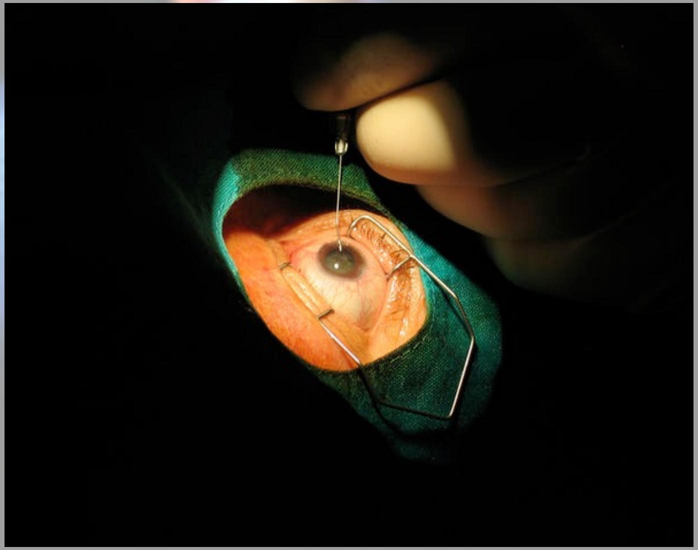
Laser Theory and Applications to Lasers in Medicine



http://upload.wikimedia.org/wikipedia/commons/a/a0/Military_laser_experiment.jpg

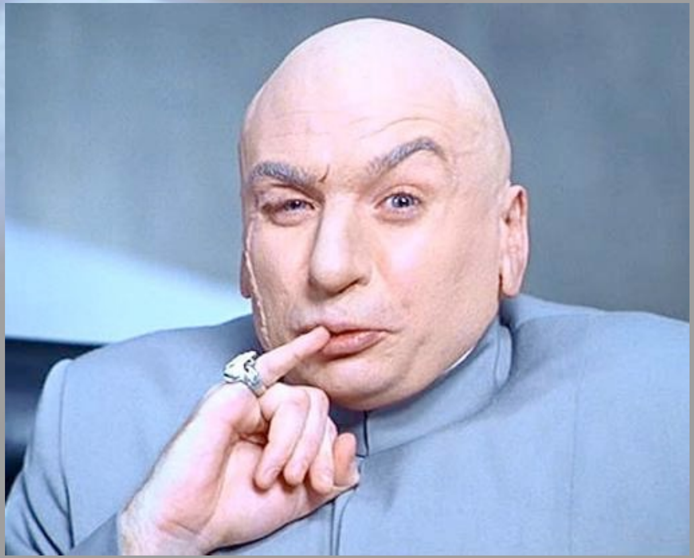


http://www.life123.com/bm.pix/bigstockphoto_close_up_of_eye_surgery_catar_2264267.s600x600.jpg

Background Image: http://www.nano.org.uk/news/july2008/1483.jpg

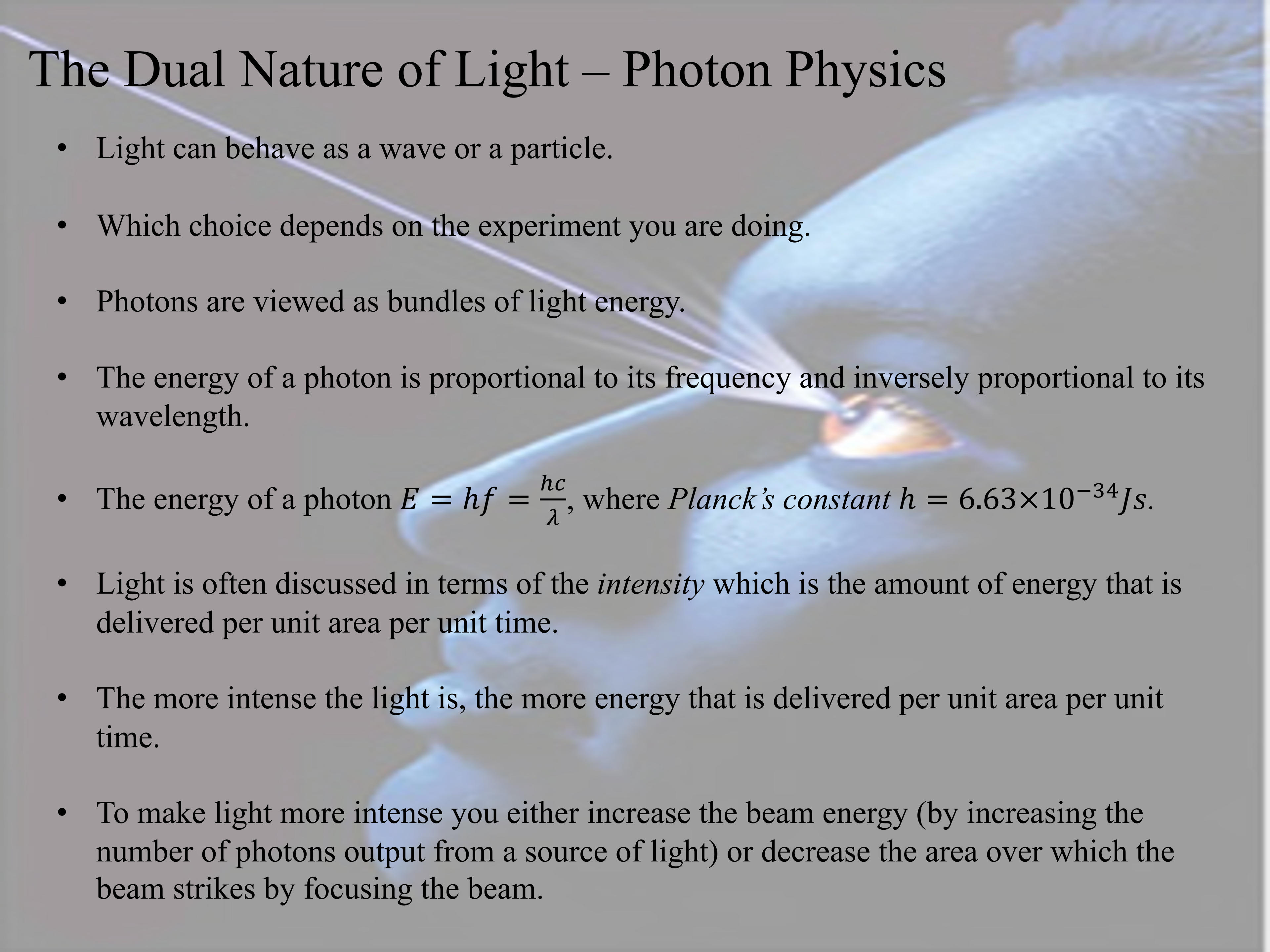
Outline

- Dual Nature of Light – The Physics of Photons
- Energy Transitions in Atoms
- Building a “LASER”
- Interaction of Light and Matter
- Laser ablation
- Photocoagulation
- LASERs in Medicine
- LASER Surgeries



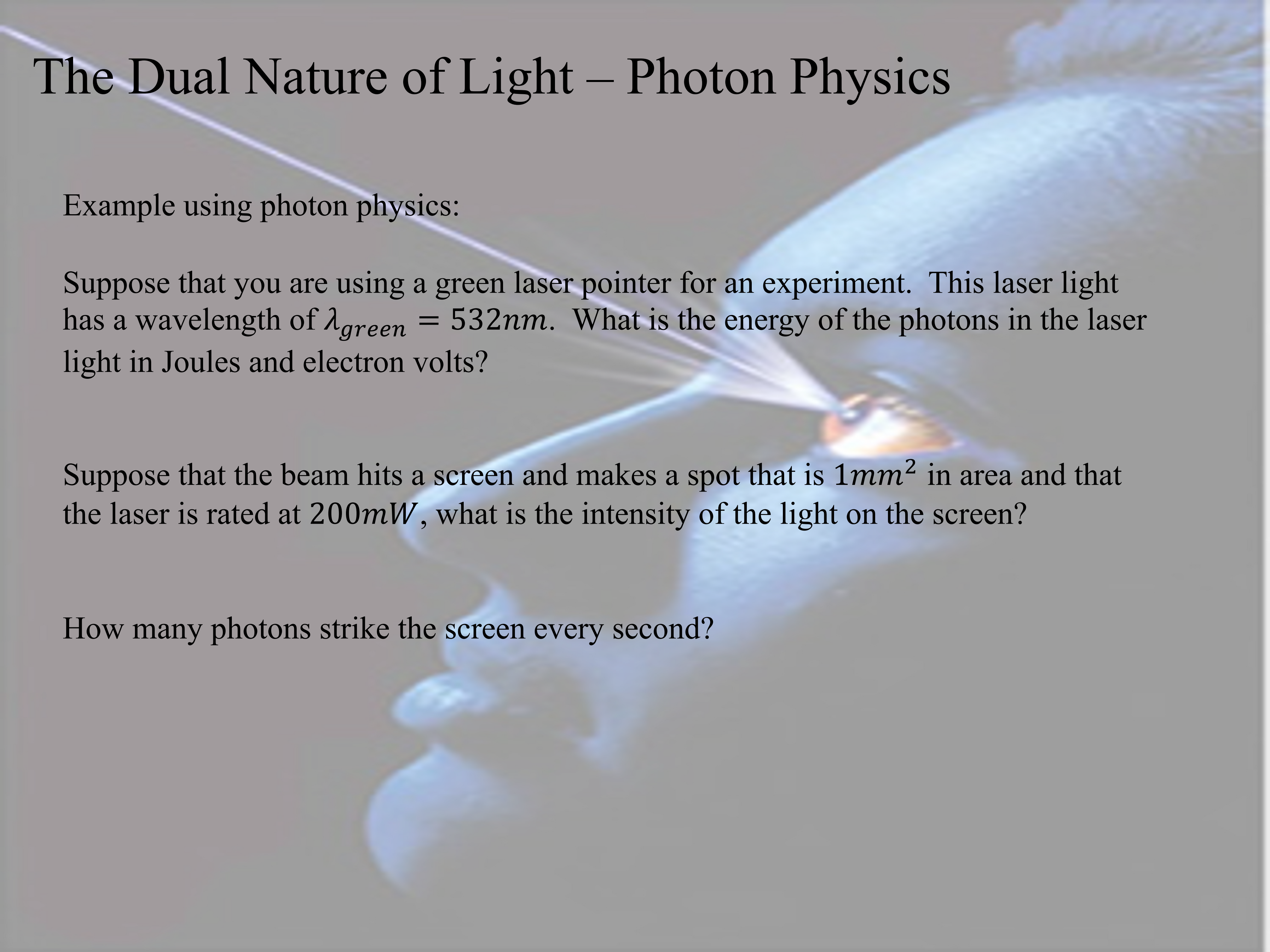
http://www.solarnavigator.net/films_movies_actors/film_images/Austin_Powers_Mike_Myers_as_Dr_Evil.jpg

The Dual Nature of Light – Photon Physics



- Light can behave as a wave or a particle.
- Which choice depends on the experiment you are doing.
- Photons are viewed as bundles of light energy.
- The energy of a photon is proportional to its frequency and inversely proportional to its wavelength.
- The energy of a photon $E = hf = \frac{hc}{\lambda}$, where *Planck's constant* $h = 6.63\times10^{-34} Js$.
- Light is often discussed in terms of the *intensity* which is the amount of energy that is delivered per unit area per unit time.
- The more intense the light is, the more energy that is delivered per unit area per unit time.
- To make light more intense you either increase the beam energy (by increasing the number of photons output from a source of light) or decrease the area over which the beam strikes by focusing the beam.

The Dual Nature of Light – Photon Physics



Example using photon physics:

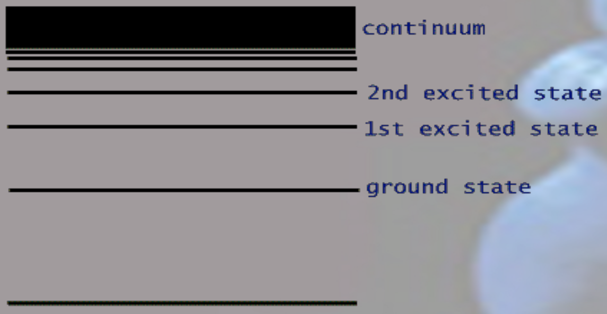
Suppose that you are using a green laser pointer for an experiment. This laser light has a wavelength of $\lambda_{green} = 532nm$. What is the energy of the photons in the laser light in Joules and electron volts?

Suppose that the beam hits a screen and makes a spot that is $1mm^2$ in area and that the laser is rated at $200mW$, what is the intensity of the light on the screen?

How many photons strike the screen every second?

Energy Transitions in the Atom

- Atoms are constructed of a heavy positively charged nucleus (containing protons and neutrons) surrounded by a cloud of negatively charged electrons (orbitals).
- The orbital shapes and allowed energies are determined by solving the “Schrodinger equation.”
- The electrons are found in energy levels and the levels are filled according to the Pauli Exclusion principle – two electrons with opposite spin states per orbital.
- This determines the energies associated with the electrons and the total energy of the atom.
- All electrons are in their respective lowest energy states unless an external agent perturbs them.



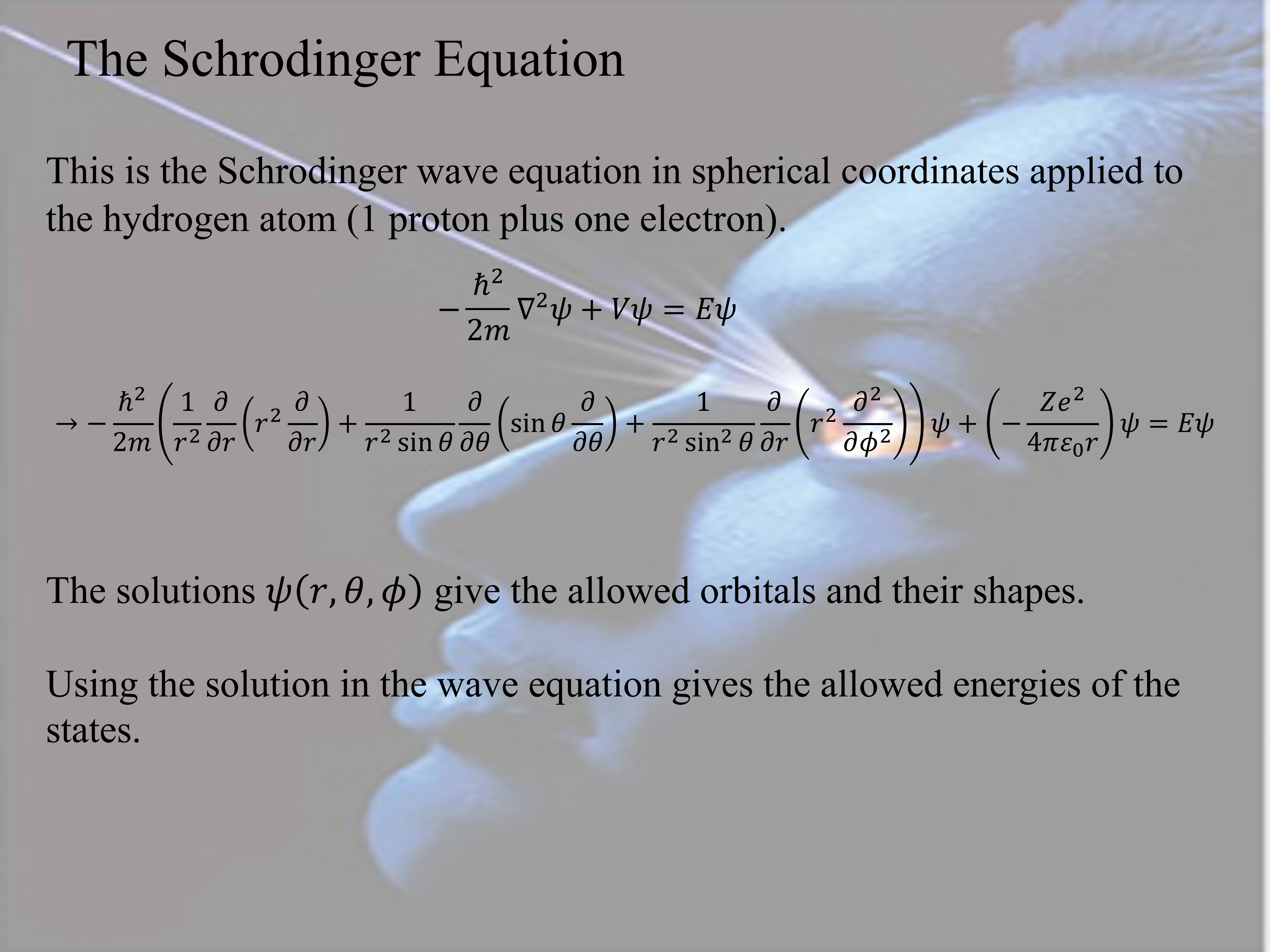
Atomic Energy Level Diagram

http://www1.union.edu/newmanj/lasers/Light%20Production/EnergyLevelDiagram.gif

- The lowest energy level is called the ground state and the higher energy states are called excited energy states.
- The Schrodinger equation, where $\Psi(r,\theta,\phi,t)$ is assumed separable, can be written as $\psi(r,\theta,\phi)e^{-i\omega t}$.

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi$$

The Schrodinger Equation



This is the Schrodinger wave equation in spherical coordinates applied to the hydrogen atom (1 proton plus one electron).

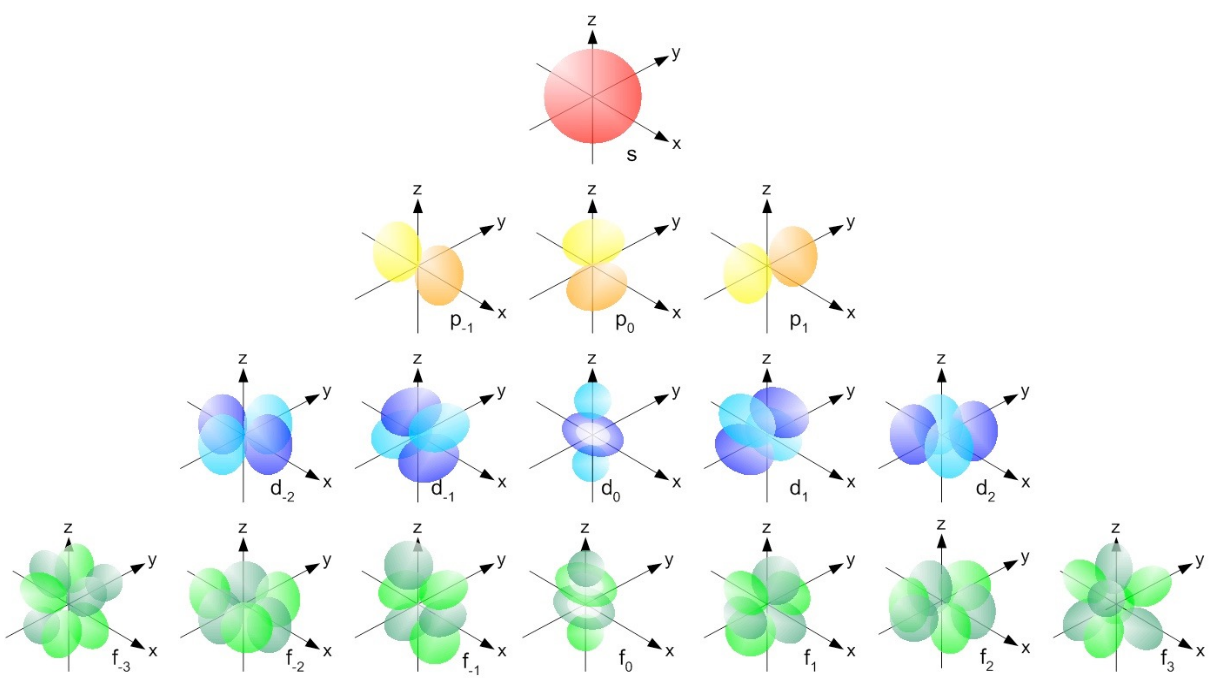
$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi$$

$$\rightarrow -\frac{\hbar^2}{2m}\left(\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial}{\partial r}\left(r^2\frac{\partial^2}{\partial\phi^2}\right)\right)\psi + \left(-\frac{Ze^2}{4\pi\varepsilon_0 r}\right)\psi = E\psi$$

The solutions $\psi(r,\theta,\phi)$ give the allowed orbitals and their shapes.

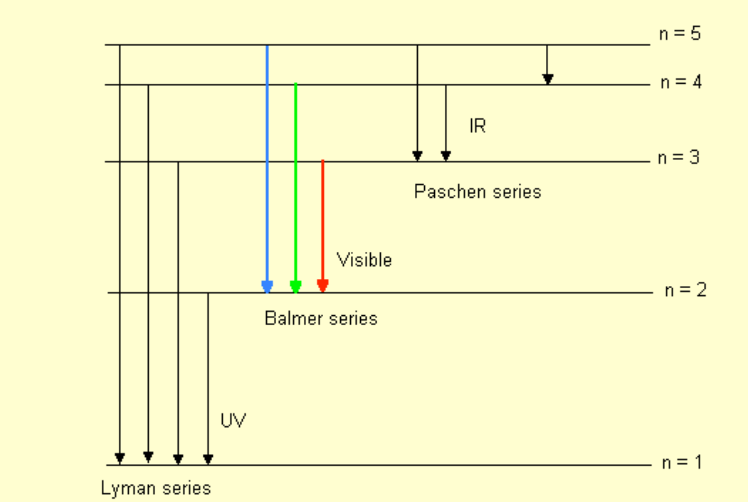
Using the solution in the wave equation gives the allowed energies of the states.

The Schrodinger Equation



http://chemwiki.ucdavis.edu/Physical_Chemistry/Quantum_Mechanics/09._The_Hydrogen_Atom/Atomic_Theory/Electrons_in_Atoms/Electronic_Orbitals

$$\psi(r,\theta,\phi)$$

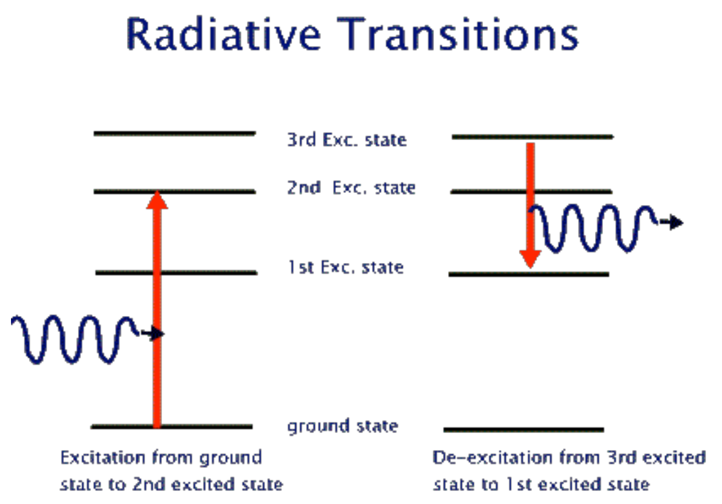


http://www.kcvs.ca/martin/astro/course/lectures/fall/a200l10f.htm

$$E_n = -\frac{me^4}{8\pi^2\varepsilon_0^2\hbar^2n^2}$$

Energy Transitions in the Atom

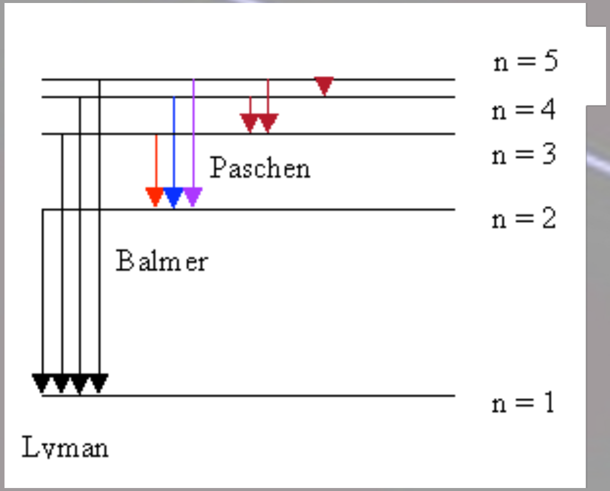
- Electrons can transition between levels. An atomic *excitation* is a transition between a lower energy state to a higher energy state while a *de-excitation* is the reverse.
- The energy needed to excite an electronic transition comes from the absorption of a photon of light *OR* through a collision with another atom or electron.
- This latter process is called a *collisional transition*.
- Energy is liberated by the emission of a photon of light with frequency *f*, as an electron de-excites. This is called a *radiative transition*.
- During any *radiative transition,* the energy absorbed by the electron in the excitation or liberated by the electron in the de-excitation is given by the difference between electronic orbitals.



http://www1.union.edu/newmanj/lasers/Light%20Production/radiative%20transitions.gif

$$\Delta E = E_{upper} - E_{lower} = hf_{photon} = \frac{hc}{\lambda_{photon}}$$

Energy Transitions in the Atom



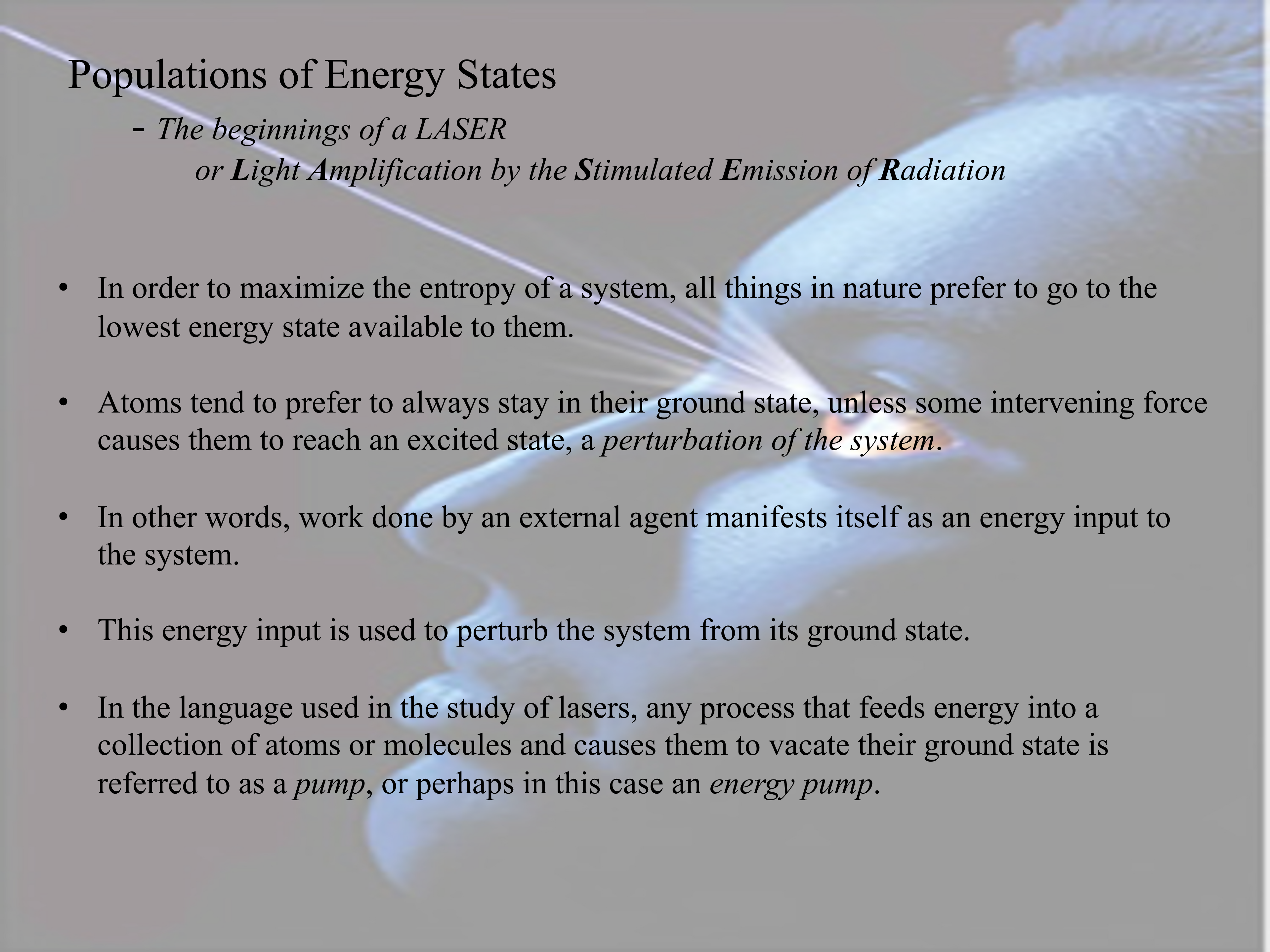
http://www1.union.edu/newmanj/lasers/Light%20Production/Hspectrum.gif

- If a collection of identical atoms are excited by a broad energy source (say an electric discharge) so that all the excited states become populated, radiative de-excitation from the different states will produce an emission spectrum of emitted photons.

- Different atoms will have different sets of possible emitted photon energies that are characteristic of that element. For example, when hydrogen is excited in this manner, the de-excitation transitions are shown in the diagram as an emission spectrum (called the *Balmer Series* – the only visible transitions) and the spectrum is viewed by using a spectrometer.

http://www.physics.siu.edu/events/fieldtrip/IMG_3406.JPG

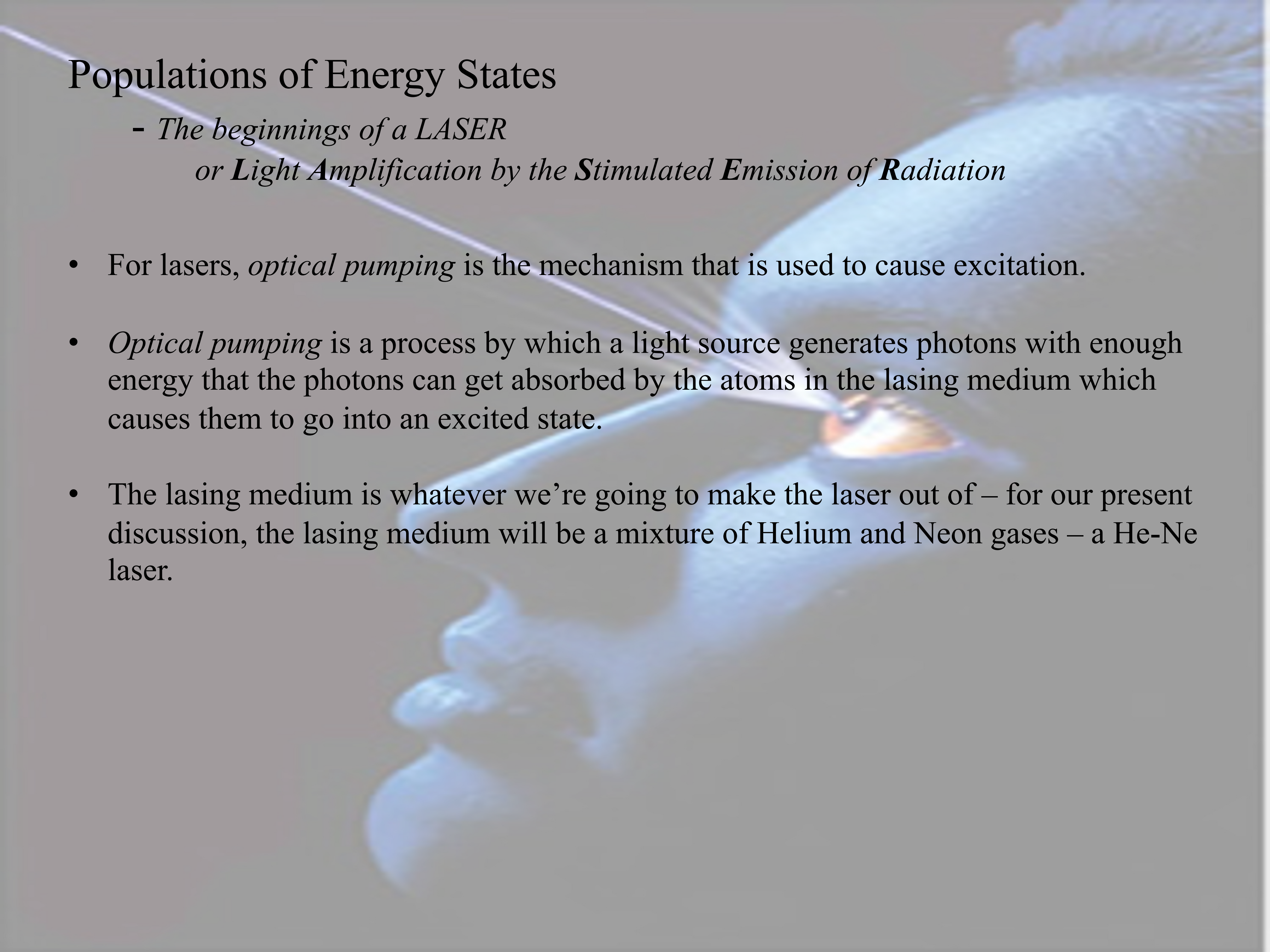
$$E_n = -\frac{mZ^2e^4}{8\pi^2\varepsilon_0^2\hbar^2n^2} = -C\frac{Z^2}{n^2}$$



Populations of Energy States

- *The beginnings of a LASER*
*or **L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation*

- In order to maximize the entropy of a system, all things in nature prefer to go to the lowest energy state available to them.
- Atoms tend to prefer to always stay in their ground state, unless some intervening force causes them to reach an excited state, a *perturbation of the system*.
- In other words, work done by an external agent manifests itself as an energy input to the system.
- This energy input is used to perturb the system from its ground state.
- In the language used in the study of lasers, any process that feeds energy into a collection of atoms or molecules and causes them to vacate their ground state is referred to as a *pump*, or perhaps in this case an *energy pump*.



Populations of Energy States

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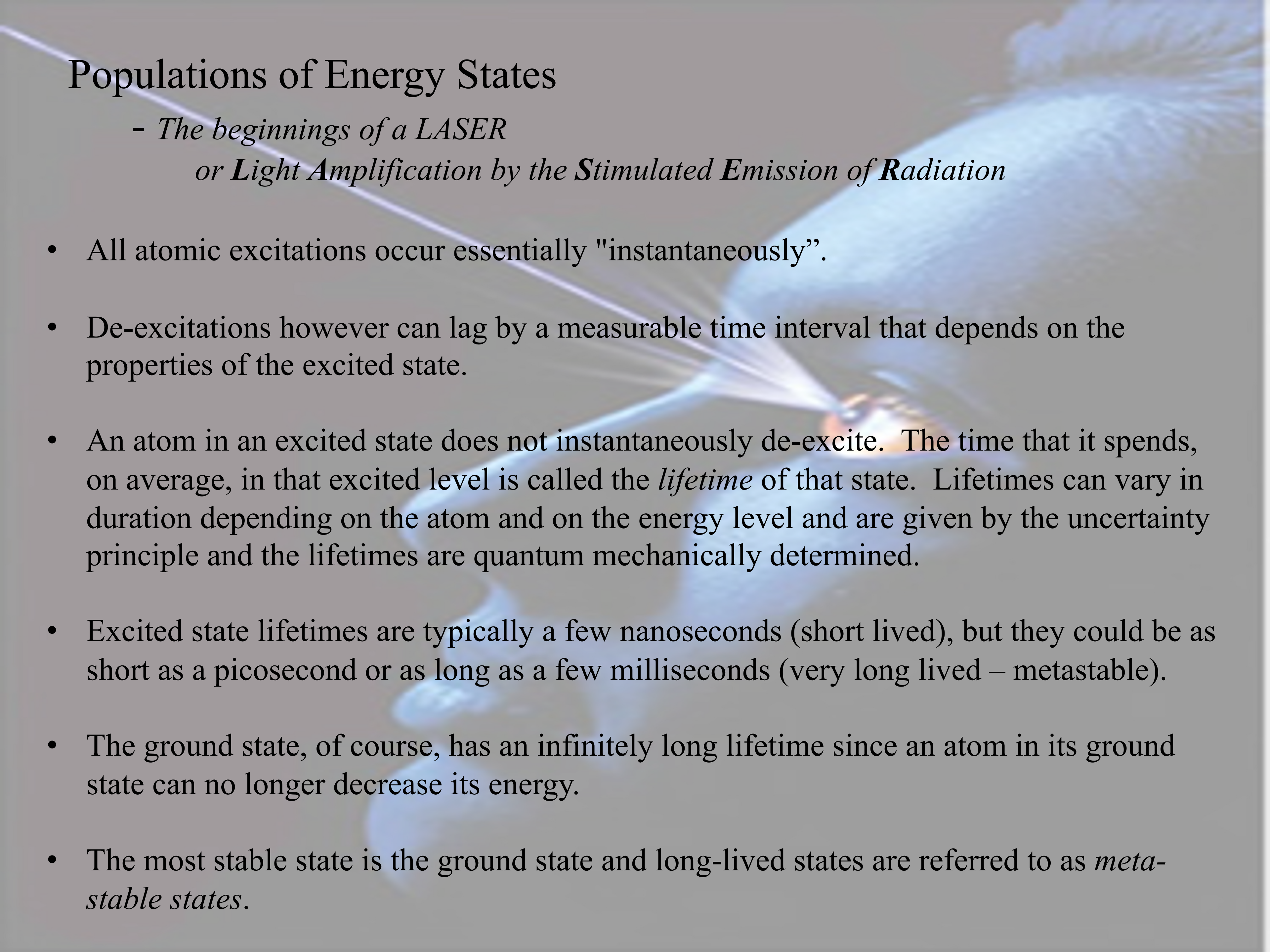
- For lasers, *optical pumping* is the mechanism that is used to cause excitation.
- *Optical pumping* is a process by which a light source generates photons with enough energy that the photons can get absorbed by the atoms in the lasing medium which causes them to go into an excited state.
- The lasing medium is whatever we’re going to make the laser out of – for our present discussion, the lasing medium will be a mixture of Helium and Neon gases – a He-Ne laser.



Populations of Energy States

- The beginnings of a LASER
or ***L****ight* ***A****mplification by the* ***S****timulated* ***E****mission of* ***R****adiation*

- All atomic excitations occur essentially "instantaneously”.
- De-excitations however can lag by a measurable time interval that depends on the properties of the excited state.
- An atom in an excited state does not instantaneously de-excite. The time that it spends, on average, in that excited level is called the *lifetime* of that state. Lifetimes can vary in duration depending on the atom and on the energy level and are given by the uncertainty principle and the lifetimes are quantum mechanically determined.
- Excited state lifetimes are typically a few nanoseconds (short lived), but they could be as short as a picosecond or as long as a few milliseconds (very long lived – metastable).
- The ground state, of course, has an infinitely long lifetime since an atom in its ground state can no longer decrease its energy.
- The most stable state is the ground state and long-lived states are referred to as *meta-stable states*.

Populations of Energy States

- *The beginnings of a LASER*
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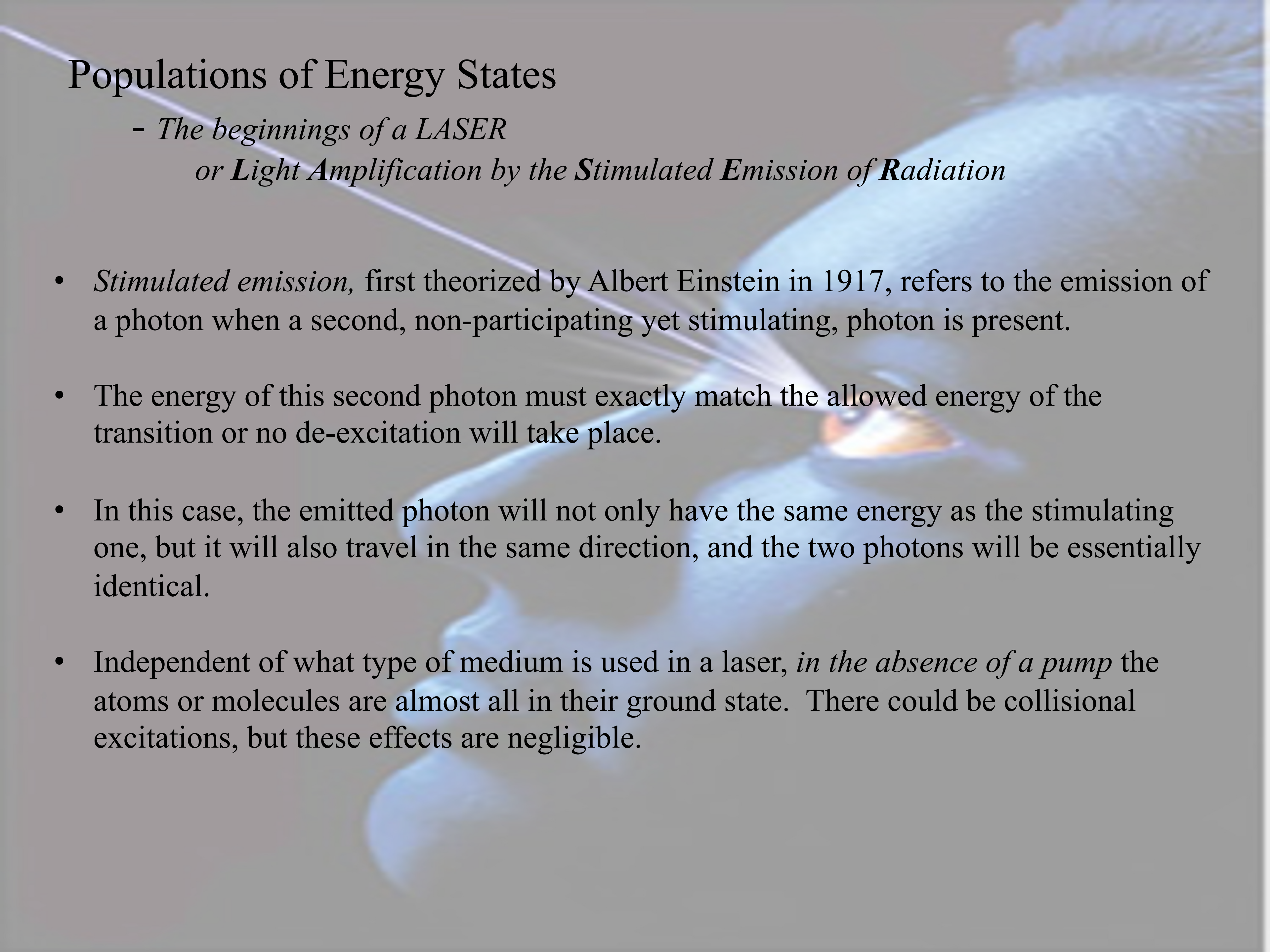
- In the case of radiative emission, atoms happen to take two very distinctly different approaches to the emission of radiation: *spontaneous emission*, or *stimulated emission*.

- *Spontaneous emission* refers to the case when the excited atom de-excites, rather randomly whenever it "feels like it", and emits a photon.

- Most atomic transitions are spontaneous emissions, and most transitions are from short lived states.

- This photon has an energy equal to the difference between the two energy levels of the transition, but its direction of travel and its other properties, such as polarization are random.

https://chem.libretexts.org/Courses/Solano_Community_College/Chem_160/Chapter_07%3A_Atomic_Structure_and_Periodicity/7.03_The_Atomic_Spectrum_of_Hydrogen

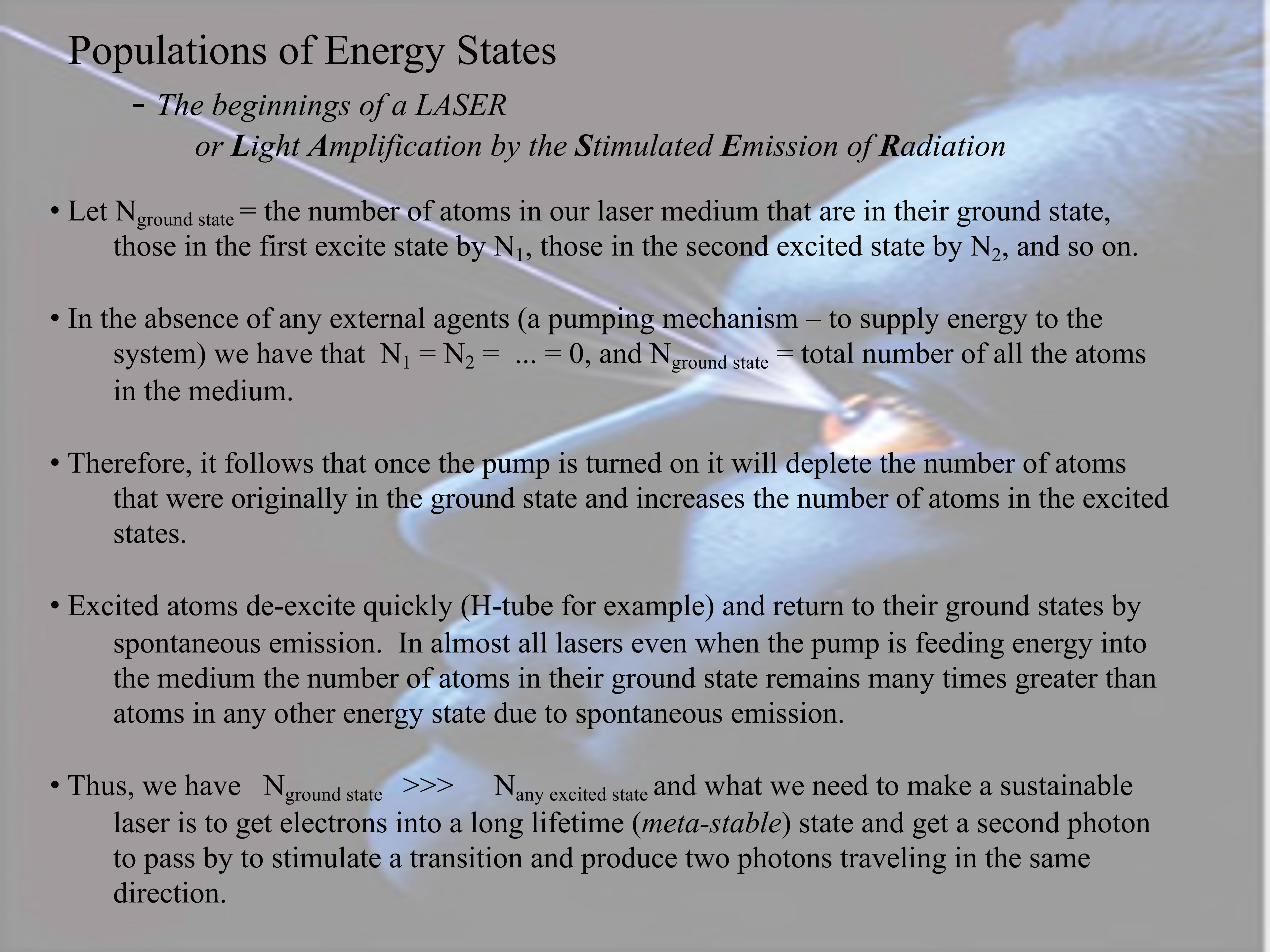


Populations of Energy States

- The beginnings of a LASER

or ***L****ight* ***A****mplification by the* ***S****timulated* ***E****mission of* ***R****adiation*

- *Stimulated emission,* first theorized by Albert Einstein in 1917, refers to the emission of a photon when a second, non-participating yet stimulating, photon is present.
- The energy of this second photon must exactly match the allowed energy of the transition or no de-excitation will take place.
- In this case, the emitted photon will not only have the same energy as the stimulating one, but it will also travel in the same direction, and the two photons will be essentially identical.
- Independent of what type of medium is used in a laser, *in the absence of a pump* the atoms or molecules are almost all in their ground state. There could be collisional excitations, but these effects are negligible.



Populations of Energy States

- *The beginnings of a LASER*
or ***L****ight* ***A****mplification by the* ***S****timulated* ***E****mission of* ***R****adiation*

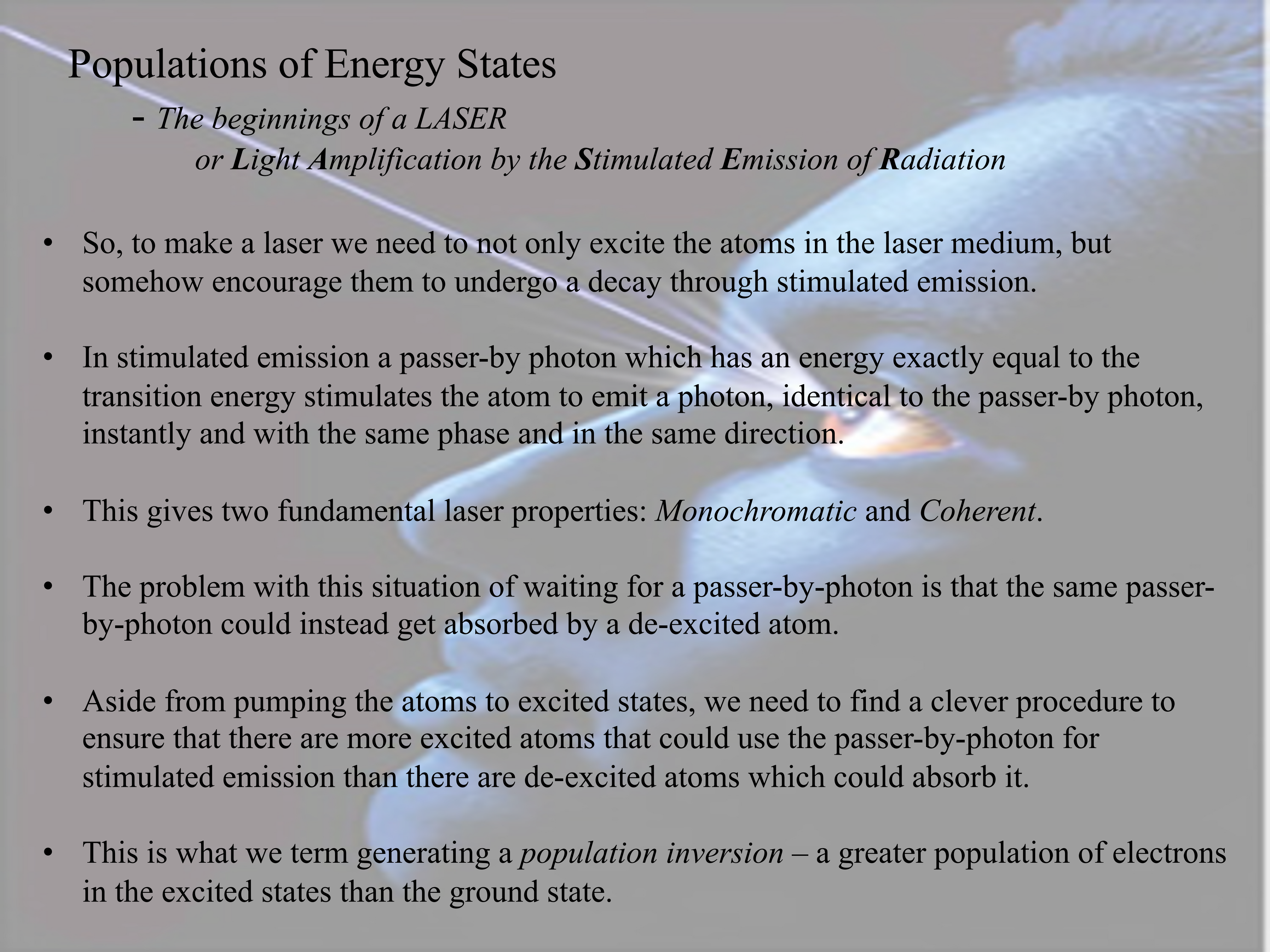
- Let $N_{\text{ground state}}$ = the number of atoms in our laser medium that are in their ground state, those in the first excite state by N_1, those in the second excited state by N_2, and so on.

- In the absence of any external agents (a pumping mechanism – to supply energy to the system) we have that $N_1 = N_2 = \ldots = 0$, and $N_{\text{ground state}}$ = total number of all the atoms in the medium.

- Therefore, it follows that once the pump is turned on it will deplete the number of atoms that were originally in the ground state and increases the number of atoms in the excited states.

- Excited atoms de-excite quickly (H-tube for example) and return to their ground states by spontaneous emission. In almost all lasers even when the pump is feeding energy into the medium the number of atoms in their ground state remains many times greater than atoms in any other energy state due to spontaneous emission.

- Thus, we have $N_{\text{ground state}} \ggg N_{\text{any excited state}}$ and what we need to make a sustainable laser is to get electrons into a long lifetime (*meta-stable*) state and get a second photon to pass by to stimulate a transition and produce two photons traveling in the same direction.



Populations of Energy States

- The beginnings of a LASER

or ***L****ight* ***A****mplification by the* ***S****timulated* ***E****mission of* ***R****adiation*

- So, to make a laser we need to not only excite the atoms in the laser medium, but somehow encourage them to undergo a decay through stimulated emission.

- In stimulated emission a passer-by photon which has an energy exactly equal to the transition energy stimulates the atom to emit a photon, identical to the passer-by photon, instantly and with the same phase and in the same direction.

- This gives two fundamental laser properties: *Monochromatic* and *Coherent*.

- The problem with this situation of waiting for a passer-by-photon is that the same passer-by-photon could instead get absorbed by a de-excited atom.

- Aside from pumping the atoms to excited states, we need to find a clever procedure to ensure that there are more excited atoms that could use the passer-by-photon for stimulated emission than there are de-excited atoms which could absorb it.

- This is what we term generating a *population inversion* – a greater population of electrons in the excited states than the ground state.

Building a continuous output "LASER"

- Suppose we have an atom that has at least 3 excited states and we pump (that is, electrically do work on the electrons $W = -q\Delta V = hf = E$) the ground state atoms electrons into the 3rd excited state.

- The lifetime of this state is very short (say a nanosecond perhaps).

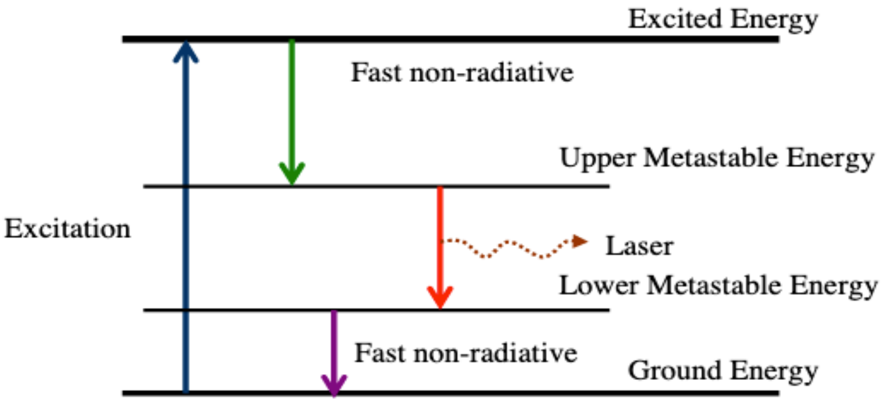
- A certain portion of time, the electron very quickly decays to the 2nd excited state.

- If this is a relatively long-lived state (say a millisecond) then there will be more electrons in this state (and less likely to absorb any photons) than in the ground state and hence we've created a *population inversion*. ***Can we find atoms that behave like this?***

- For this long-lived state, the electron can "wait" for the passer-by photon to stimulate the de-excitation to the ground state.

- And yes, we can find atoms like this.

- A typical four-level atom is neon.



https://www.researchgate.net/publication/48189940_Elemental_Analysis_of_Biological_Matrices_by_Laser_Ablation_High_Resolution_Inductively_Coupled_Plasma_Mass_Spectrometry_LA-HR-ICP-MS_and_High_Resolution_Inductively_Coupled_Plasma_Mass_Spectrometry_H

A Four Level He-Ne “LASER”

- We take a mixture of Helium and Neon gases and recall that neon is a four-level atom.

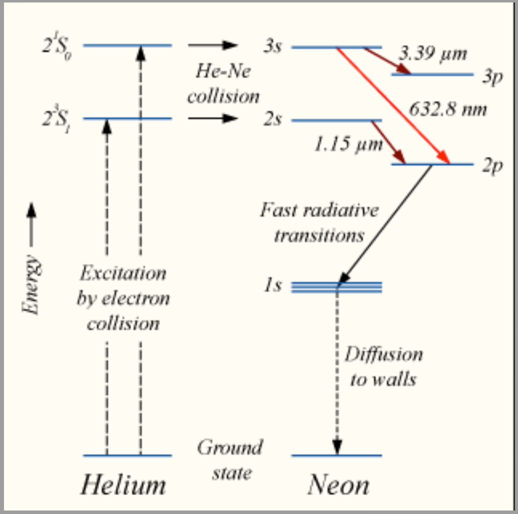
- In these lasers, electric pumping will heat the gas mixture, and this excites the helium atoms to excited states. The higher energy states of helium are mostly short lived, and one state is relatively long lived, and the energy of this state is same as the upper short-lived state in the neon atom.

- The sole purpose of the helium atoms is to exchange energy with neon atoms via collisional excitation and this is how the helium atoms electrons de-excite back into the ground state.

- This collisional exchange causes electrons in neon to leave their ground state. It is purely by chance that there are two energy levels with almost the same energy.

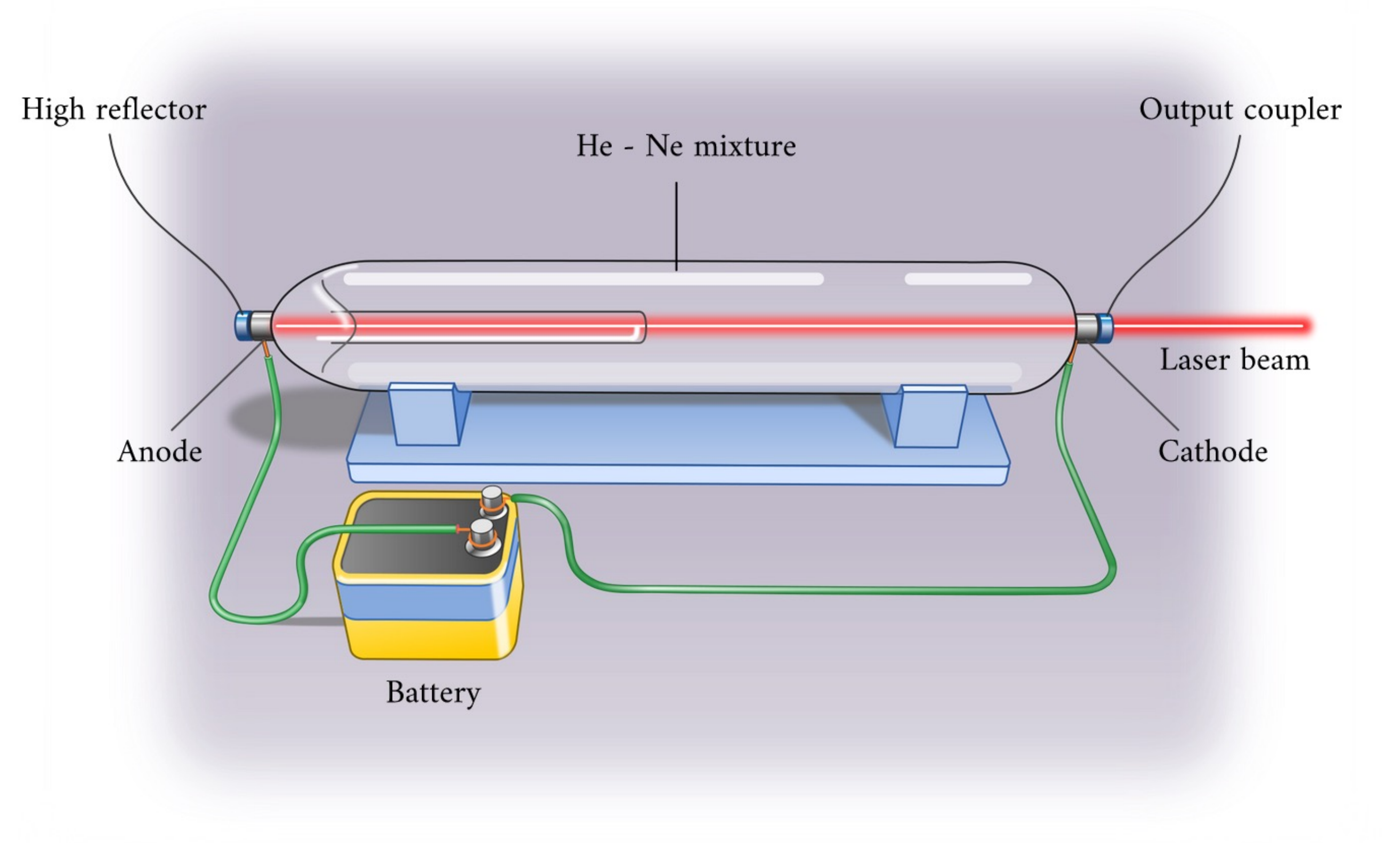
- This pumps neon’s electrons into excited states, and we create a population inversion in this meta-stable state.

- Eventually an electron in neon will spontaneously decay and this will produce the stimulating photon. This causes the neon atoms to emit photons and the only visible transition that will lase is the $633 nm$ transition.



https://www.miniphysics.com/helium-neon-laser.html

A Four Level He-Ne “LASER”



https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Physical_Chemistry_(LibreTexts)/15%3A_Lasers_Laser_Spectroscopy_and_Photochemistry/15.06%3A_The_Helium-Neon_Laser

A 4-Level He-Ne “LASER”

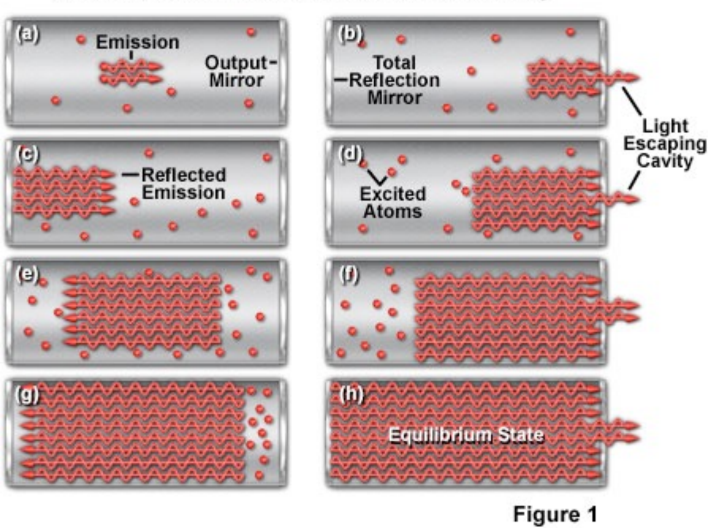
- We have many photons all with the same color and frequency (*monochromatic*) traveling in the same direction (*coherent*) – this is not exactly the laser we want. It would pulse and we’d have to wait for another pulse. We want a continuous output.

- To make a continuous laser beam we need to amplify the light. To do this we put mirrors on the ends of the tube of gas.

- The back mirror is highly reflective, and the front mirror is partially reflective.

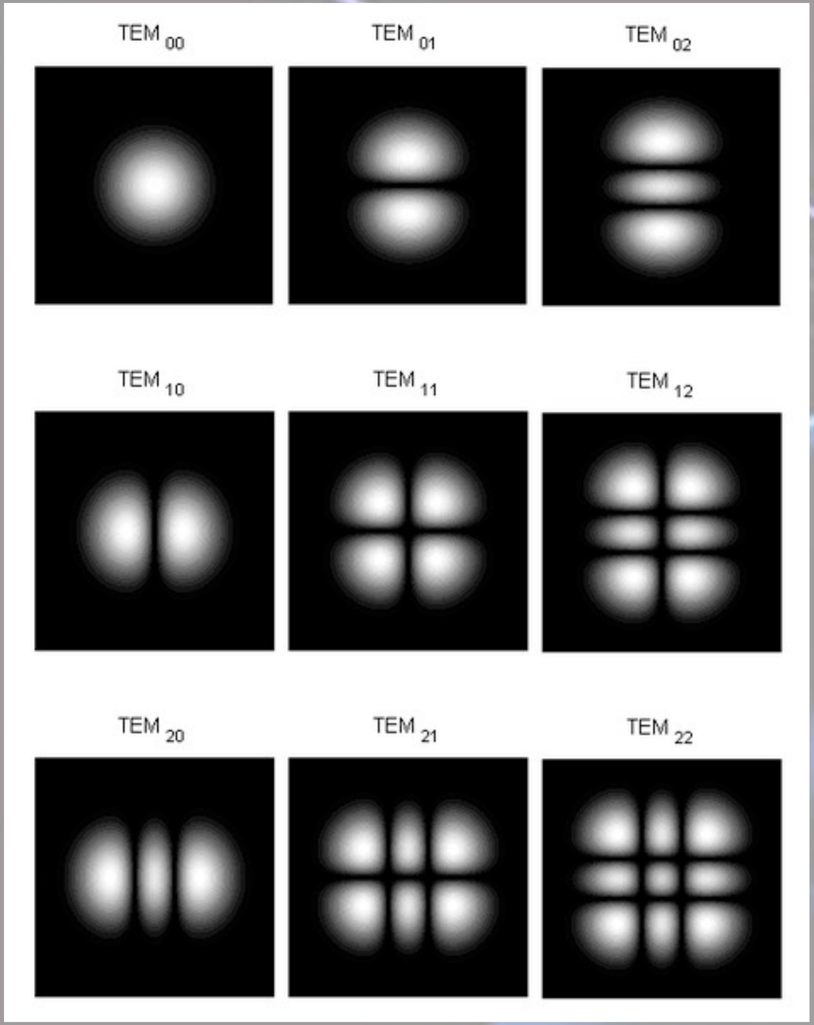
- Thus, the photons bounce off each mirror and only a small fraction of the beam can escape. The remainder are reflected to produce more stimulated emissions.

- Any other spontaneous transitions do not get amplified, and this light leaks out of the tube.



http://micro.magnet.fsu.edu/primer/java/lasers/heliumneonlaser/laserfigure1.jpg

“Laser” Modes



http://photonicswiki.org/index.php?title=File:TEMmn.png

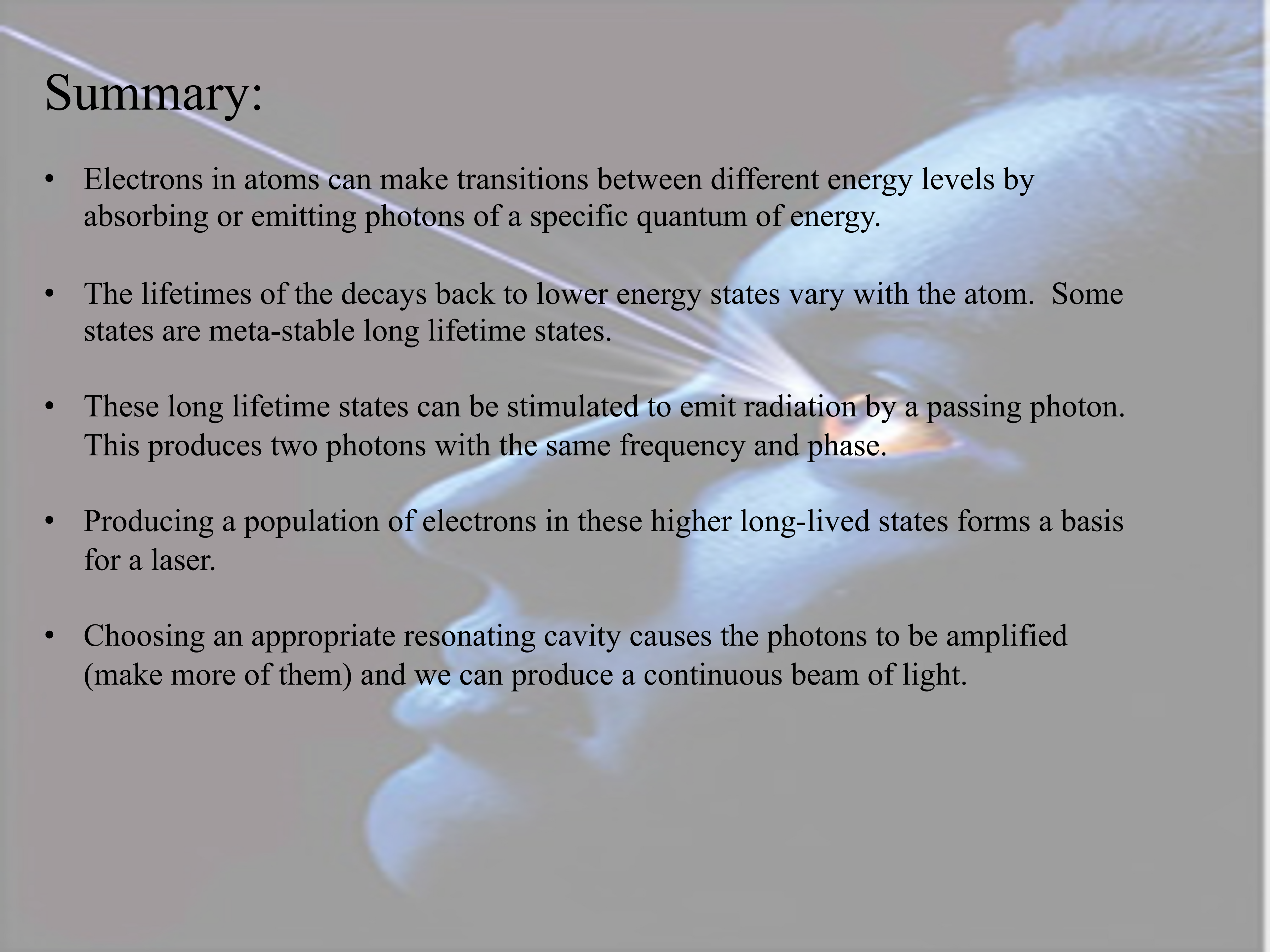
- For resonance in the cavity the length of the tube plays an important role.
- A laser cavity is a resonant feedback system necessary for a laser (provides for the amplification of the light).
- For resonance condition, there must be integral numbers of half wavelength in between these two mirrors.

$$L = n\frac{\lambda}{2}$$

- And this corresponds to a frequency

$$f = \frac{c}{\lambda} = n\left(\frac{c}{2L}\right)$$

- This means only discrete frequencies are resonant inside the cavity and contribute to the lasing



Summary:

- Electrons in atoms can make transitions between different energy levels by absorbing or emitting photons of a specific quantum of energy.
- The lifetimes of the decays back to lower energy states vary with the atom. Some states are meta-stable long lifetime states.
- These long lifetime states can be stimulated to emit radiation by a passing photon. This produces two photons with the same frequency and phase.
- Producing a population of electrons in these higher long-lived states forms a basis for a laser.
- Choosing an appropriate resonating cavity causes the photons to be amplified (make more of them) and we can produce a continuous beam of light.