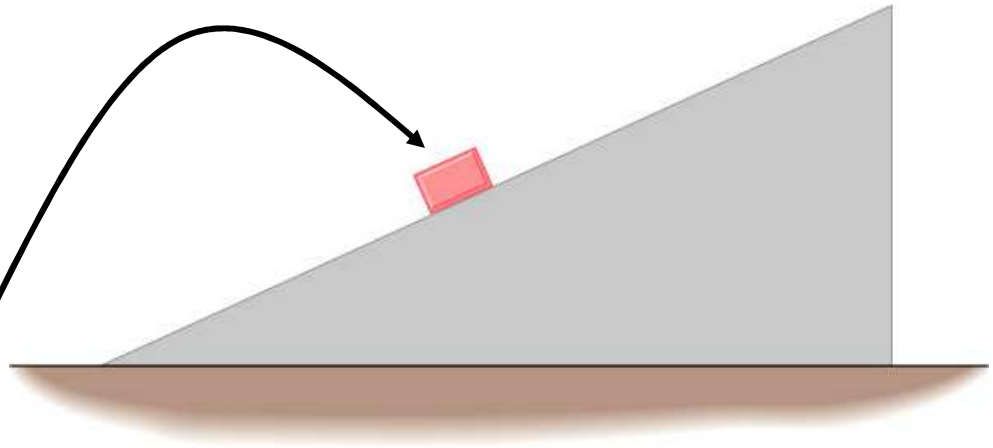
EXAM 2 is next week

Time: 8:00-9:30 pm Wed Mar 7
Place: Elliott Hall
Material: lectures 1-15, HW 1-15, Recitations 1-8, Labs 1-8
focus will be on second half of material (not on Exam 1)
Problems: multiple choice, 10 questions (70 points)
write-up part, hand graded (30 points)
Equation sheet: provided with exam
Practice exam + equation sheet: will be posted at the end of this week

Note: **no lecture on Thursday Mar 8** !

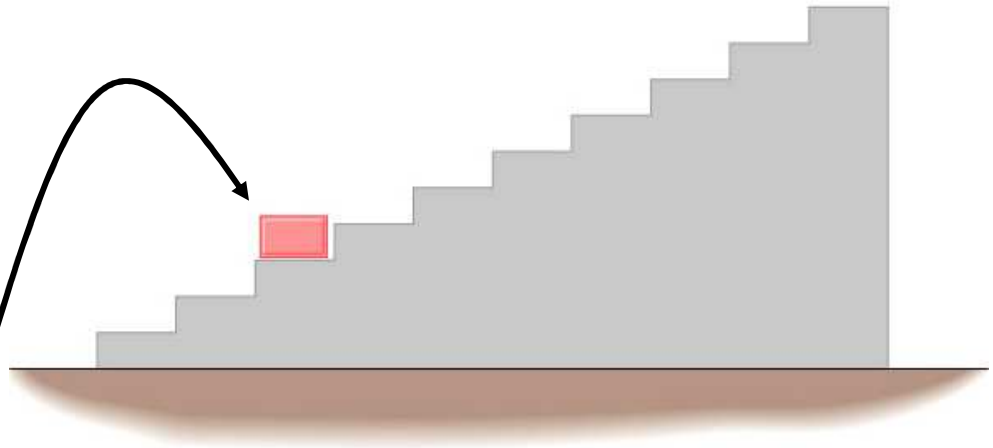
Quantization

•Classical Physics:
quantities are continuous.



(a)

• Quantum Physics:
Some quantities are limited to a discrete set of values.



Example: charge, $Q = N \cdot e$

Quantum means quantized

Answers come in whole numbers

Example: The number of unopened Coke cans in your refrigerator is quantized.

Quantum Waves are Quantized

There are discrete vibrational modes (normal modes)

1D: One Dimension

Violin string, jumprope

2D: Two Dimensions

Modes of a drumhead, coffee sloshing in your mug

http://demonstrations.wolfram.com/NormalModesOfACircularDrumHead/

3D: Three Dimensions

Electron Waves around Atomic Nuclei!

http://www.daugerresearch.com/orbitals/index.shtml

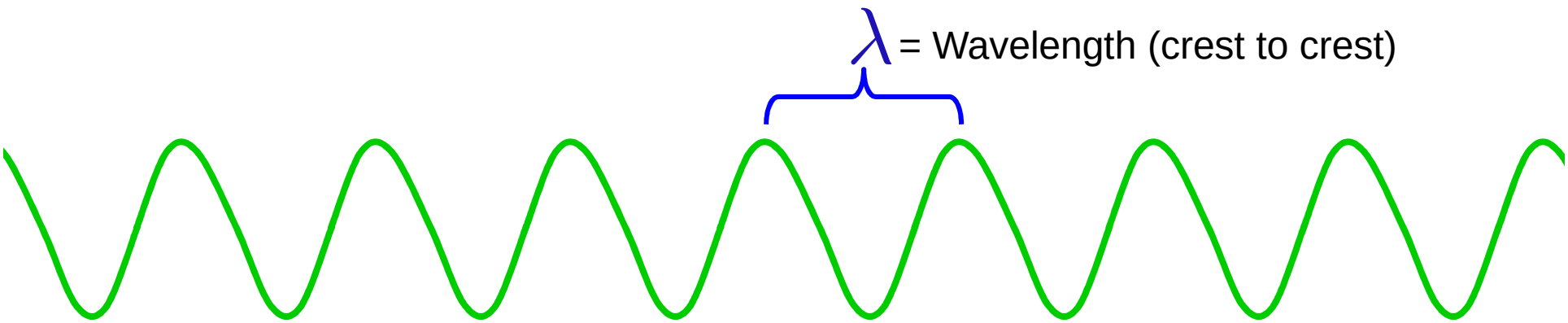
Higher Frequency = Higher Energy

Photons

Photons come in discrete particles, or packets of energy.

One PHOTON = One packet of light

And yet it's still a **wave**:



$$\lambda\nu = c$$

λ wavelength [m]

ν frequency [1/s] ← Number of wavelengths which go by per second

c speed of light [m/s]

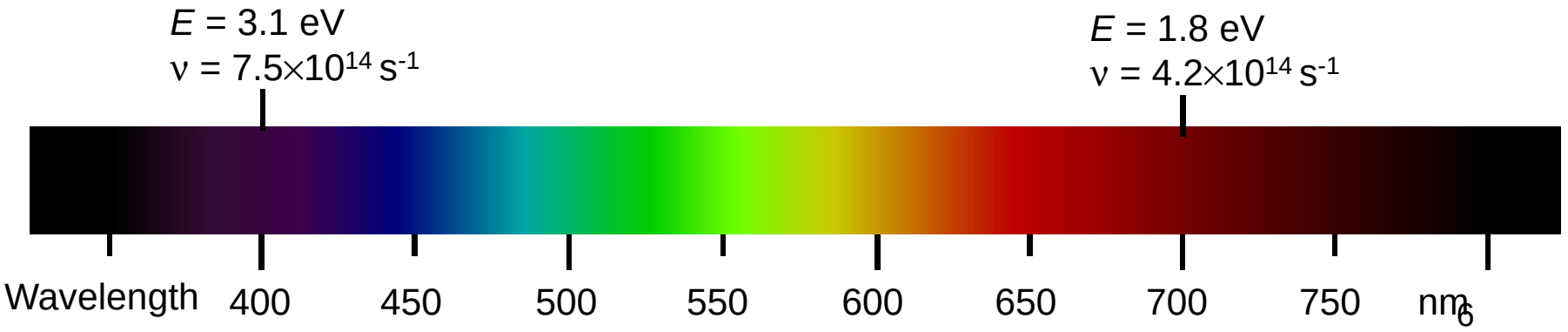
Photons

Photons come in discrete particles, or packets of energy.

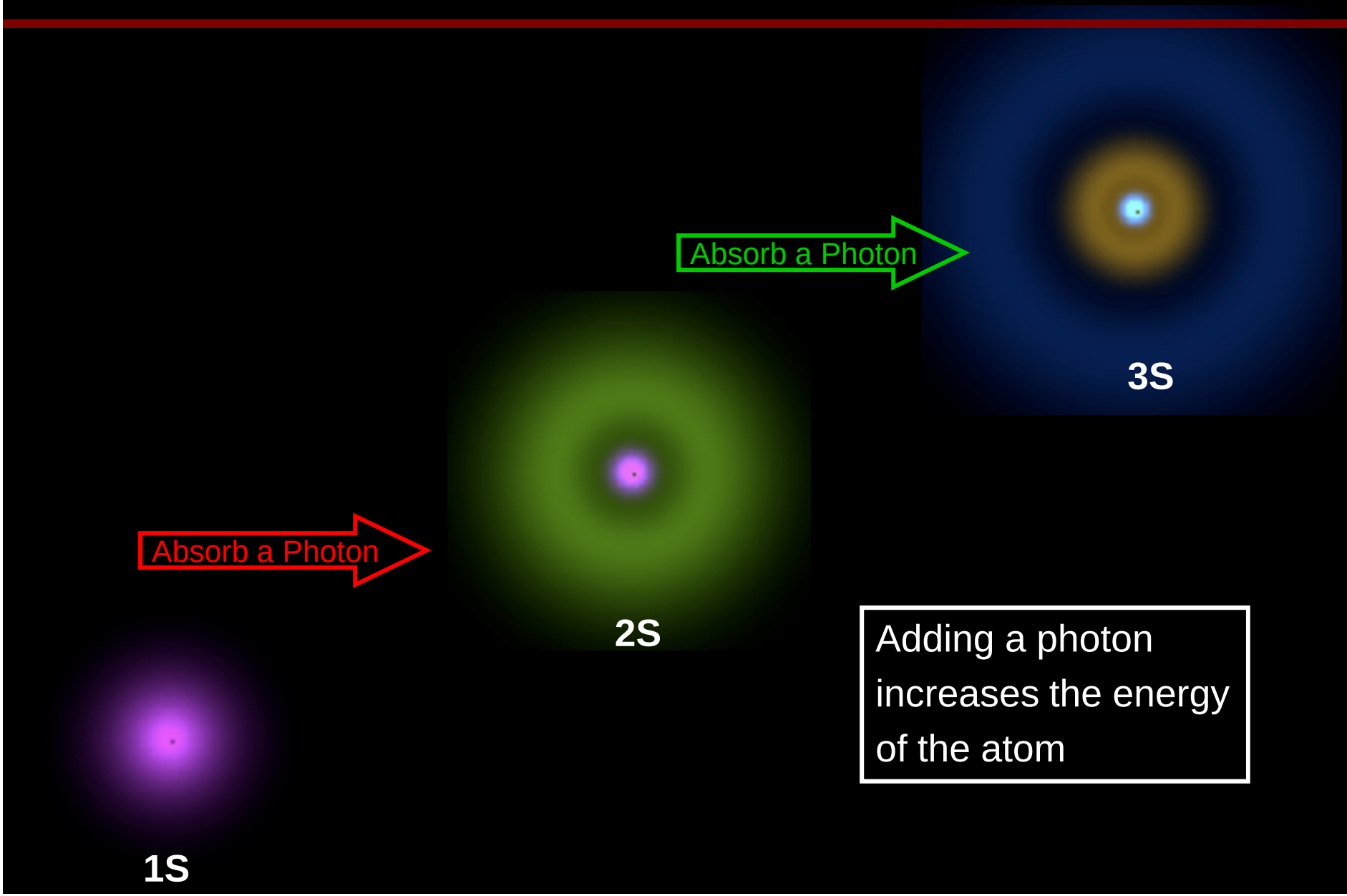
One PHOTON = One packet of light

Photon energy and wavelength: $E_{photon} = h\nu_{light} = \frac{hc}{\lambda_{light}}$

Visible light Electromagnetic spectrum



Atoms and Light



Adding a photon increases the energy of the atom

Atoms and Light

3S

Release a Photon

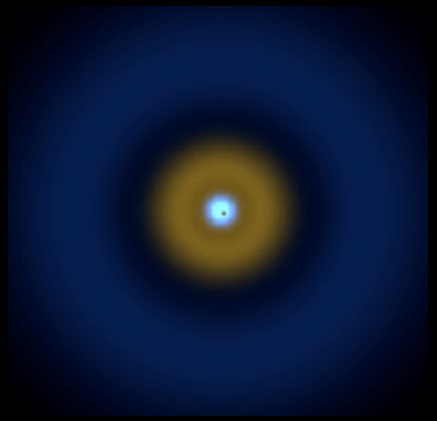
2S

Release a Photon

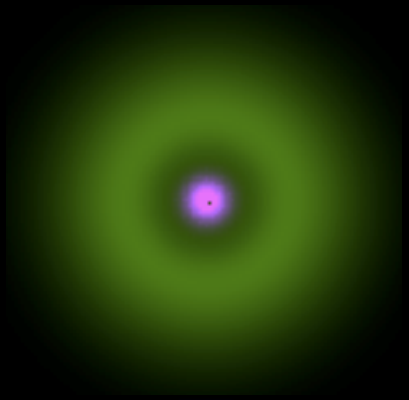
1S

Releasing a photon decreases the energy of the atom

Atoms and Light

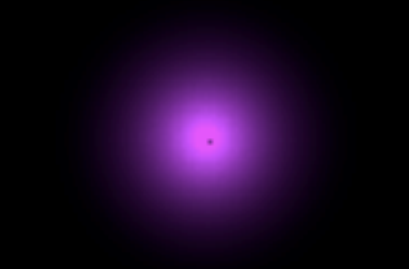


QUANTUM MECHANICS
says each ELEMENT (type of atom)
can only have specific, *QUANTIZED* energies.



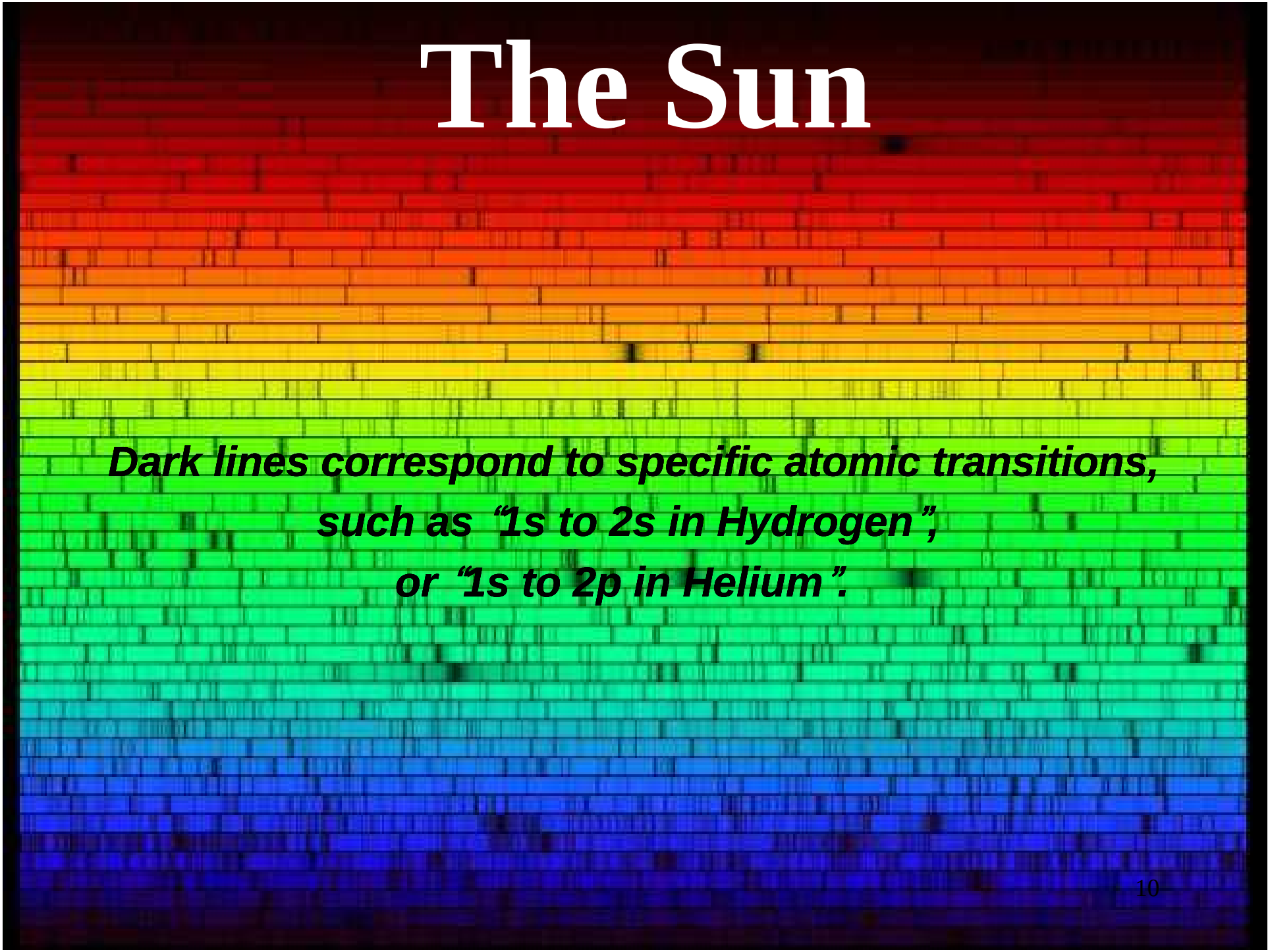
Each atomic transition has a

CHARACTERISTIC COLOR



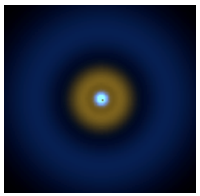
Photon Energy = Frequency = Color

The Sun

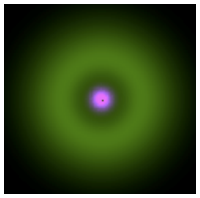


Dark lines correspond to specific atomic transitions, such as "1s to 2s in Hydrogen", or "1s to 2p in Helium".

Hydrogen atom: electron energy

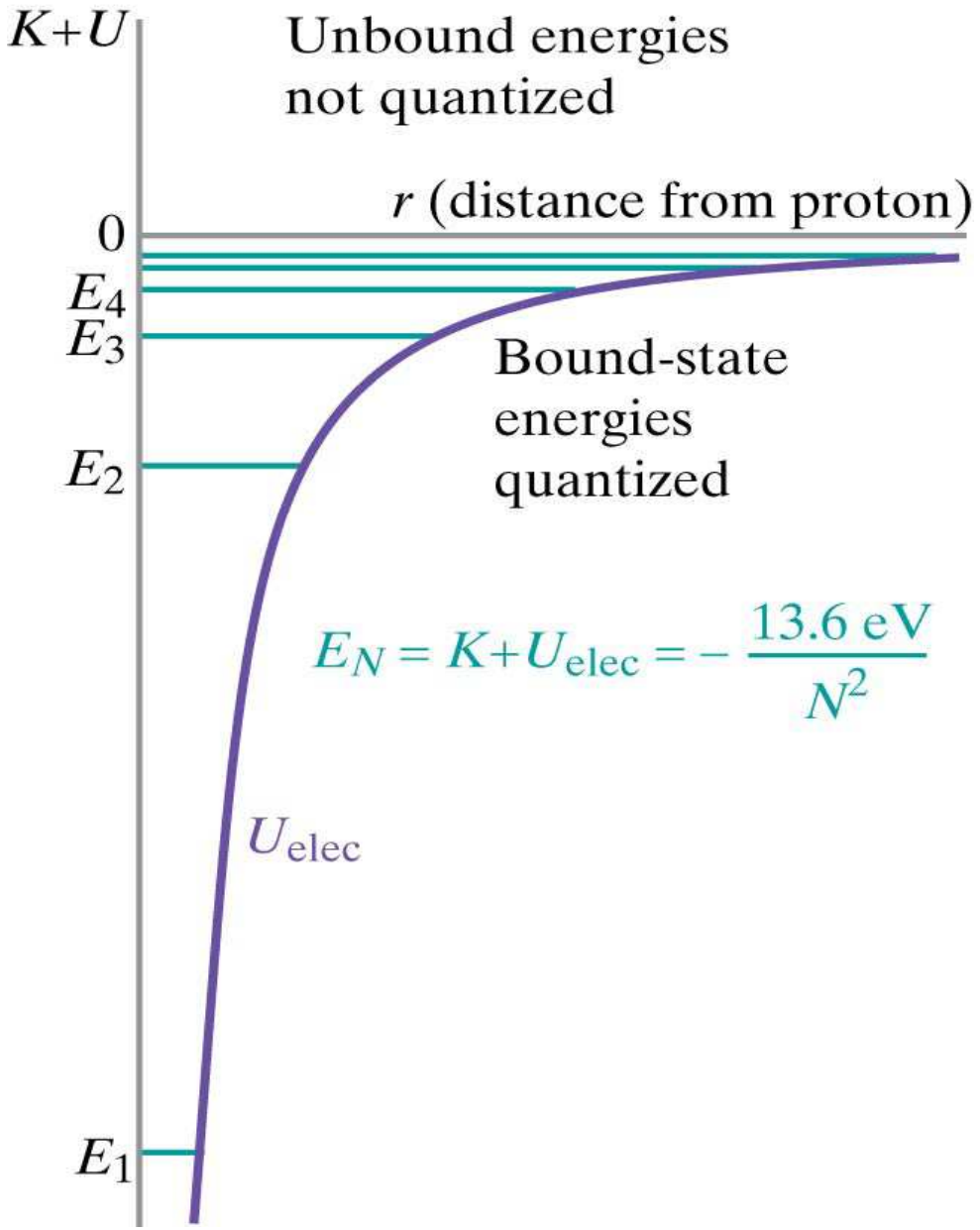


3S



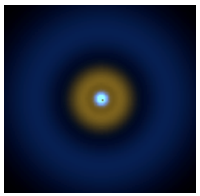
2S

1S

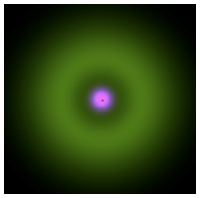


Emission spectra

Hydrogen atom:

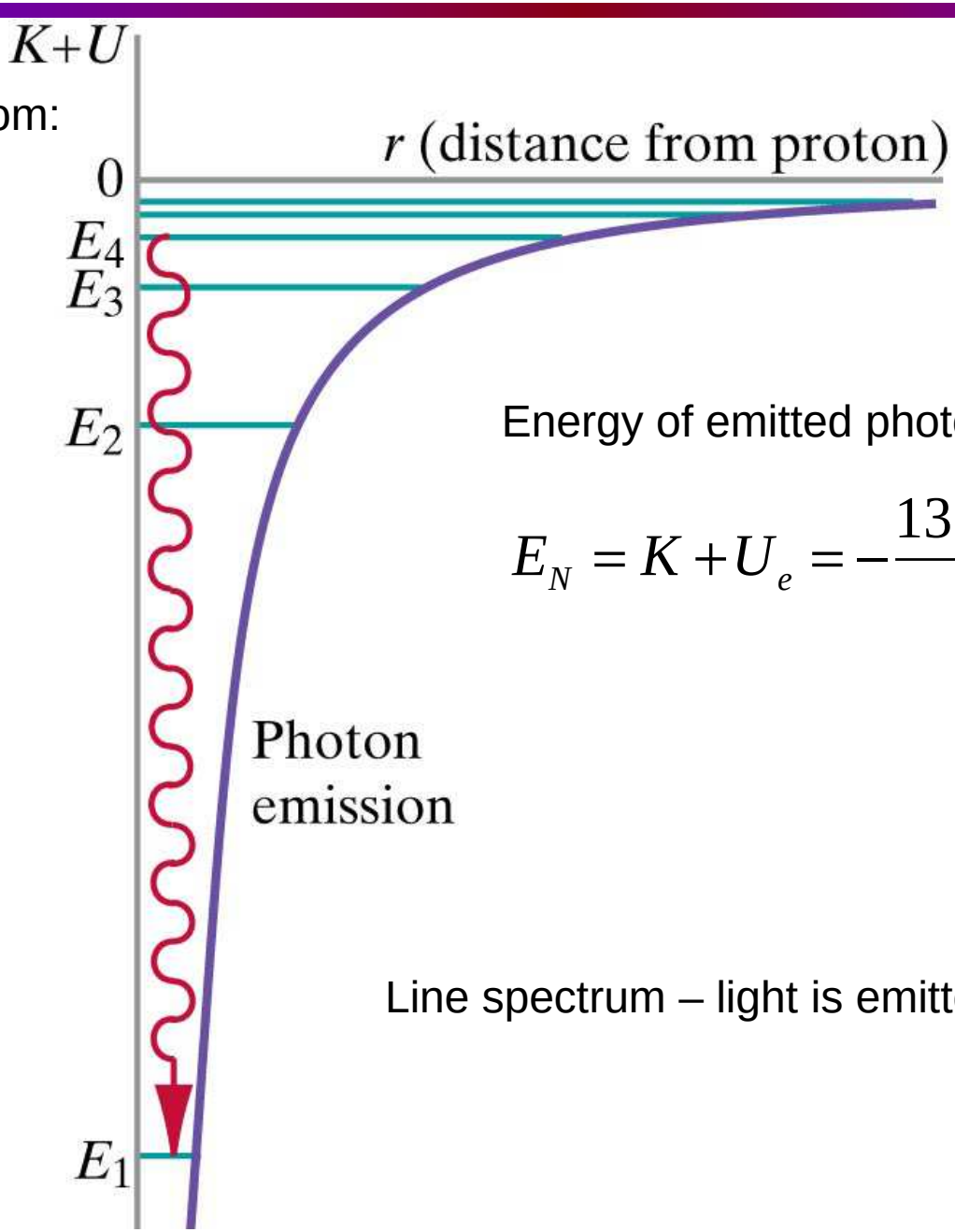


3S



2S

1S



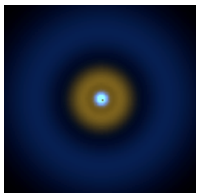
Energy of emitted photon: $h\nu = E_4 - E_1$

$$E_N = K + U_e = -\frac{13.6\ \text{eV}}{N^2}$$

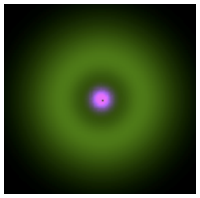
Line spectrum – light is emitted at fixed frequencies

Absorption spectra

Hydrogen atom:

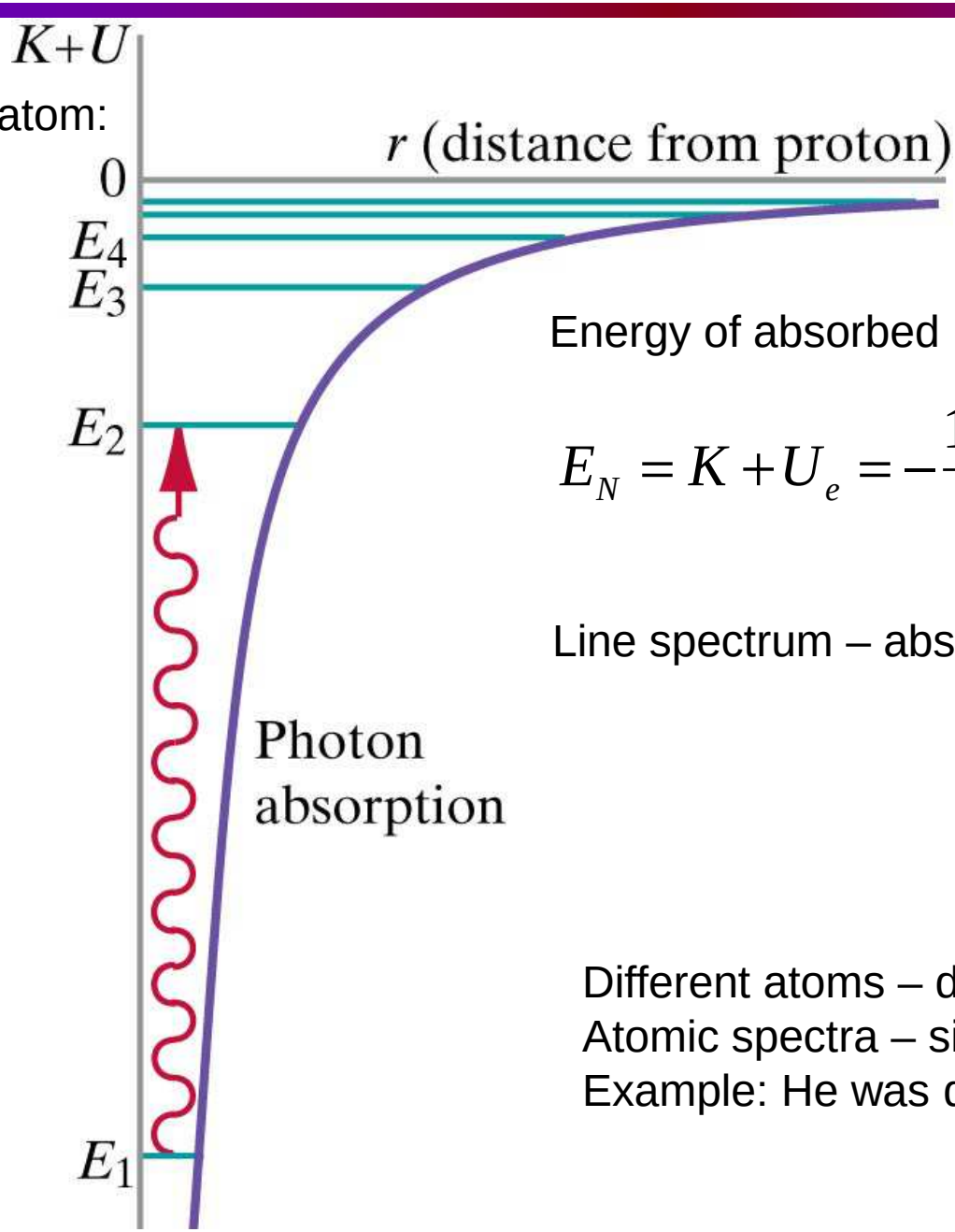


3S



2S

1S



Energy of absorbed photon:

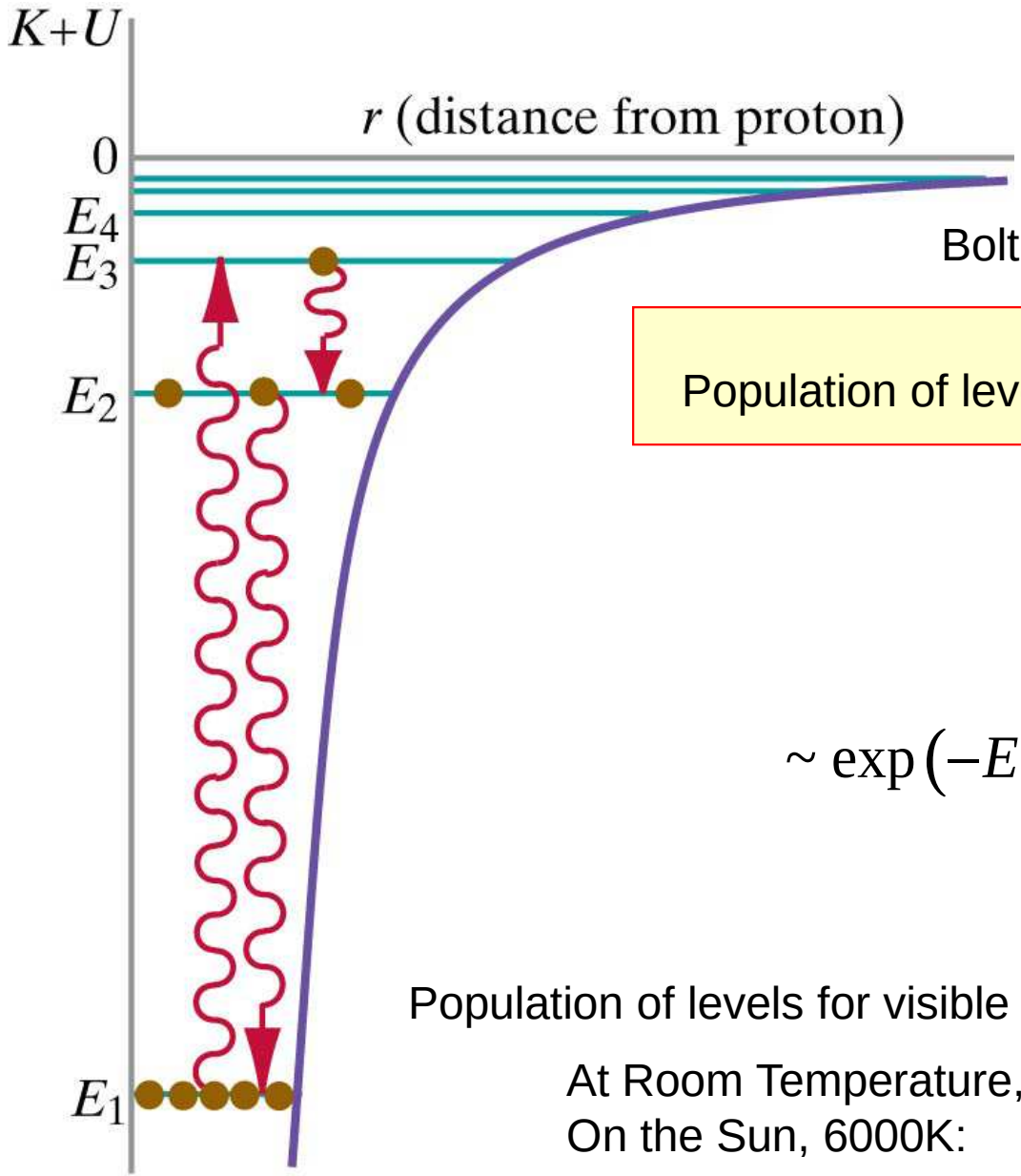
$$E_N = K + U_e = -\frac{13.6\ \text{eV}}{N^2}$$

$$h\nu = E_2 - E_1$$

Line spectrum – absorption at fixed frequencies

Different atoms – different energies
Atomic spectra – signature of element
Example: He was discovered on Sun first

Effect of temperature



Boltzmann constant: k=1.4×10^{-23}J/K

Population of level: $\sim \exp\left(-E/kT\right)$

Temperature, K

Energy of the level above the "ground state", $E_N - E_1$

$$\sim \exp\left(-E/kT\right) = 10^{-33}$$

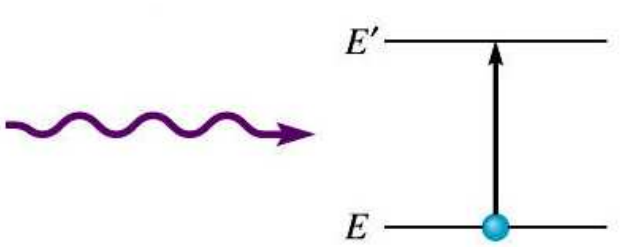
Population of levels for visible light transition (E = 2eV):

At Room Temperature, 300K: $exp(-E/kT) = 10^{-33}$

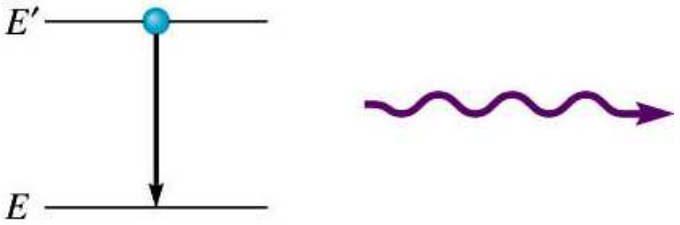
On the Sun, 6000K: $exp(-E/kT) = 10^{-2}$

Energy conversion: light and matter

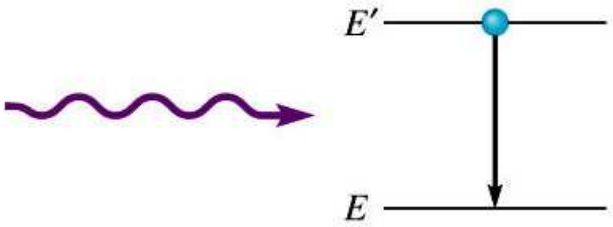
Absorption:
- photon is *absorbed*
- electron jumps to *higher* level



Spontaneous emission:
- photon is *emitted*
- electron jumps to *lower* level



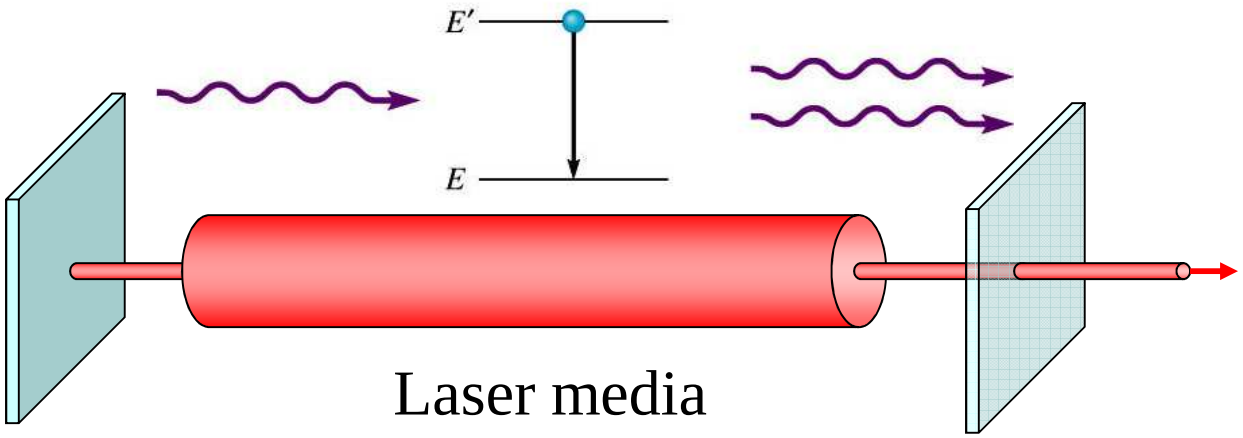
Stimulated emission:
- external photon causes electron jump to *lower* level
- a photon is emitted
- the original photon is *not* absorbed!



← Makes laser work!

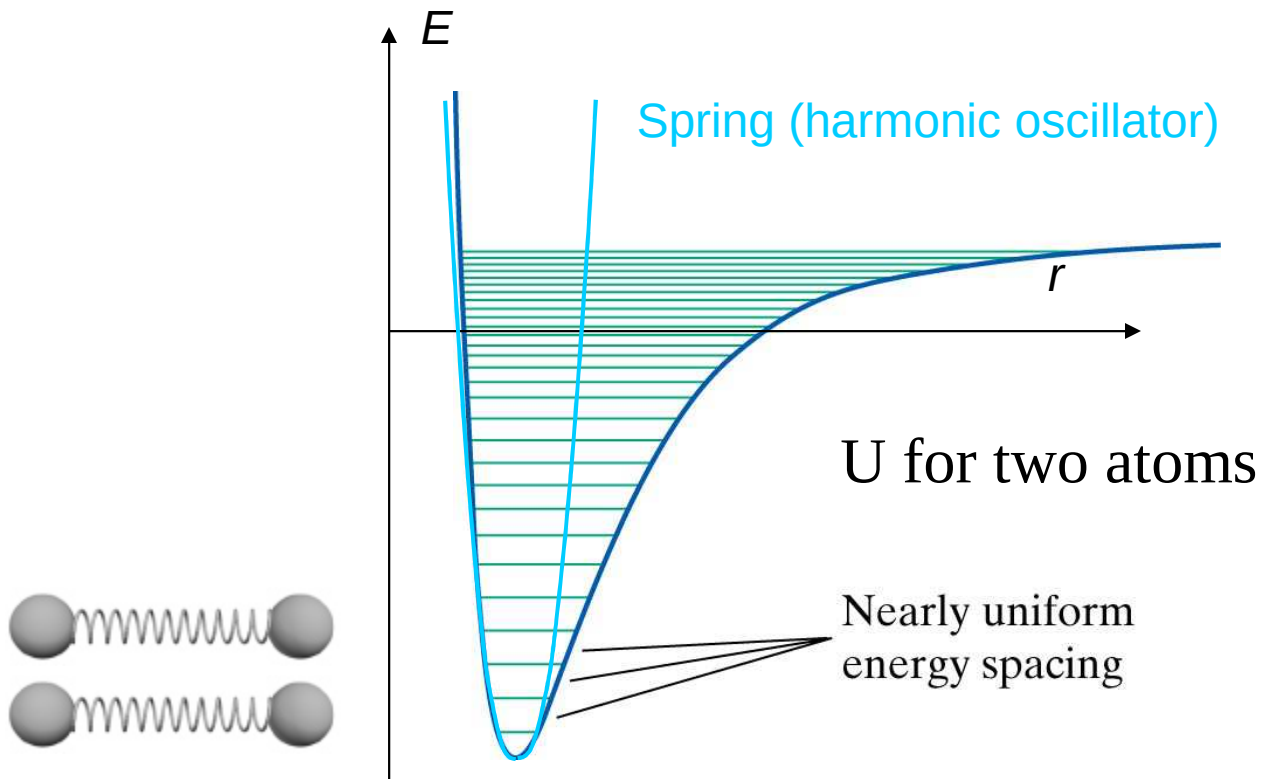
Laser

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



Requirement:
inverted population, more atoms must be in excited state *E′* than in state *E*.

Quantizing two interacting atoms

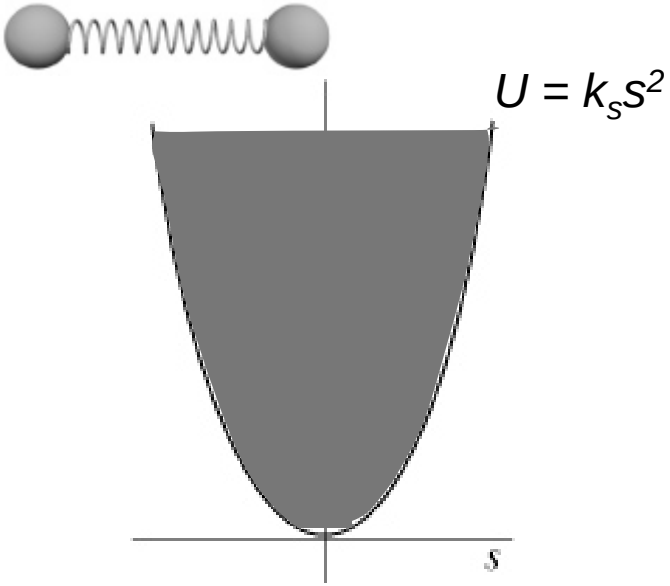


If atoms don't move too far from equilibrium, U looks like U_{spring}.

Thus, energy levels should correspond to a quantized spring . . .

Quantizing two interacting atoms

Classical harmonic oscillator:

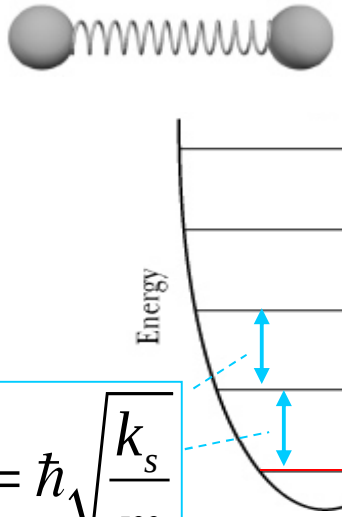


$$E = \tfrac{1}{2}mv^2 + \tfrac{1}{2}kx^2 = \tfrac{1}{2}kA^2_{\max}$$

Any value of A is allowed

$\rightarrow$ any E is possible.

Quantum harmonic oscillator:



$$E_2 = 2\hbar\omega_0 + E_0$$

$$E_1 = \hbar\omega_0 + E_0$$

$$E_0 = \tfrac{1}{2}\hbar\omega_0$$

ground state

$$\hbar\omega_0 = \hbar\sqrt{\frac{k_s}{m}}$$

equidistant spacing

$$\omega_0 = \sqrt{k_s / m}$$

$$\hbar \equiv \frac{h}{2\pi} = 1.05\times10^{-34}\ \mathrm{J\cdot s}$$

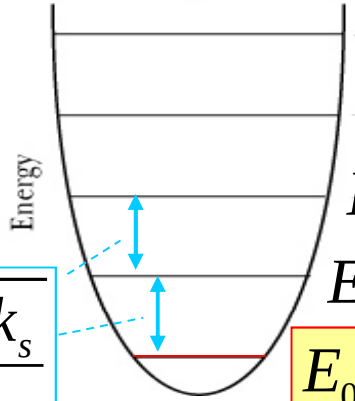
Energy levels:

$$E_N = N\hbar\omega_0 + \tfrac{1}{2}\hbar\omega_0$$

Yes, Tiny Harmonic Oscillators are Quantized

Quantum harmonic oscillator:

$U = k_s s^2$



$E_2 = 2\hbar\omega_0 + E_0$

$E_1 = \hbar\omega_0 + E_0$

$E_0 = \frac{1}{2}\hbar\omega_0$

ground state

$\hbar\omega_0 = \hbar\sqrt{\frac{k_s}{m}}$

equidistant spacing

$\omega_0 = \sqrt{k_s / m}$

$\hbar \equiv \frac{h}{2\pi} = 1.05\times10^{-34}\ \mathrm{J\cdot s}$

Energy levels:

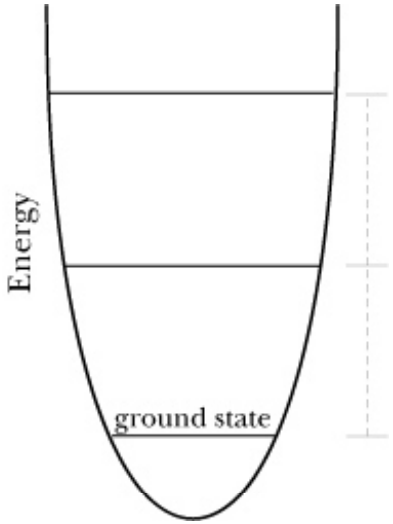
$E_N = N\hbar\omega_0 + \frac{1}{2}\hbar\omega_0$

WEB DEMO:

http://web.ift.uib.no/AMOS/MOV/HO/

Quantized vibrational energy levels

$U = k_s x^2$

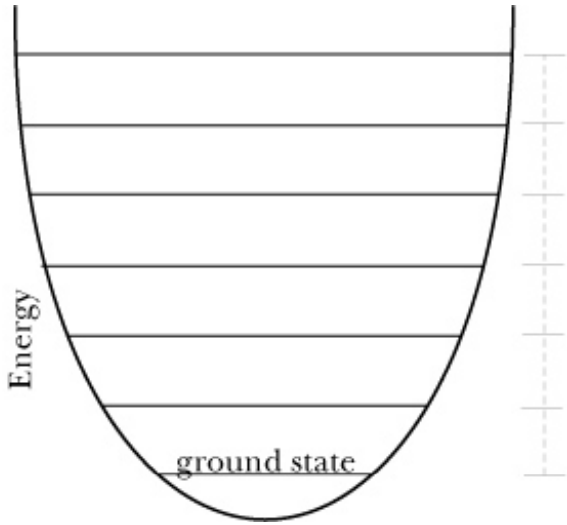


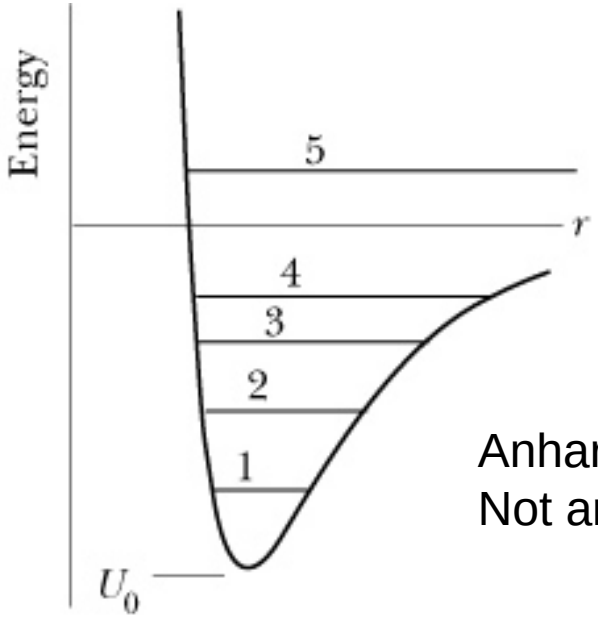
$$E_N = N\hbar\omega_0 + E_0$$

$$\omega_0 = \sqrt{k_s / m}$$

Larger resonance frequency – larger level separation

$U = k_s x^2$



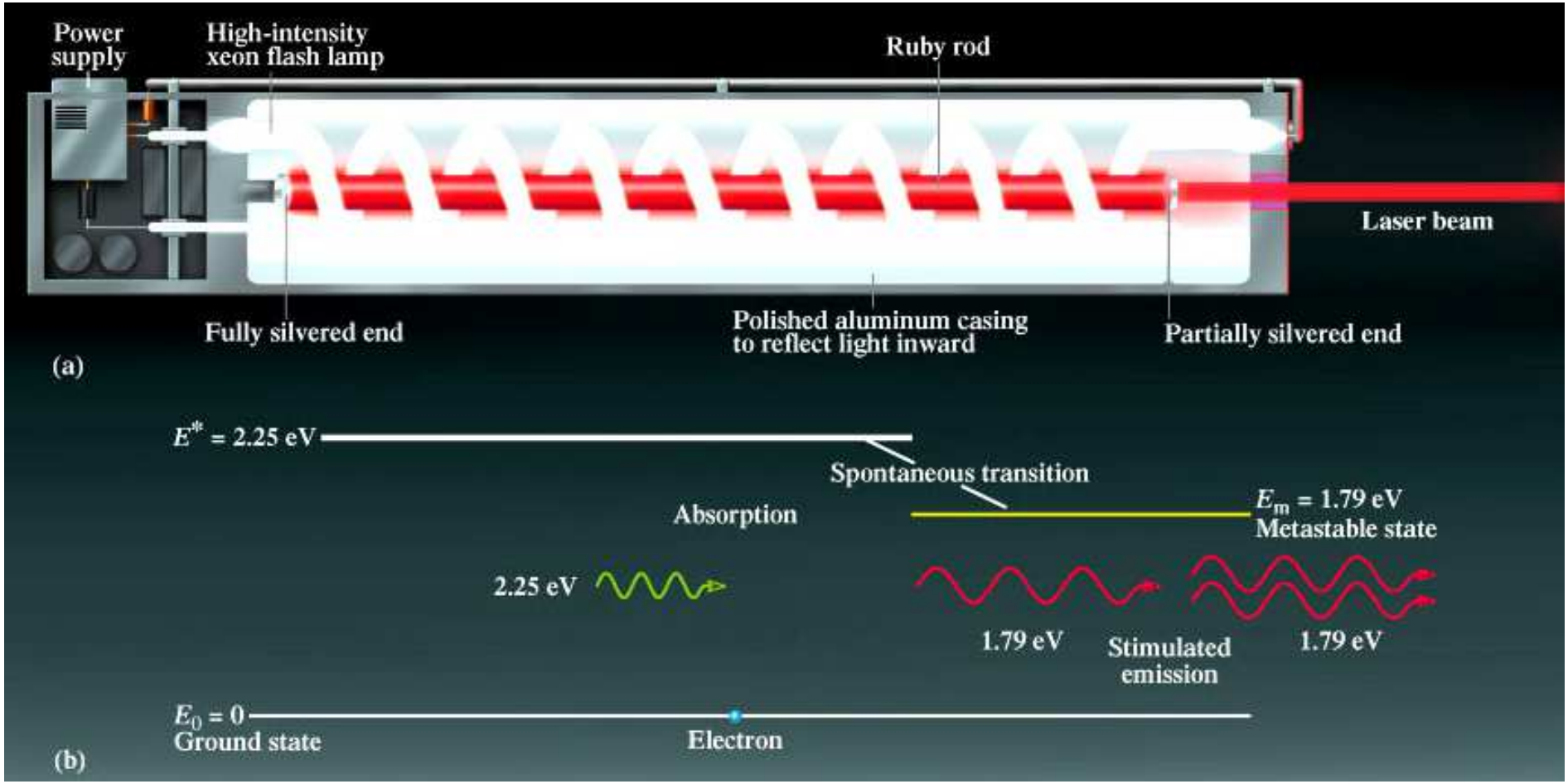


Anharmonic oscillator:
Not an equidistant spacing of levels

Home study:

Rotational energy levels (8.5,page 338)
Nuclear & Hadronic energy levels (8.6)
Comparison of energy level spacing (8.7)

Laser



Ruby: aluminum oxide crystal (sapphire) where some Al were replaced by Cr