Lecture 13

Lasers

Recap from last class: Quantum numbers of atoms

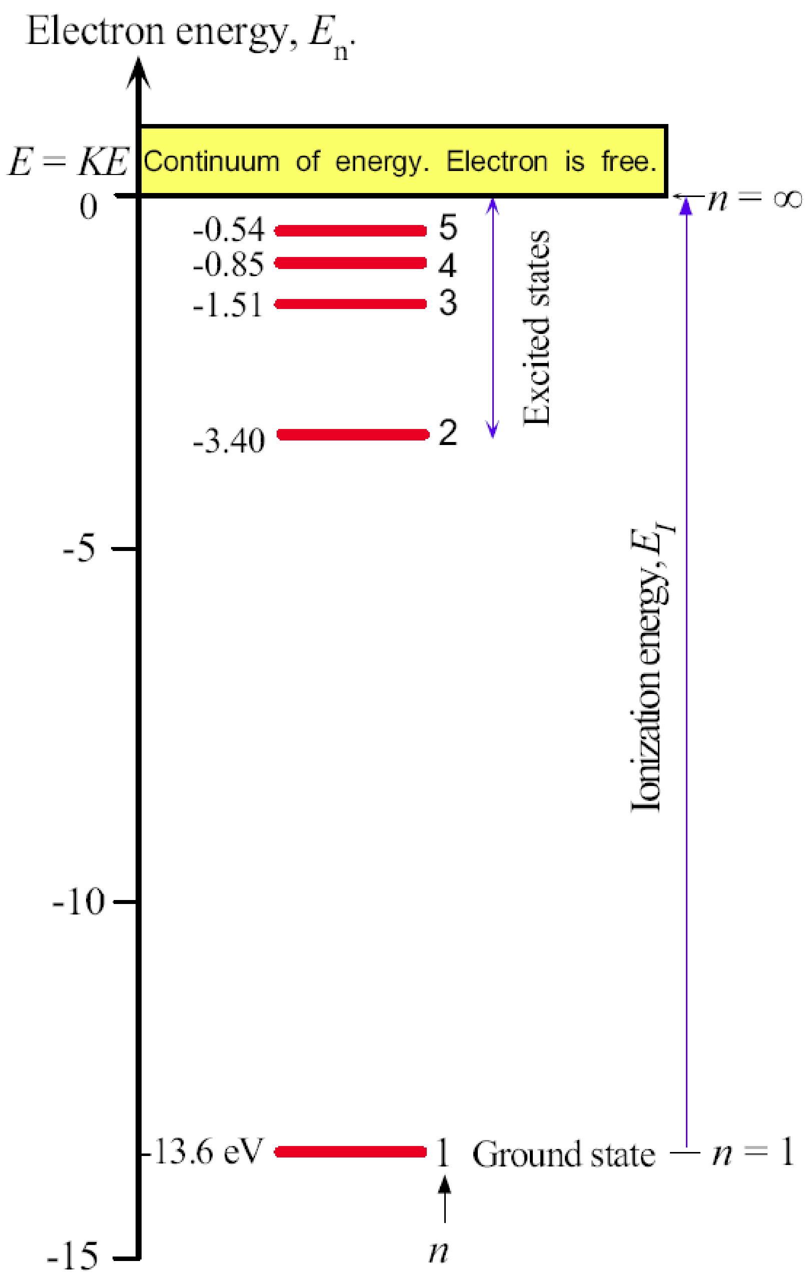
$$\psi(r,\theta,\phi) = R_{n,l}(r)Y_{l,m_l}(\theta,\phi)$$

Hydrogenic atoms = 3D spherical well → 3 quantum numbers from Schrodinger's equation (n, $_l$, m_l)

n	Principal quantum number	$n = 1, 2, 3, \ldots$	Quantizes the electron energy
ℓ	Orbital angular momentum quantum number	$\ell = 0, 1, 2, \ldots (n-1)$	Quantizes the magnitude of orbital angular momentum L
m_ℓ	Magnetic quantum number	$m_\ell = 0, \pm 1, \pm 2, \ldots, \pm \ell$	Quantizes the orbital angular momentum component along a magnetic field B_z
m_s	Spin magnetic quantum number	$m_s = \pm \frac{1}{2}$	Quantizes the spin angular momentum component along a magnetic field B_z

m_s: Arises from relativistic quantum theory

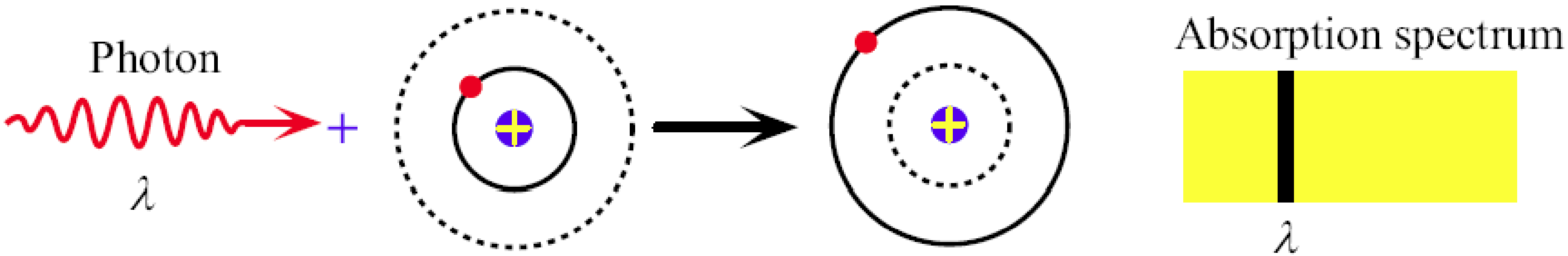
Electron energies in hydrogenic atoms



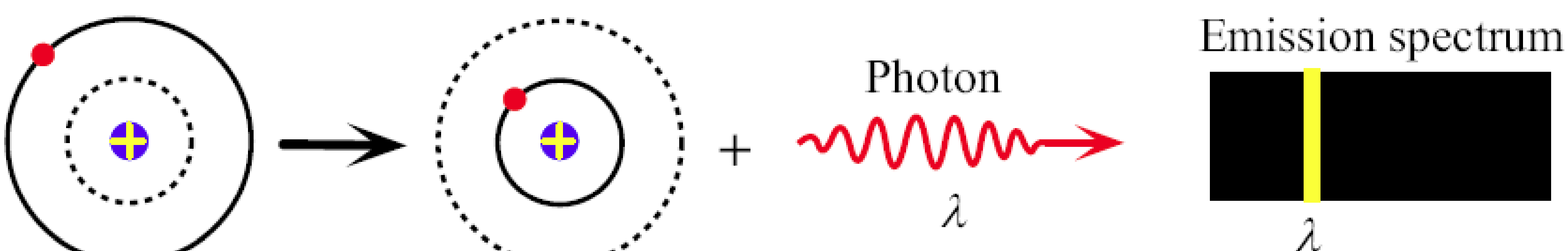
Energies are more closely spaced for higher n

Energy transitions can occur via photons

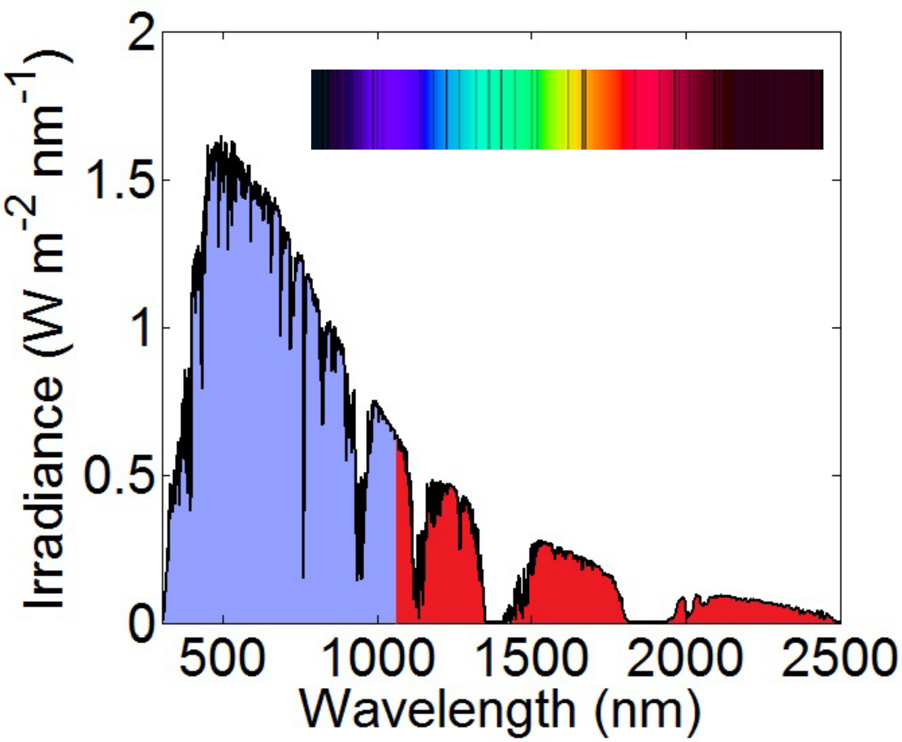
Absorption of a photon



Emission of a photon



Example: Solar Spectrum



1829: Josef von Fraunhofer

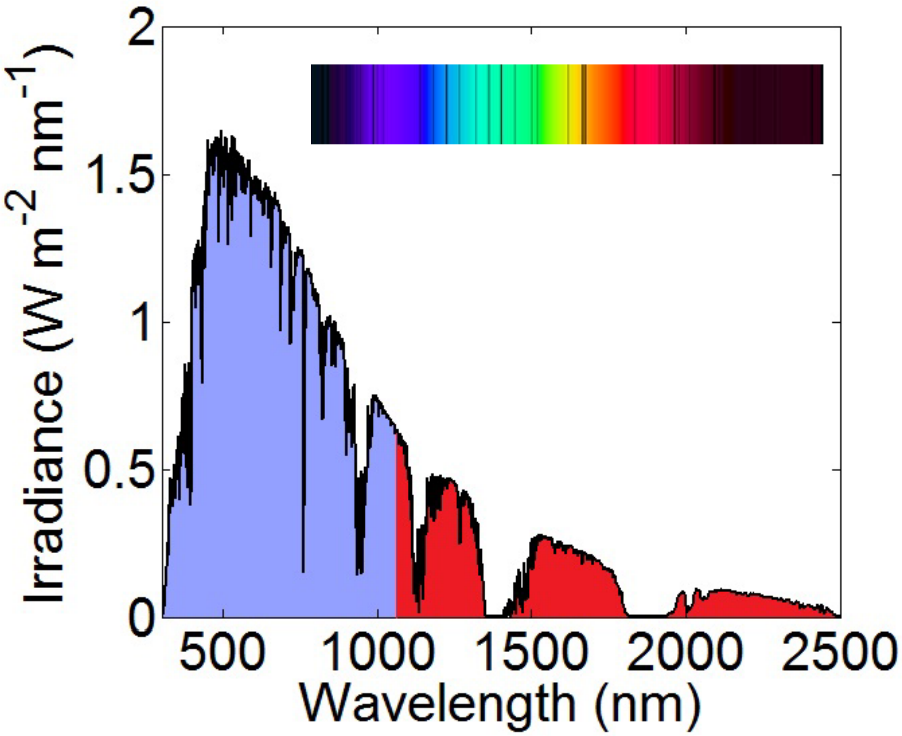
λ_{dark}^{1}=656.3 nm

λ_{dark}^{2}=486.1 nm

$$E_n = -\frac{Z^2 m e^4}{8\varepsilon_o^2 h^2 n^2} = -E_1(\frac{1}{n^2}) \rightarrow E_1 = 13.6eV$$

Convenient conversion: λ [eV]= 1241.341/λ [nm]

Example: Solar Spectrum



1829: Josef von Fraunhofer

$\lambda_{dark}{}^{1}$=656.3 nm = 1.89eV

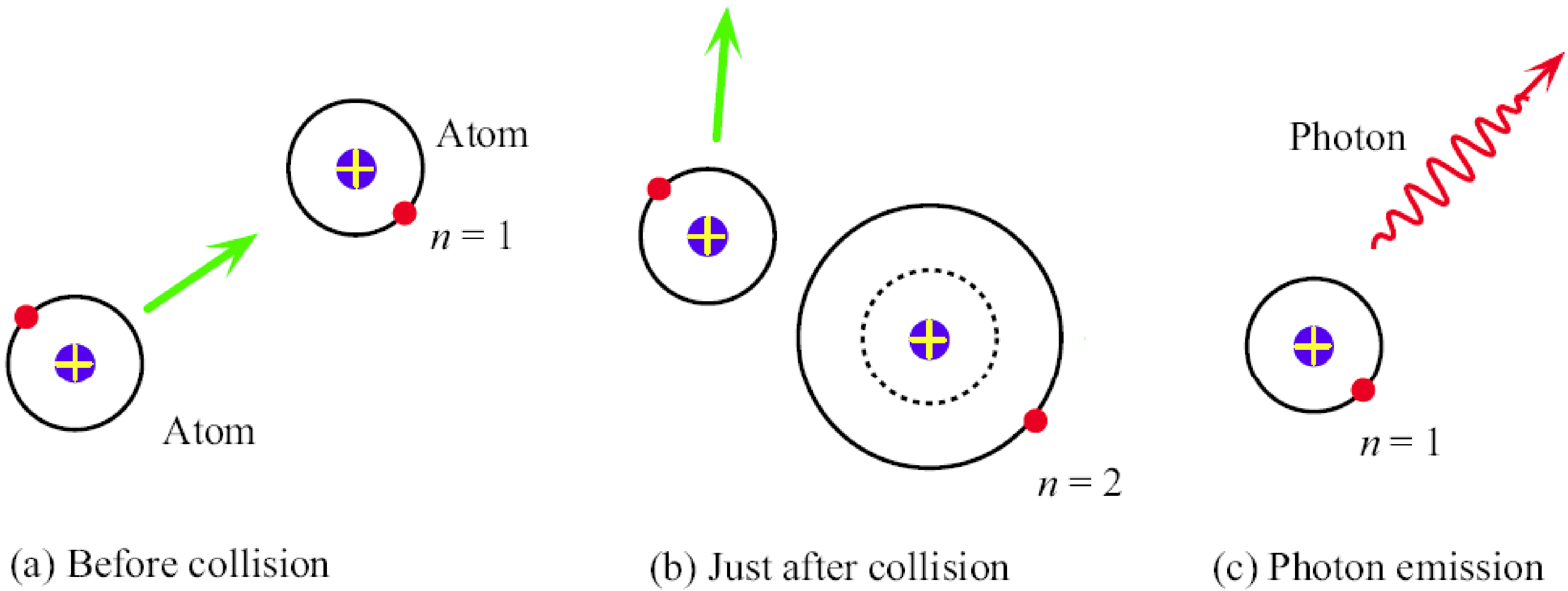
(n=3 to n=2)

$\lambda_{dark}{}^{2}$=486.1 nm = 2.55 eV

(n=4 to n=2)

$$E_n = -\frac{Z^2 m e^4}{8\varepsilon_o^2 h^2 n^2} = -E_1\left(\frac{1}{n^2}\right) \rightarrow E_1 = 13.6eV$$

Energy transitions can also occur via collisions



An atom can become excited by a collision with another atom. When it returns to its ground energy state, the atom emits a photon.

Neon lighting occurs via quantum transitions!

Laser:
Light Amplification by Stimulated Emission of Radiation

What makes a laser different from a lightbulb?

Laser:
Light Amplification by Stimulated Emission of Radiation

What makes a laser different from a lightbulb?

• coherent photons (i.e., all have the same phase)

→ high radiation intensities

• all emitted photons have the same wavelength

Rule 1: Only certain optical transitions are allowed, based on conservation of momentum

Electron orbital angular momentum

$$L = \hbar\left[\ell\left(\ell + 1\right)\right]^{1/2}$$

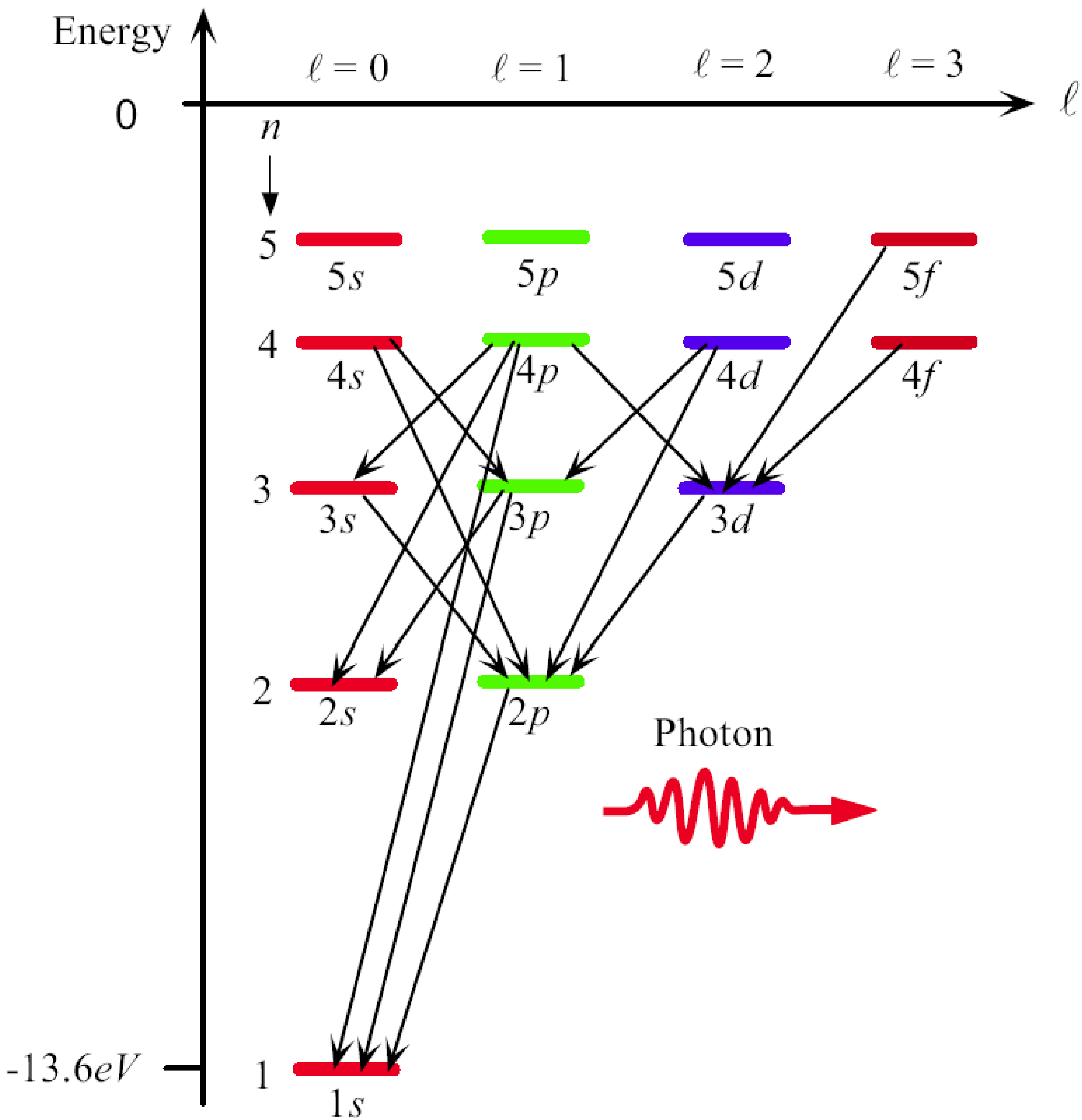
If we apply a magnetic field along z, B_z then the angular momentum is:

$$L_z = m_\ell \hbar$$

Selection rules for electromagnetic radiation absorption and emission (conservation of angular momentum)

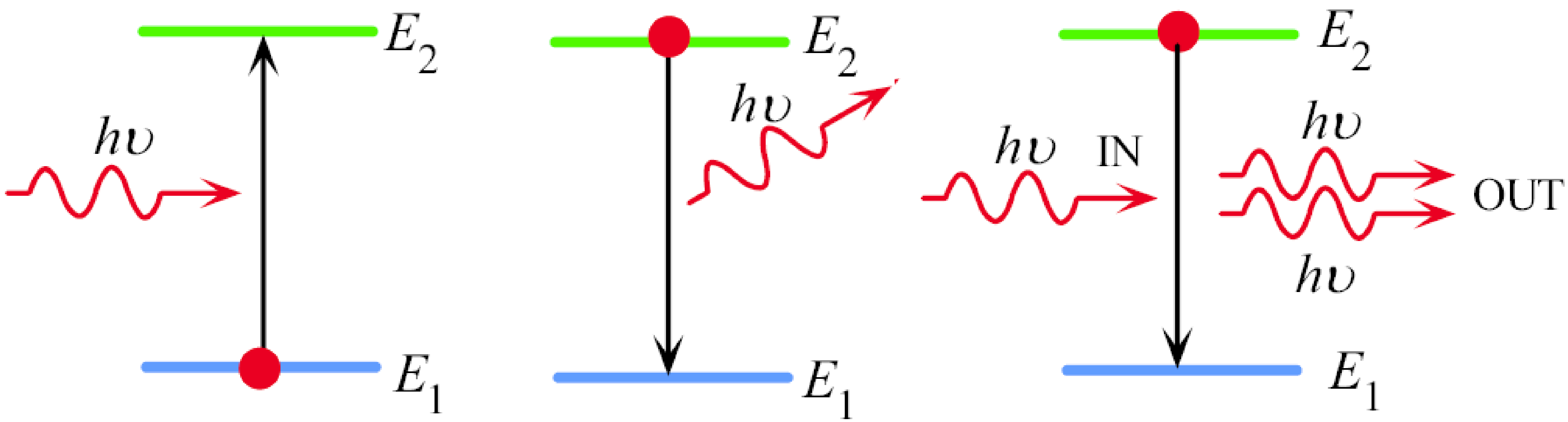
$$\Delta\ell = \pm 1 \quad \text{and} \quad \Delta m_\ell = 0, \pm 1$$

Allowed photon emission processes



Photon emission involves $\Delta\ell = \pm 1$ and $\Delta m_\ell = 0, \pm 1$

Rule 2: Photons interact with photons via the following 3 processes

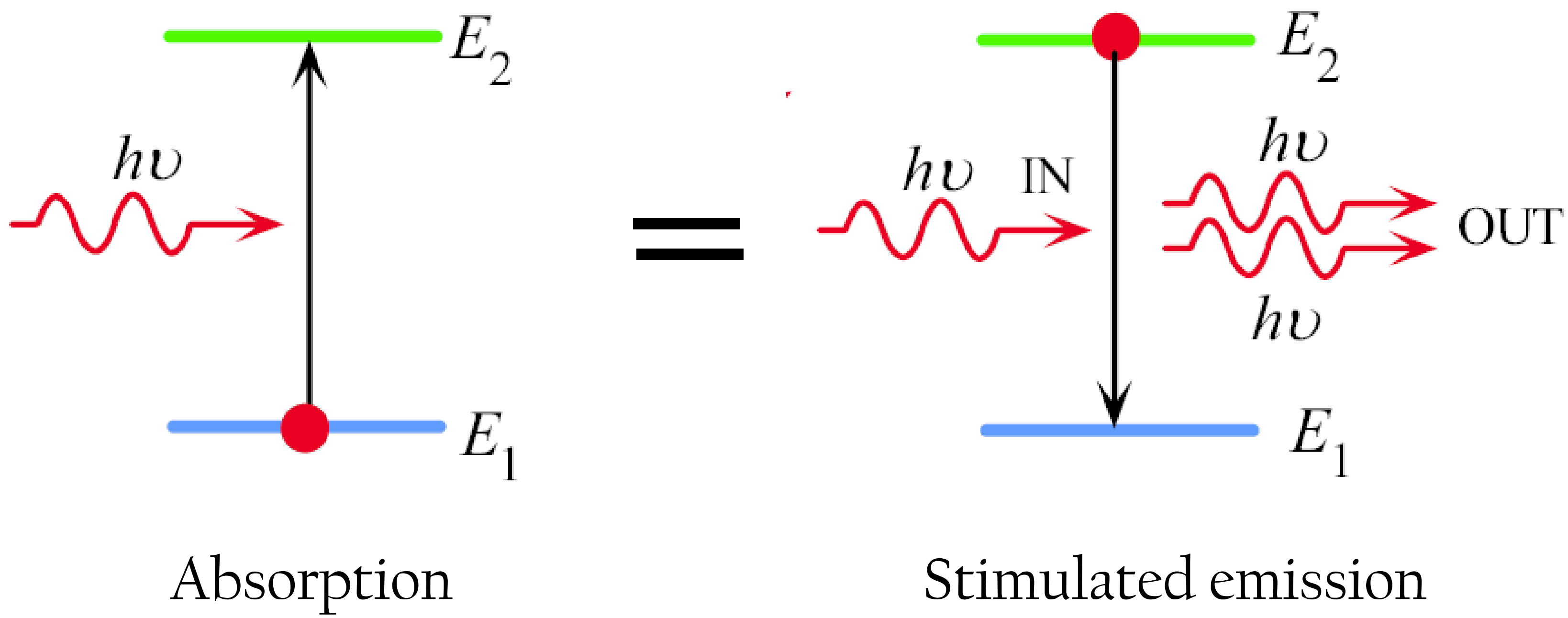


Absorption

Spontaneous emission

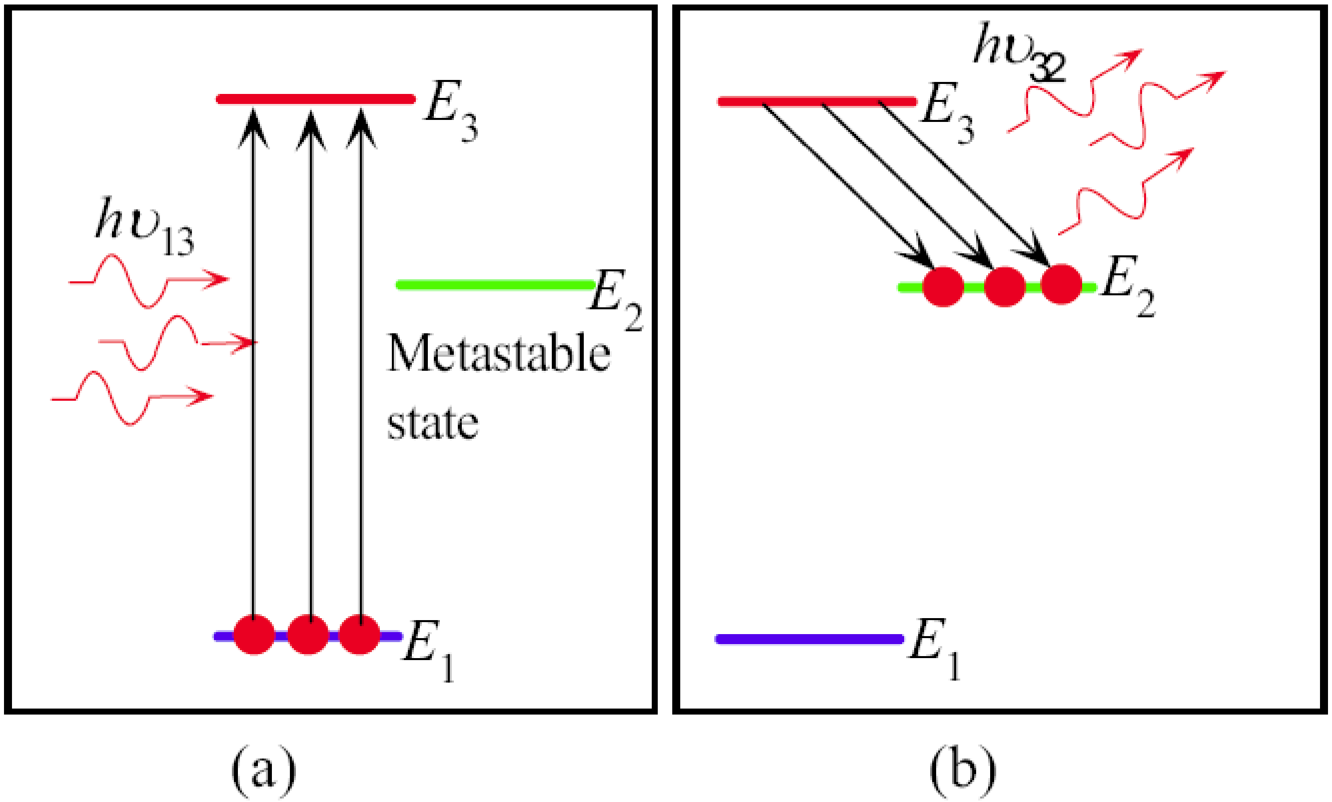
Stimulated emission

The probability of absorption equals the probability of stimulated emission



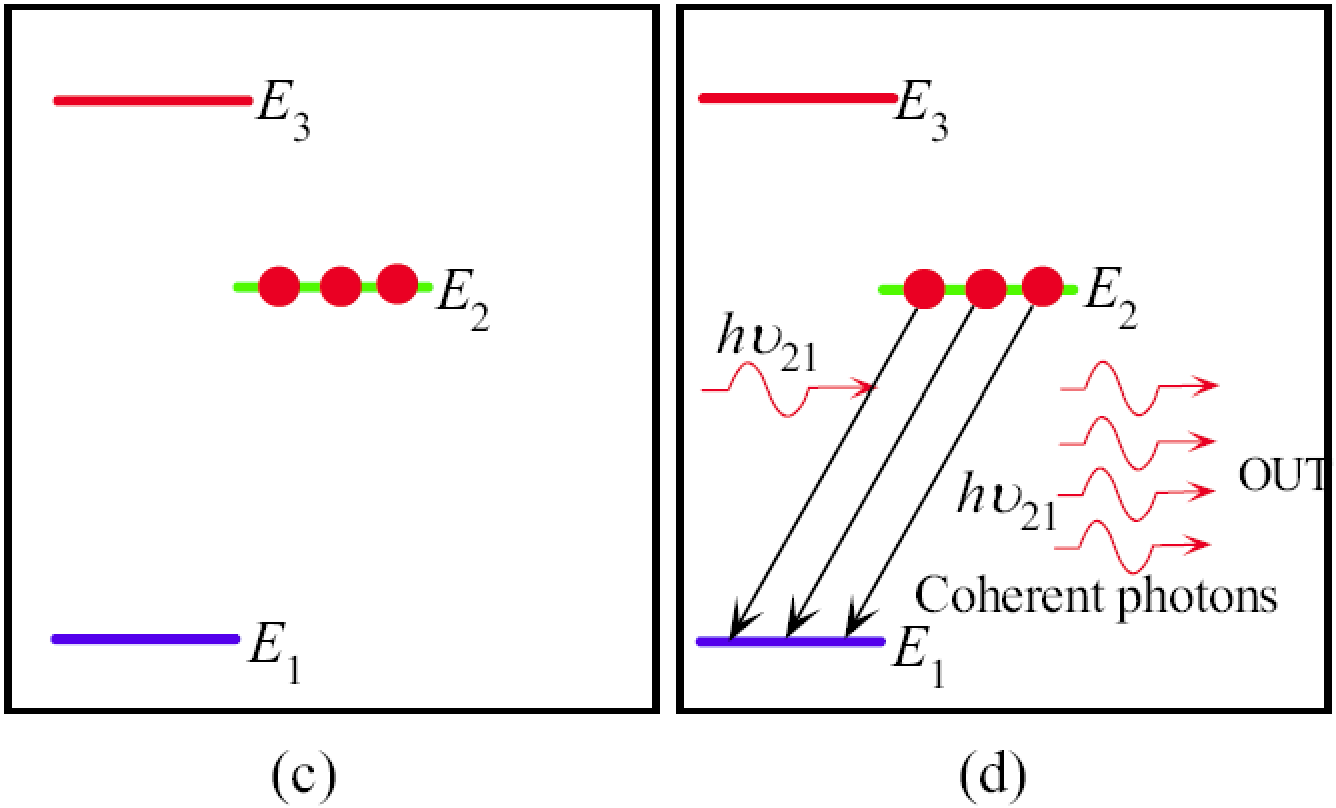
With a two level system, can not achieve "population inversion" – i.e., more electrons in the excited level E_2

Rule 3: Lasers are 'three-level' systems



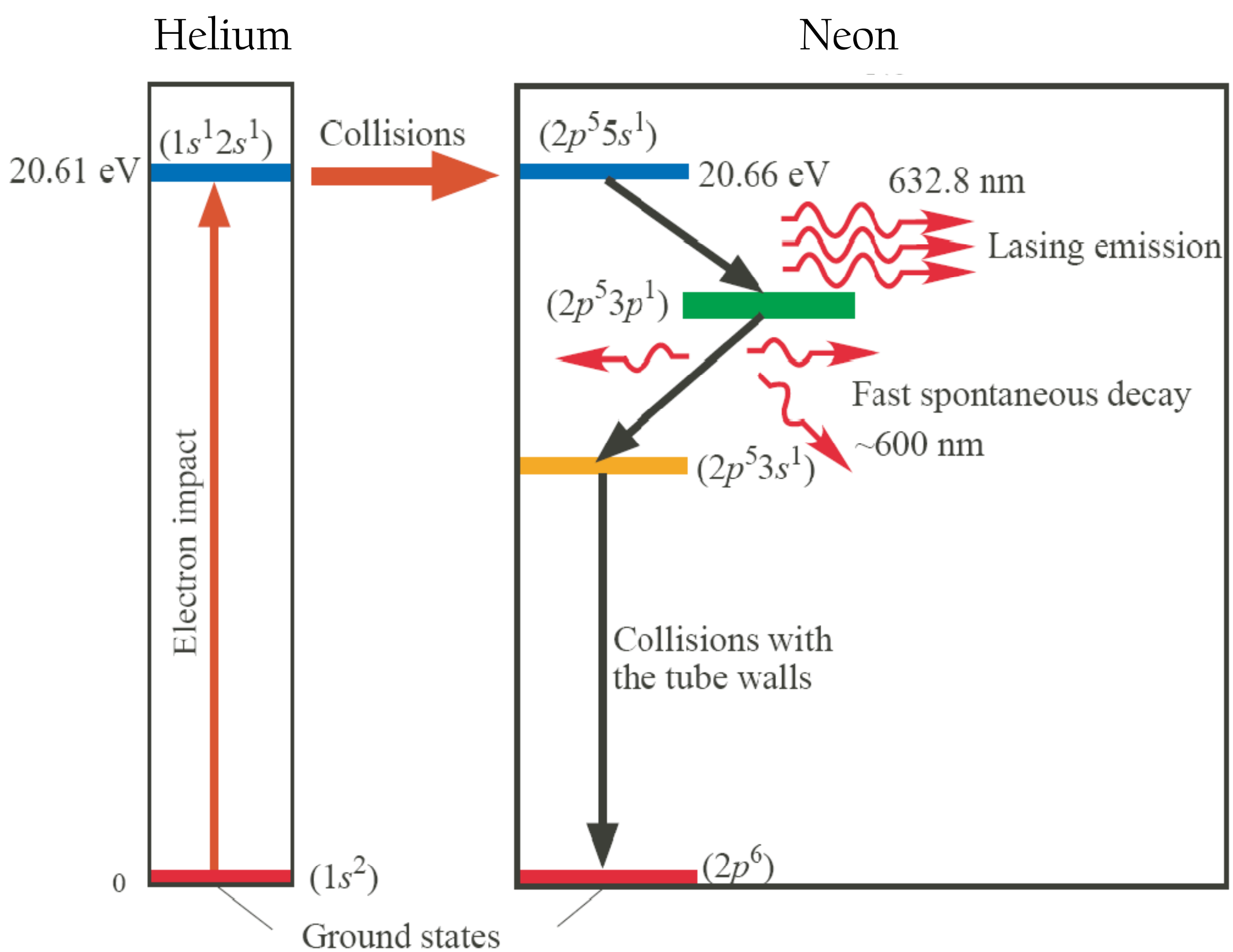
The principle of the LASER. (a) Atoms in the ground state are pumped up to the energy level E_3 by incoming photons of energy $h\nu_{13} = E_3 - E_1$. (b) Atoms at E_3 rapidly decay to the metastable state at energy level E_2 by emitting photons or emitting lattice vibrations. $h\nu_{32} = E_3 - E_2$.

Rule 3: Lasers are 'three-level' systems



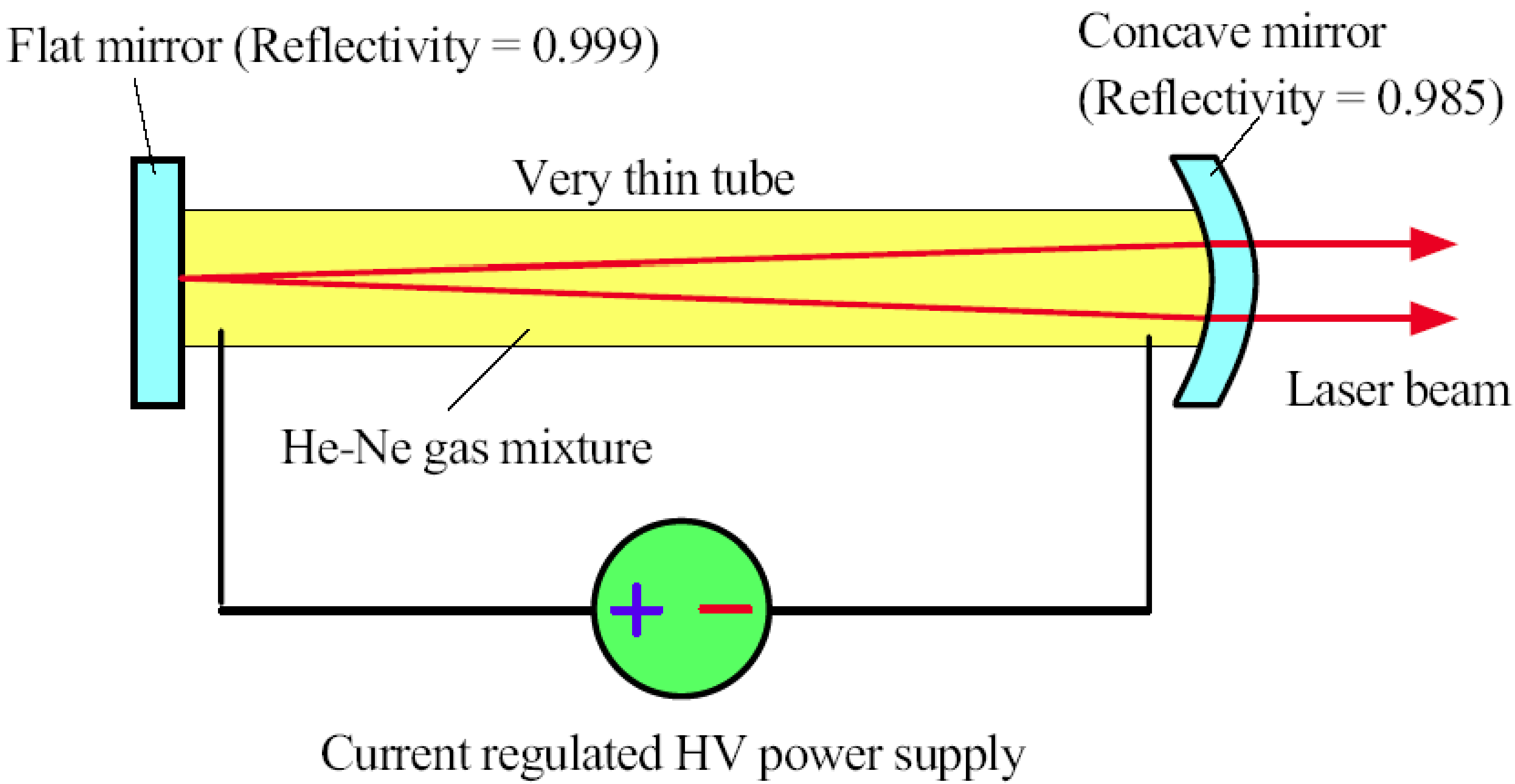
(c) As the states at E_2 are metastable, they quickly become populated and there is a <u>population inversion</u> between E_2 and E_1. (d) A random photon of energy $h\nu_{21} = E_2 - E_1$ can initiate stimulated emission. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.

HeNe laser operation



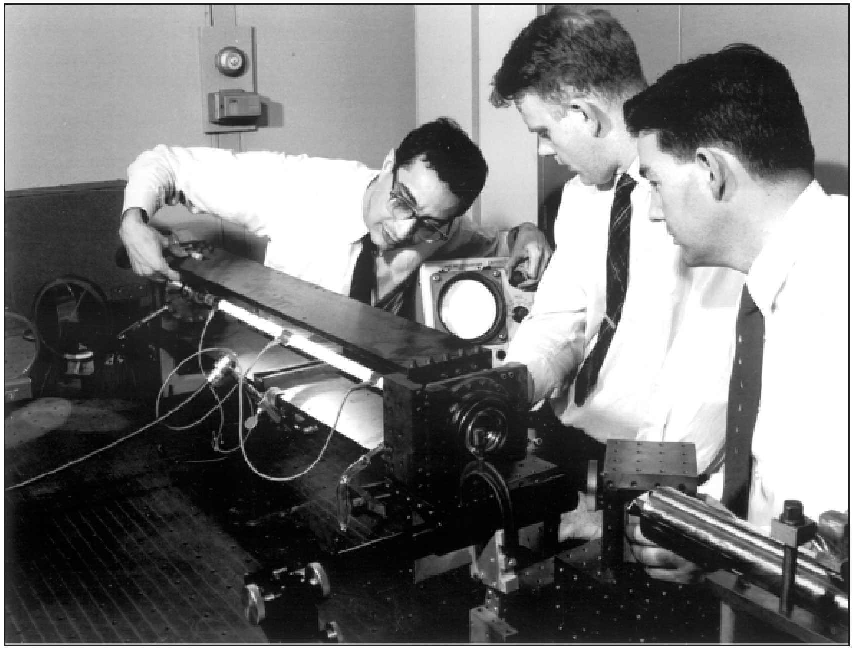
The principle of operation of the HeNe laser and important HeNe laser energy levels (for 632.8 nm emission).

Schematic of a HeNe laser



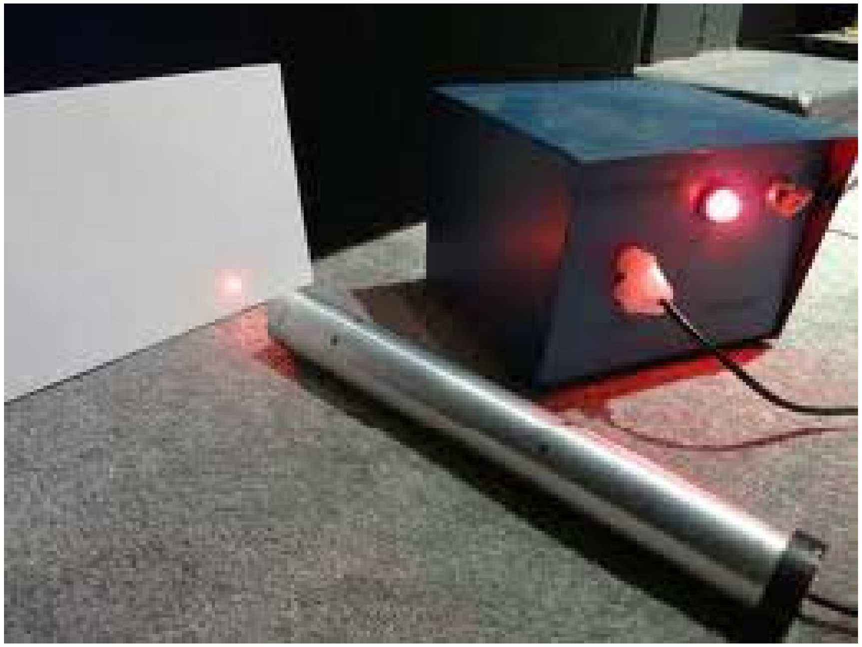
HeNe lasers, from 1960 to today

1960



Ali Javan and his associates William Bennett Jr. and Donald Herriott at Bell Labs were first to successfully demonstrate a continuous wave (cw) helium-neon laser operation (1960).
| SOURCE: Courtesy of Bell Labs, Lucent Technologies.

1980



Today

Laser output spectrum

Doppler effect: The observed photon frequency depends on whether the Ne atom is moving towards ($+v_x$) or away ($-v_x$) from the observer

$$\nu_2 = \nu_0\left(1 + \frac{v_x}{c}\right) \qquad \nu_1 = \nu_0\left(1 - \frac{v_x}{c}\right)$$

Frequency width of the output spectrum is approximately $\nu_2 - \nu_1$

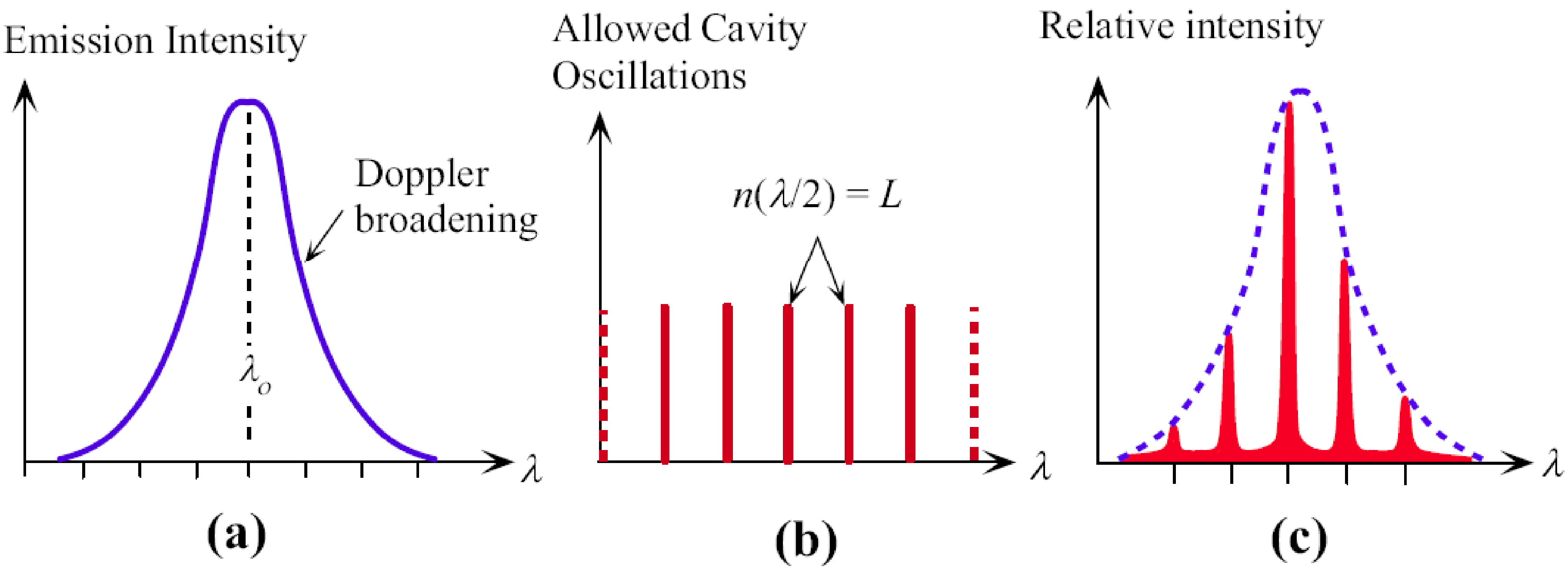
$$\Delta\nu = \frac{2\nu_0 v_x}{c}$$

Laser cavity modes: Only certain wavelengths are allowed to exist within the optical cavity L. If n is an integer, the allowed wavelength λ is

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

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

Laser output spectrum



(a) Doppler-broadened emission versus wavelength characteristics of the lasing medium.
(b) Allowed oscillations and their wavelengths within the optical cavity.
(c) The output spectrum is determined by satisfying (a) and (b) simultaneously.

Midterm topics: lectures 1-12

- ionic bonding – equilibrium bond lengths
- kinetic molecular theory
- Maxwell's principle of equipartition of energy
- Thermal expansion
- Maxwell-Boltzmann Distribution
- Thermally activated processes & diffusion
- Crystals
- Electrical conductivity (Drude Model)
- Temperature coefficient of resistivity
- Hall Effect
- Thermal conduction in metals & non-metals
- Wave/particle duality
- Photon and electron diffraction
- The photoelectric effect, compton scattering
- Blackbody radiation
- Potential wells and general extension to atoms