Part III: Modern Physics

Chapter 42

Atomic Physics

Dr. Saif M. H. Qaid

LECTURE OUTLINE

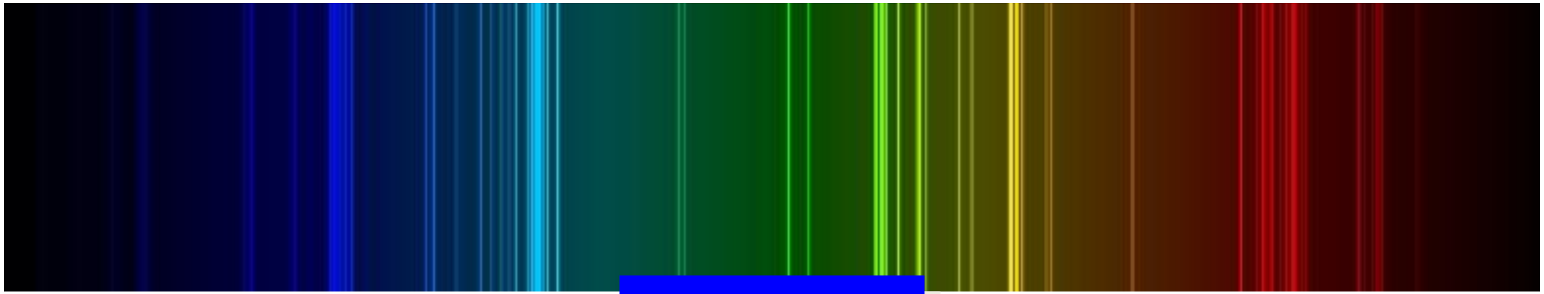
- **42.1 Atomic Spectra of Gases**
- **42.2 Early Models of the Atom**
- **42.3 Bohr’s Model of the Hydrogen Atom**
- **42.8 More on Atomic Spectra: Visible and X-Ray**
- **42.9 Spontaneous and Stimulated Transitions**
- **42.10 Lasers**

Need for Quantum Physics

- Problems remained from classical mechanics that the special theory of relativity didn’t explain.
- Attempts to apply the laws of classical physics to explain the behavior of matter on the atomic scale were consistently unsuccessful.
- Problems included:
  - Blackbody radiation
    - The electromagnetic radiation emitted by a heated object
  - Photoelectric effect
    - Emission of electrons by an illuminated metal

Atomic Spectra

Hydrogen



Nitrogen

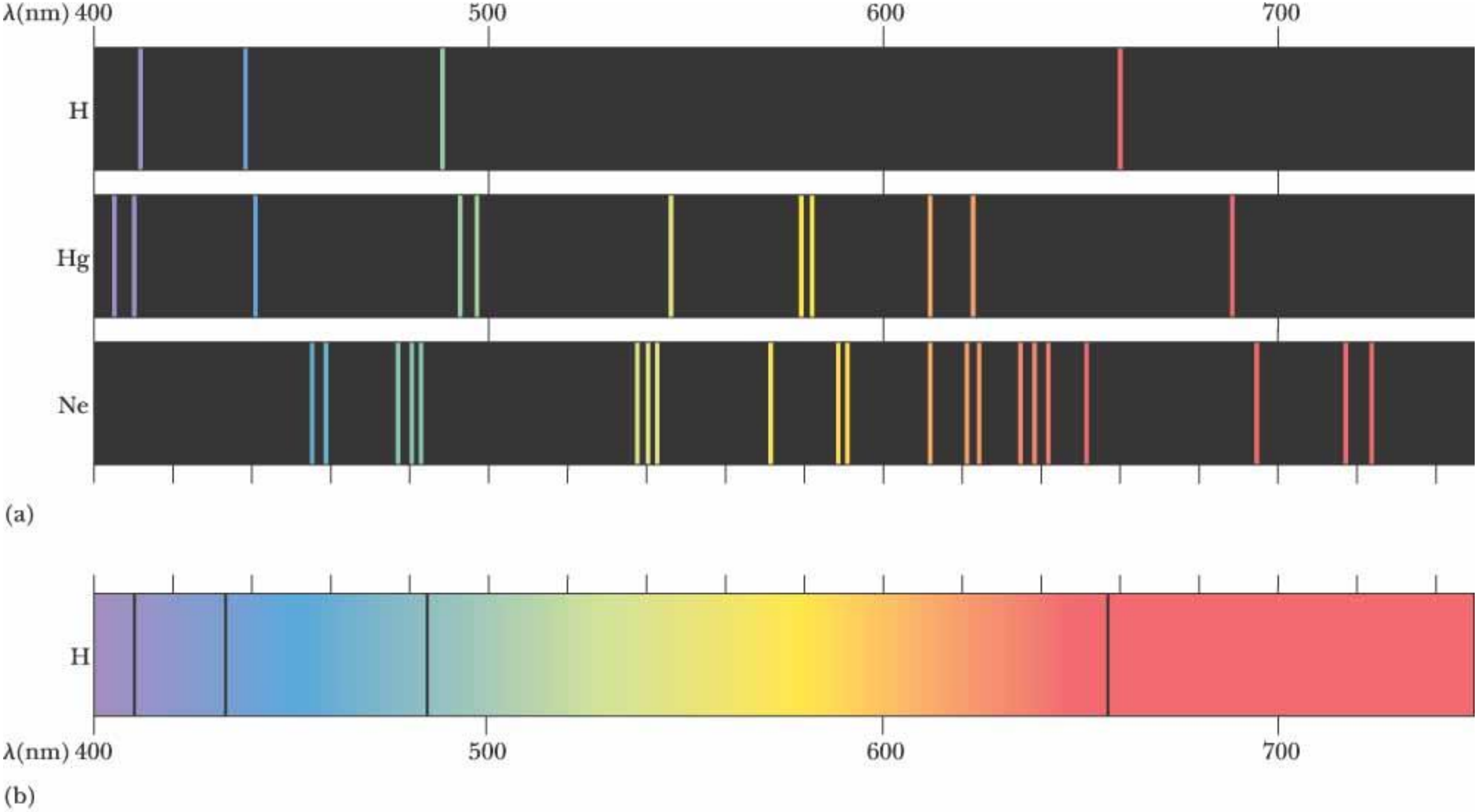


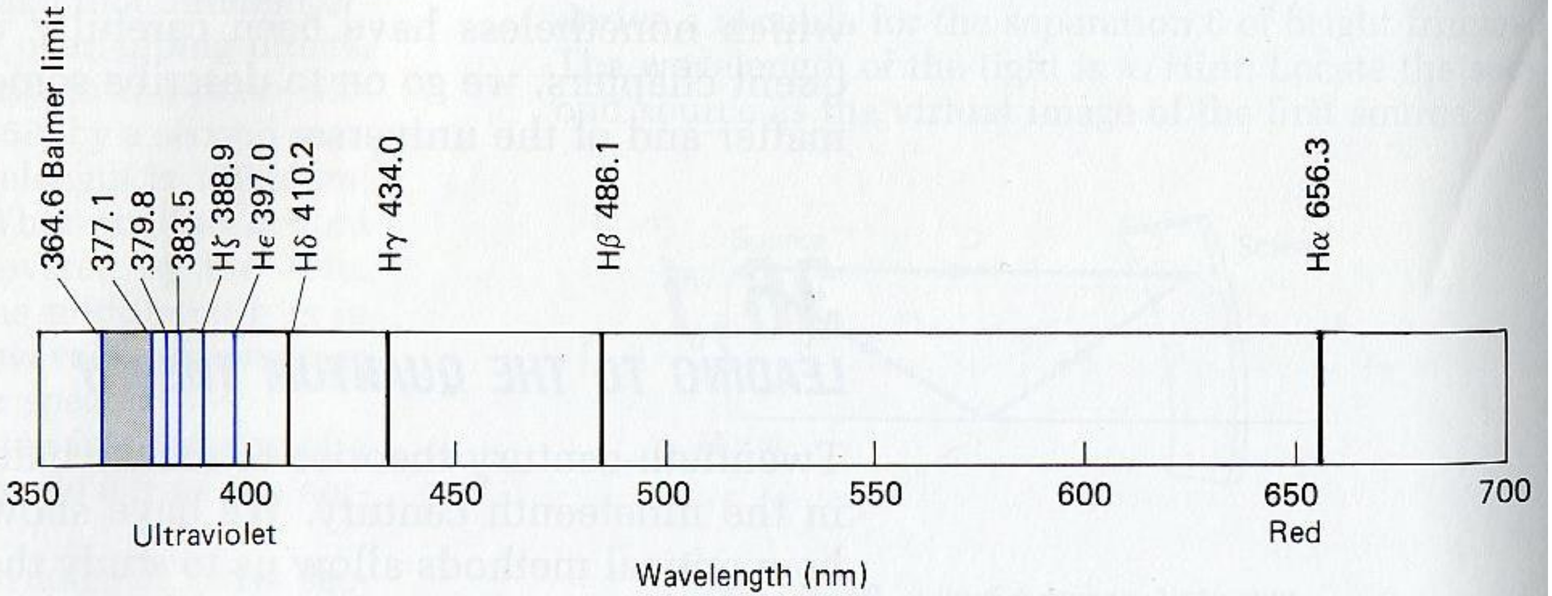
Fig 42-1, p.1353

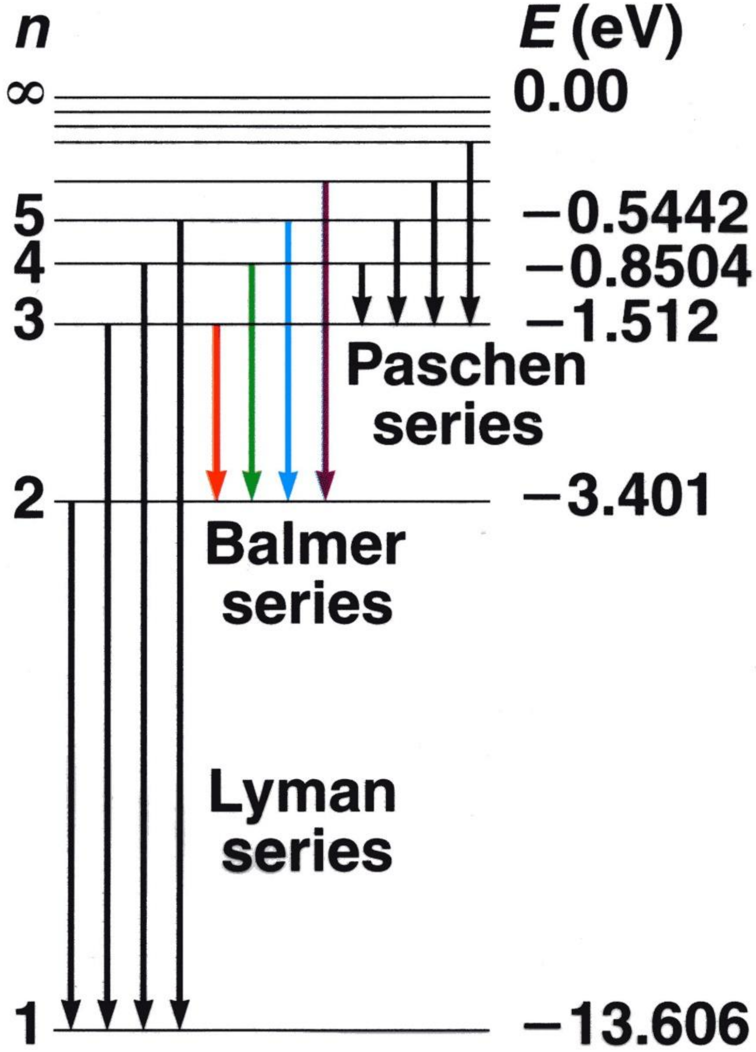
Balmer's Realization

lines could be described by the equation

$$\frac{1}{\lambda_n} \propto \left(\frac{1}{2^2} - \frac{1}{n^2}\right), \qquad (36\text{–}1)$$

where $n = 3, 4, 5$, and 6. The characteristic distribution of these "Balmer lines" (Fig. 36–2) is easily recognizable in spectra. But a numerical formula is not a physical explanation. Why did the lines take on this pattern? The answer took decades to find but the search for it led to profound insights.




n
E (eV)
∞
0.00
5
−0.5442
4
−0.8504
3
−1.512
Paschen series
2
−3.401
Balmer series
Lyman series
1
−13.606

J.J. Thompson Model

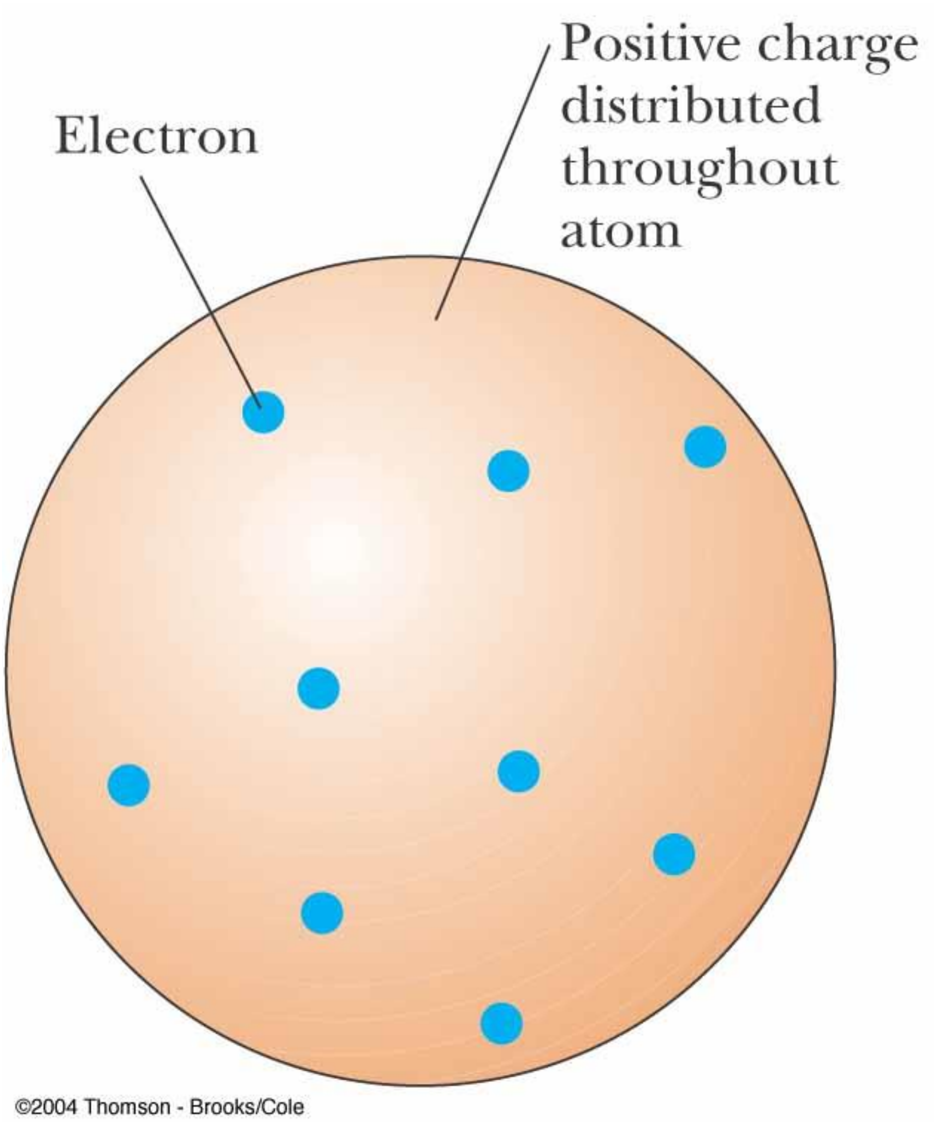


Fig 42-4, p.1355

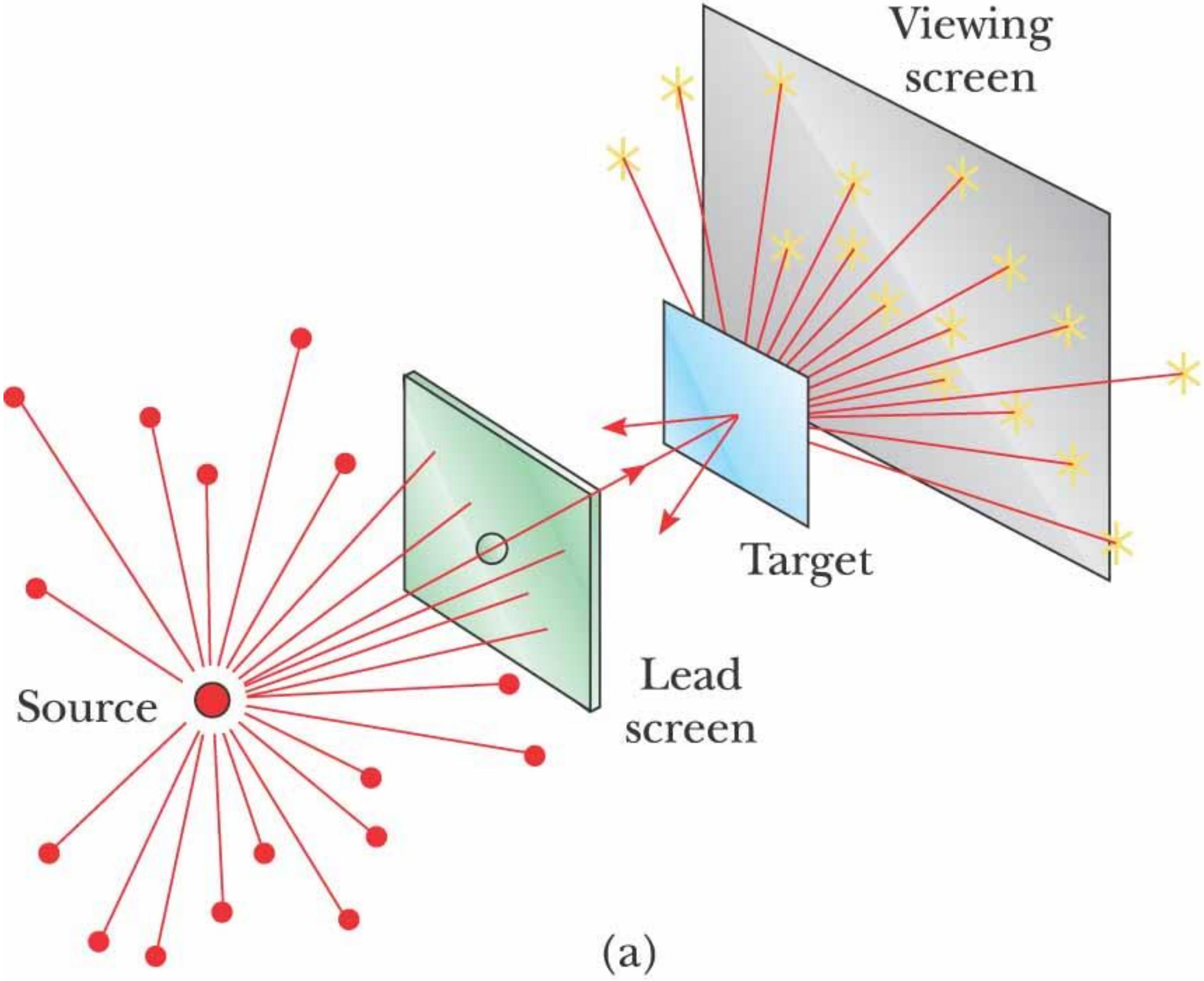
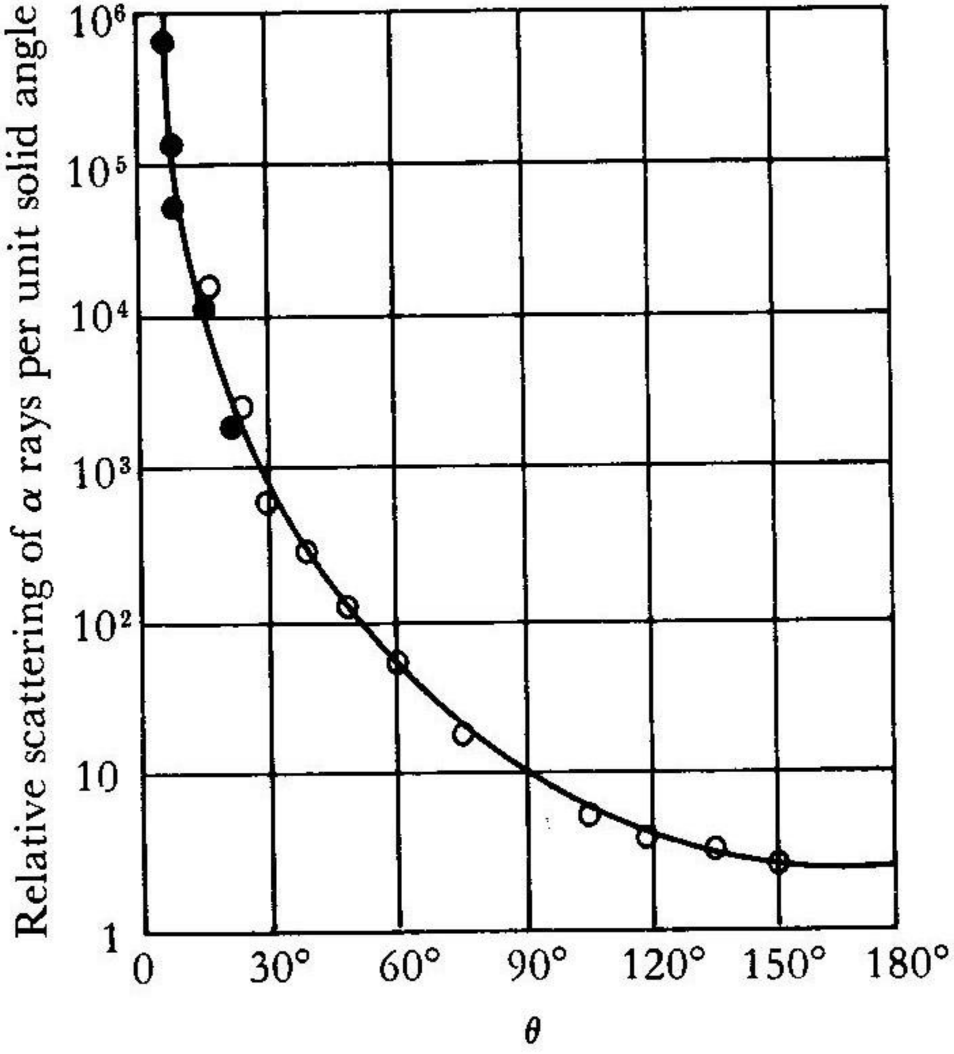
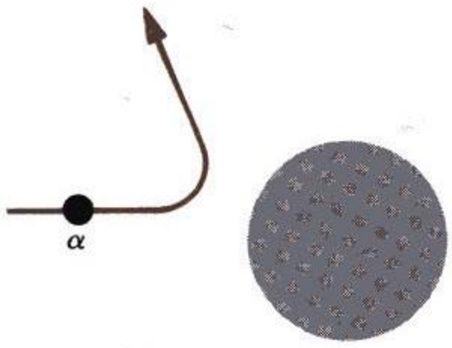


Fig 42-5a, p.1355

Rutherford Scattering of α-particles



$$\sin^{-4}\left(\frac{\theta}{2}\right)$$


α

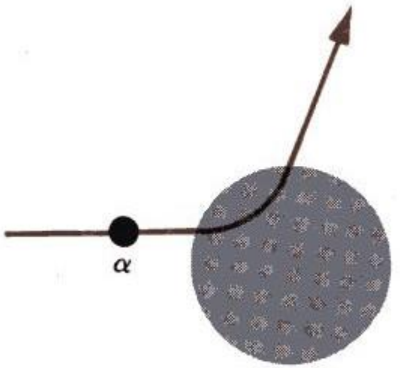

α

Figure 4–12 is a plot of their data showing the angular dependence of the scattering using 7.7 MeV α particles. For a given scattering, the distance of closest approach of the α to the nucleus can be calculated from the geometry of the collision. For the largest angle, near 180°, the collision is nearly "head-on." We can calculate the distance D of closest approach for a head-on collision by setting the potential energy at this distance equal to the original kinetic energy:

$$\frac{Kq_\alpha Q}{D} = \tfrac{1}{2}MV^2$$

or

$$D = \frac{Kq_\alpha Q}{\tfrac{1}{2}MV^2} \tag{4–13}$$

For the case of 7.7 MeV α particles, the distance of closest approach for a head-on collision is

$$D = \frac{(2)(79)14.4\ \text{eV-Å}}{7.7 \times 10^6\ \text{eV}} \approx 3 \times 10^{-4}\ \text{Å} = 3 \times 10^{-14}\ \text{meter}$$

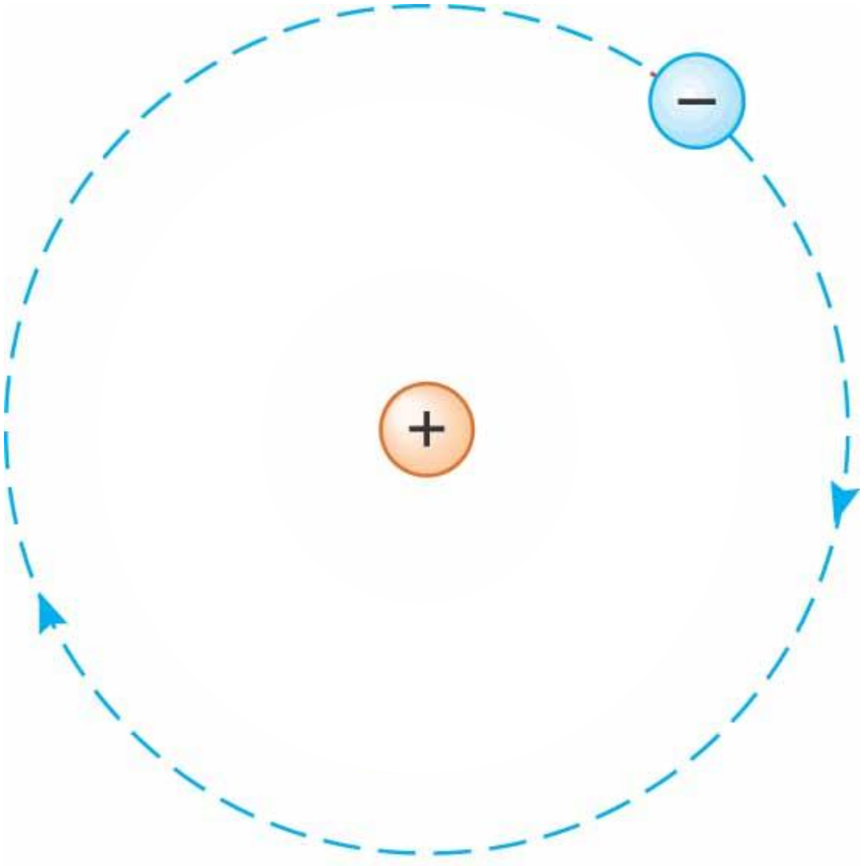


Fig 42-5b, p.1355

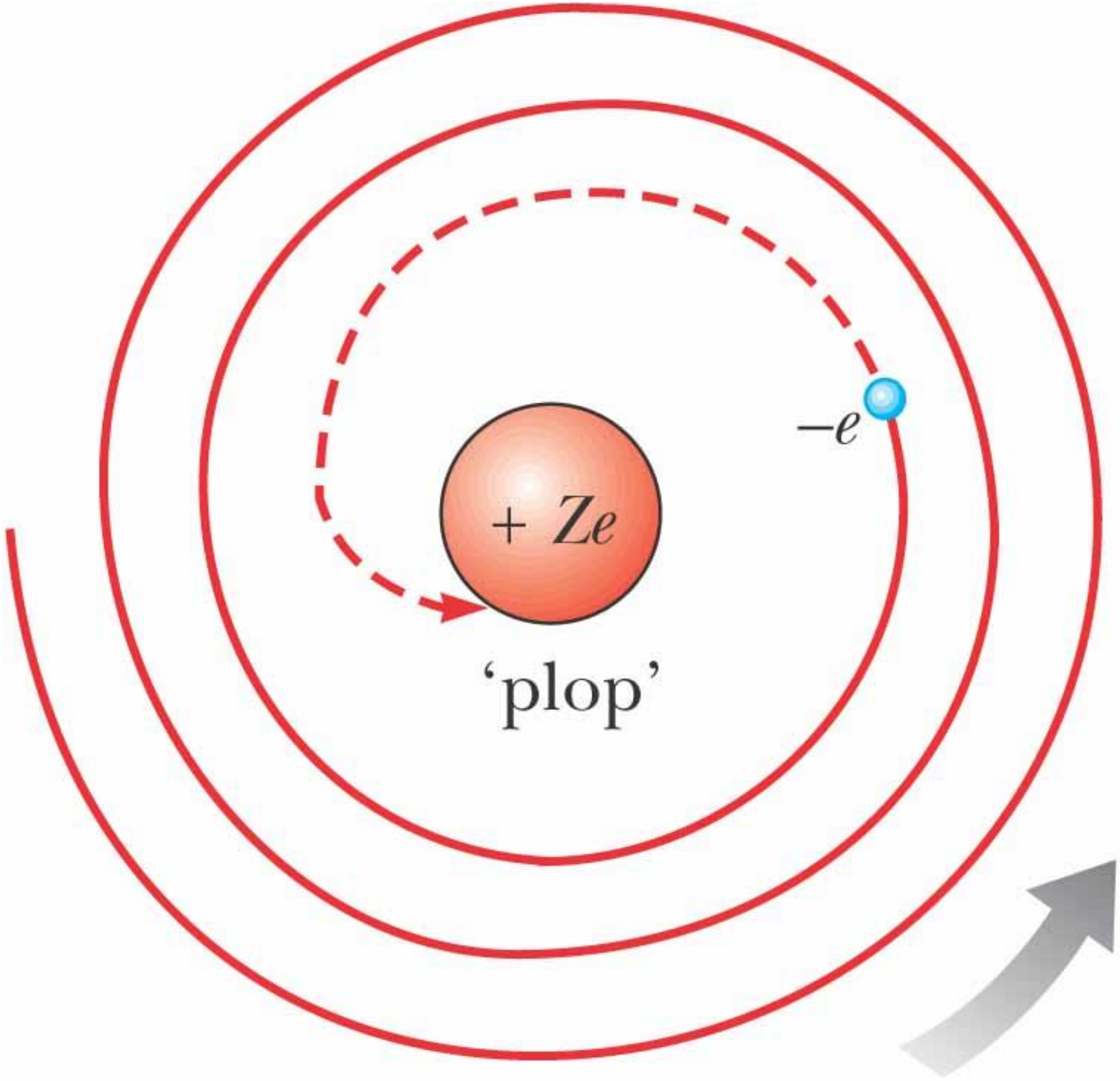


Fig 42-6, p.1356

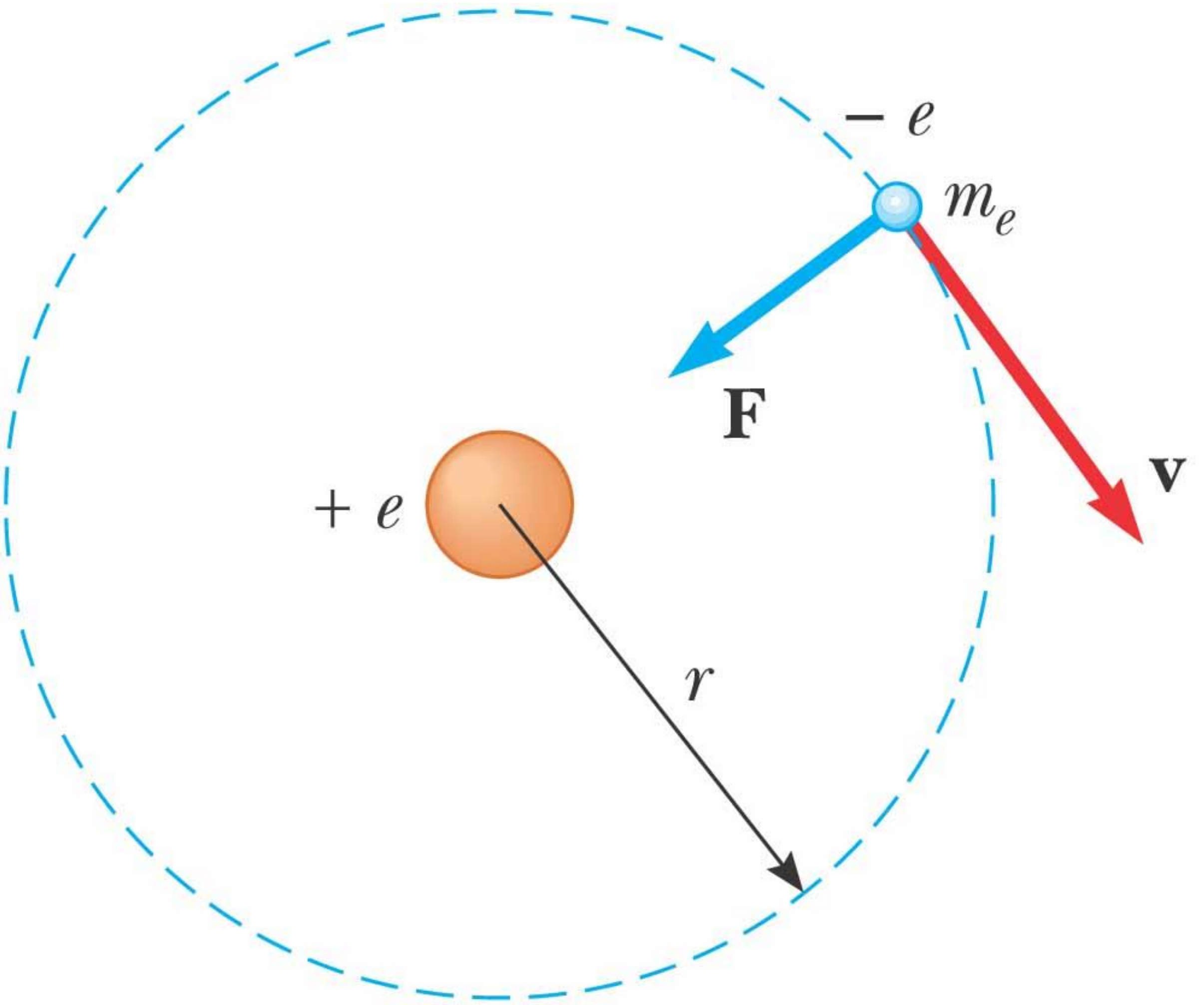


Fig 42-7, p.1356

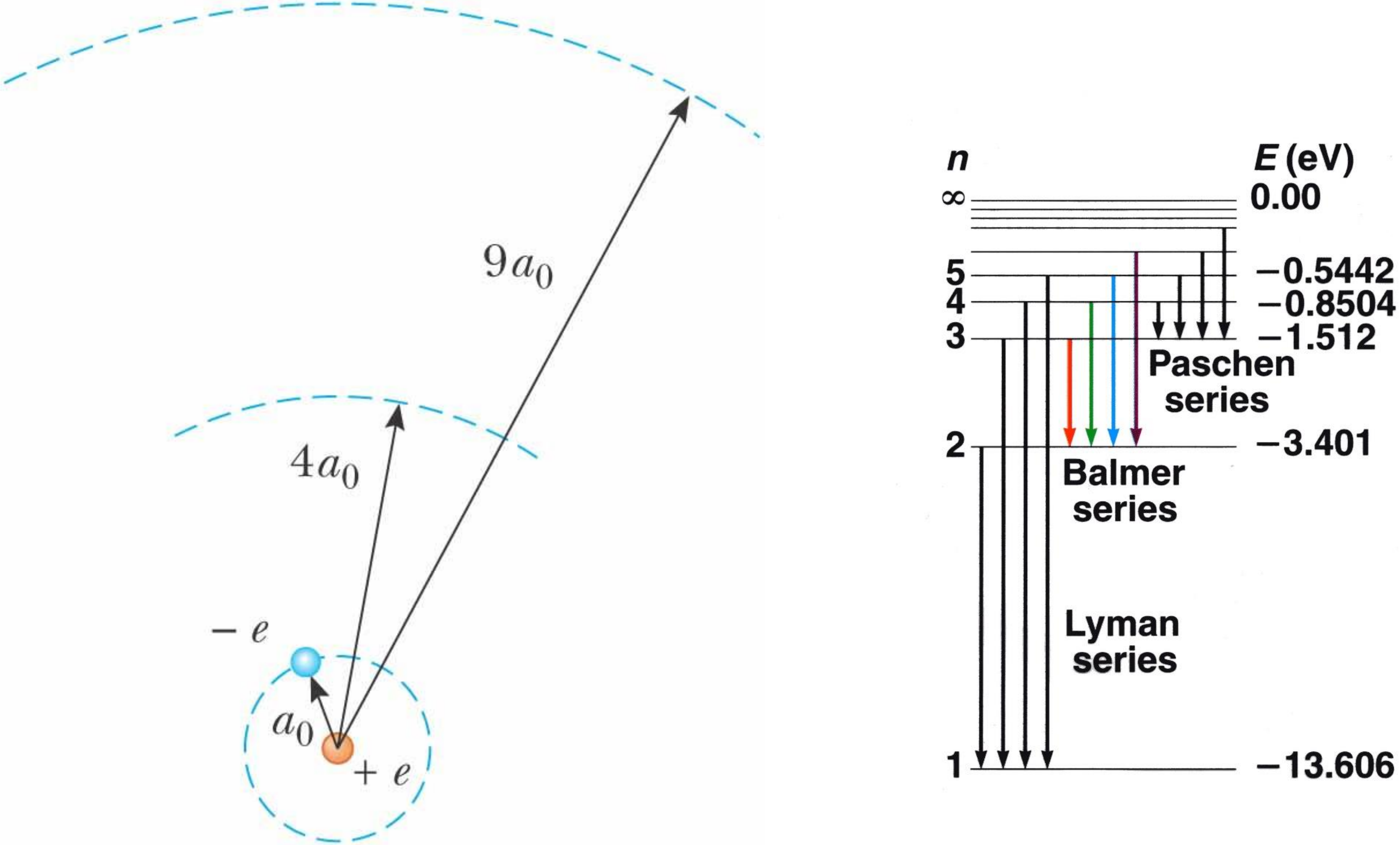
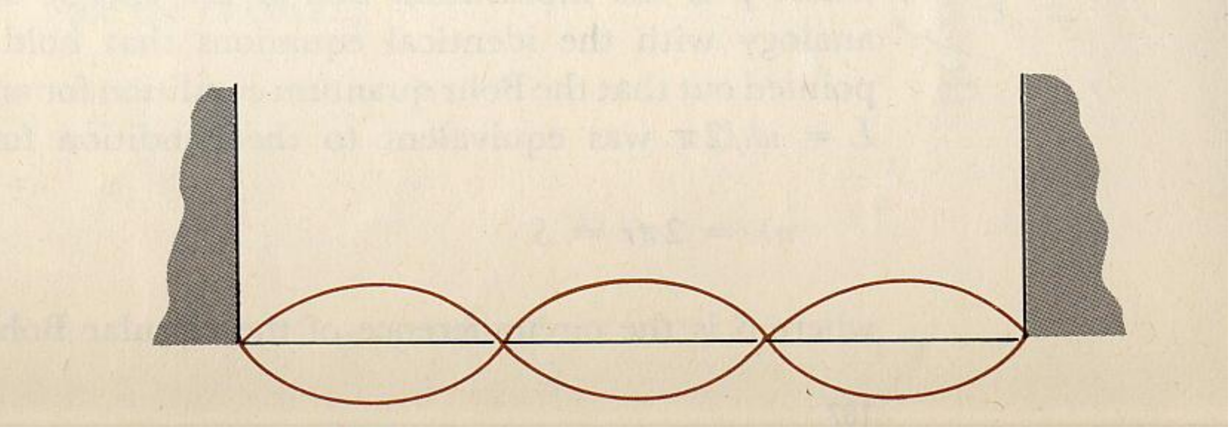


Fig 42-8, p.1358

Connection between Bohr and de Broglie



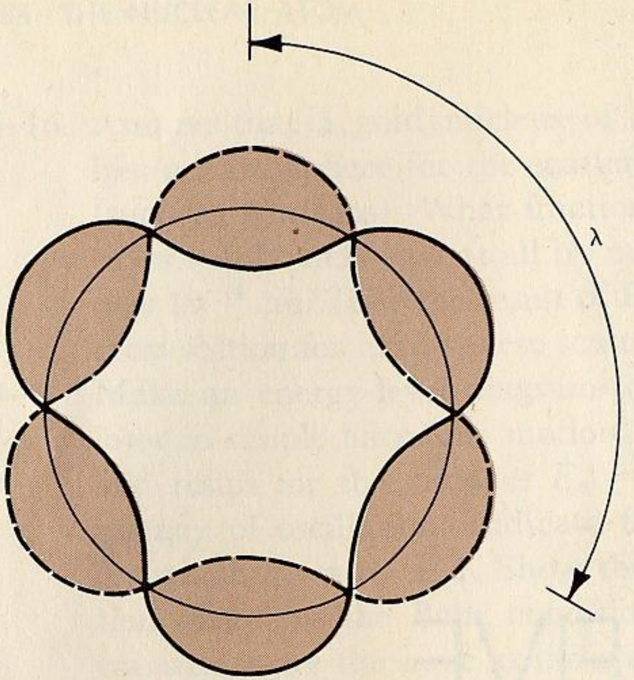
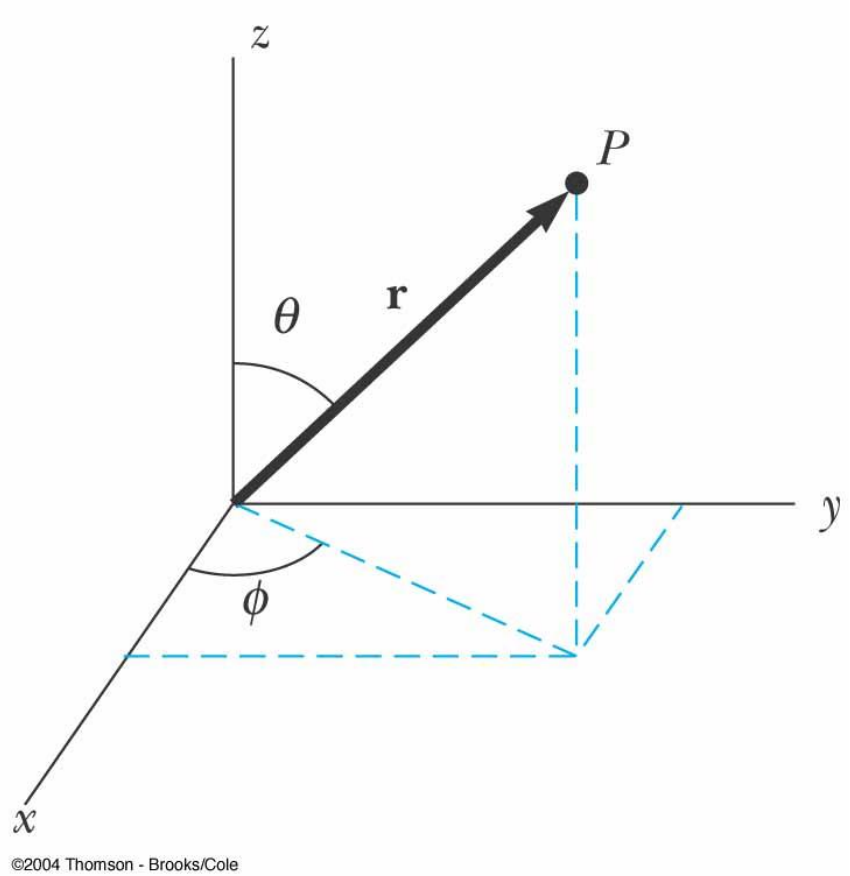


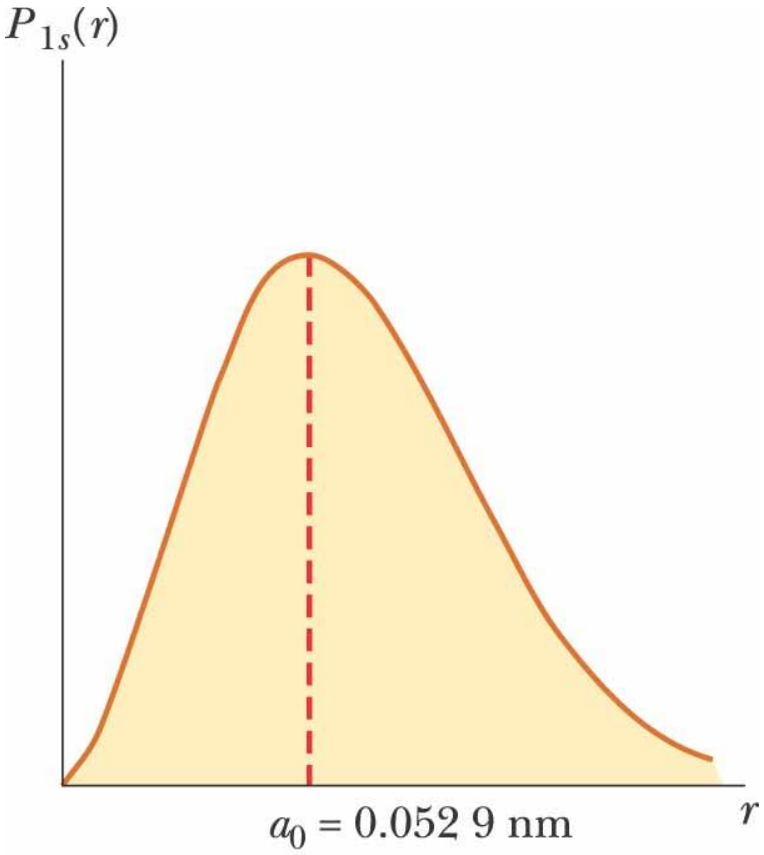
figure 5–1
Standing waves around the circumference of a circle.



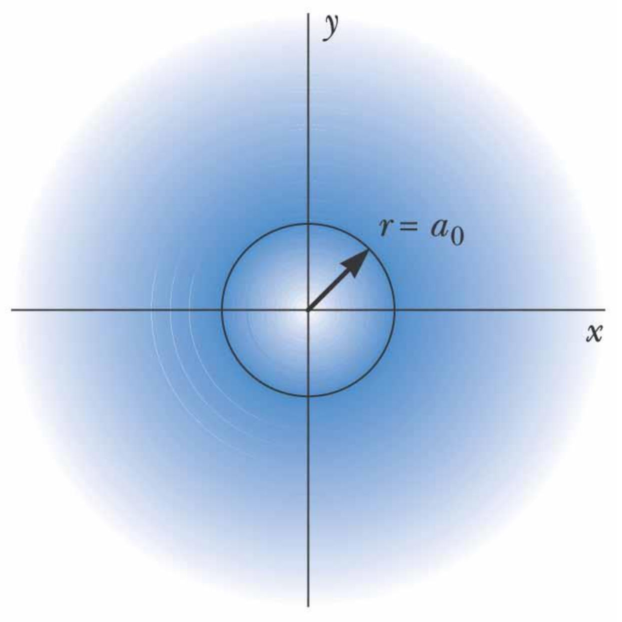
Express S. E. in spherical coordinates, solutions separate into two parts, radial Part and an angular part

Fig 42-10, p.1362

Radial solution for H in its ground state.



(a)

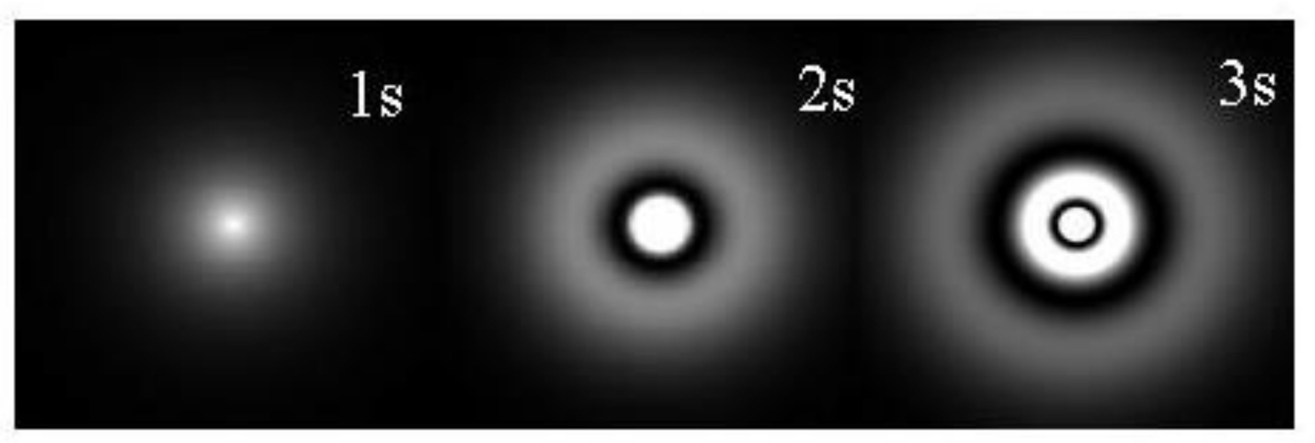


(b)

$$\langle r \rangle = a_0$$

Fig 42-12a, p.1365

Electron Probability Density for H



Probability per unit volume for finding the electron in the $n = 1$, 2 and 3 states of the hydrogen atom.

$$\psi_{1s} = \frac{1}{\sqrt{\pi a_0^3}} e^{-r/a_0}$$

$$\psi_{2s} = \frac{\left(2 - r/a_0\right)}{4\sqrt{2\pi a_0^3}} e^{-r/2a_0}$$

$$\psi_{3s} = \frac{\left(27 - 18\,r/a_0 + 2\,r^2/a_0^2\right)}{81\sqrt{3\pi a_0^3}} e^{-r/3a_0}$$

❑ الأطياف الخطية Line spectra

وجد العلماء أن لكل عنصر طيف خطي مميز له واستطاعوا قياس أطوالها الموجية ولكنهم لم يعرفوا في ذلك الوقت سبب وجودها.

فعند مرور تيار كهربائي على غاز فإنه ينبعث ضوء، إذا مر خلال موشور أو محزوز حيود تتكون منه خطوط طيفية منفصلة لكل منها طول موجي محدد.

- لأجل غاز الهيدروجين

متسلسلة پالمر(طيف مرئي):

$$\frac{1}{\lambda_n}=\mathrm{R}\left(\frac{1}{2^2}-\frac{1}{n^2}\right), n=3,4,5,.....$$

ثابت رايدبرج

$$,\mathrm{R}=1.09737\times10^{7}\,m^{-1}$$

أما متسلسلات الأطياف غير المرئية فهي:

- متسلسلة ليمان:

$$\frac{1}{\lambda_n} = \mathrm{R}(\frac{1}{1^2} - \frac{1}{n^2}), n = 2,3,4,5,.....$$

- متسلسلة باشن:

$$\frac{1}{\lambda_n} = \mathrm{R}(\frac{1}{3^2} - \frac{1}{n^2}), n = 4,5,6.....$$

- متسلسلة براكيت:

$$\frac{1}{\lambda_n} = \mathrm{R}(\frac{1}{4^2} - \frac{1}{n^2}), n = 5,6,7.....$$

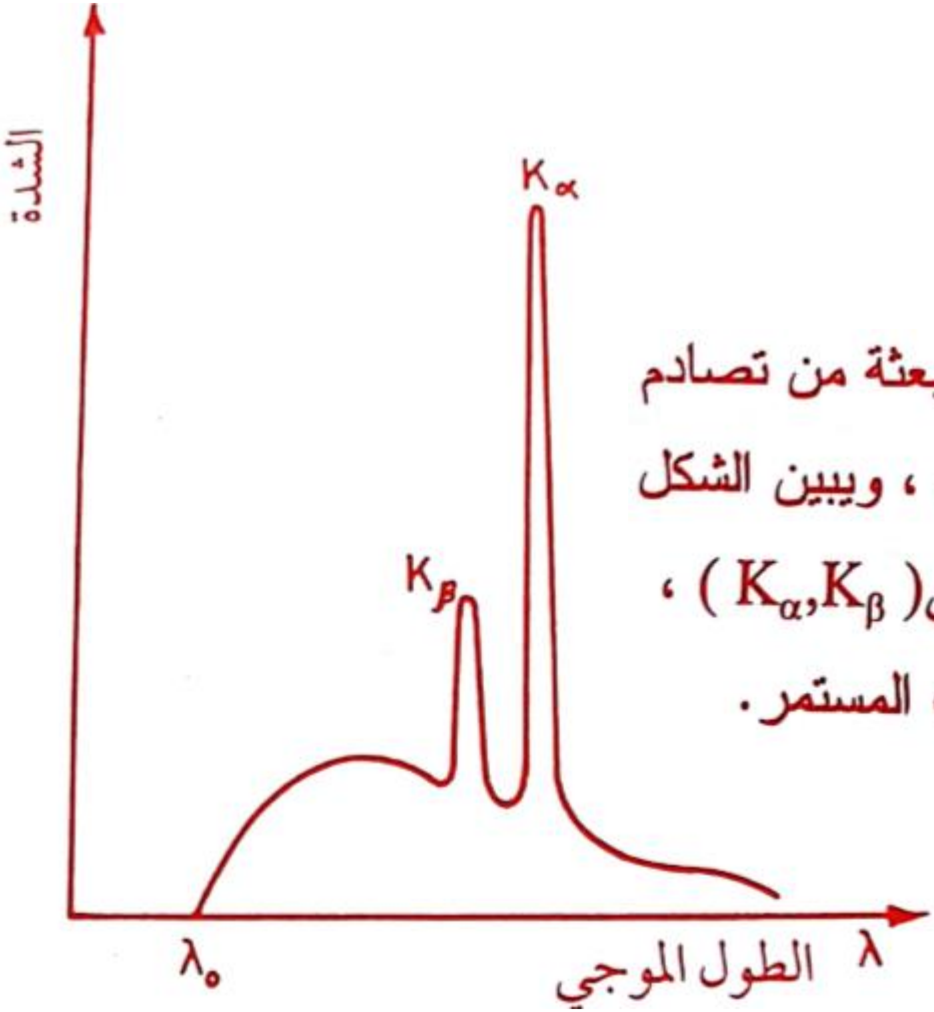
☐ أطياف الأشعة السينية X-ray spectra

وجد العالم رونتجن أن إشعاعات قوية تخترق المواد ذات طبيعة مجهولة تنبعث عندما تصطدم إلكترونات سريعة على هدف من مادة معدنية ثقيلة، ولعدم معرفته بطبيعتها وسبب انبعاثها أسماءها x-ray.

وعرفت بعد ذلك طبيعة هذه الأشعة بأنها موجات كهرومغناطيسية أطوال موجاتها قصيرة جدا في حدود 0.01 nm و 10 nm.

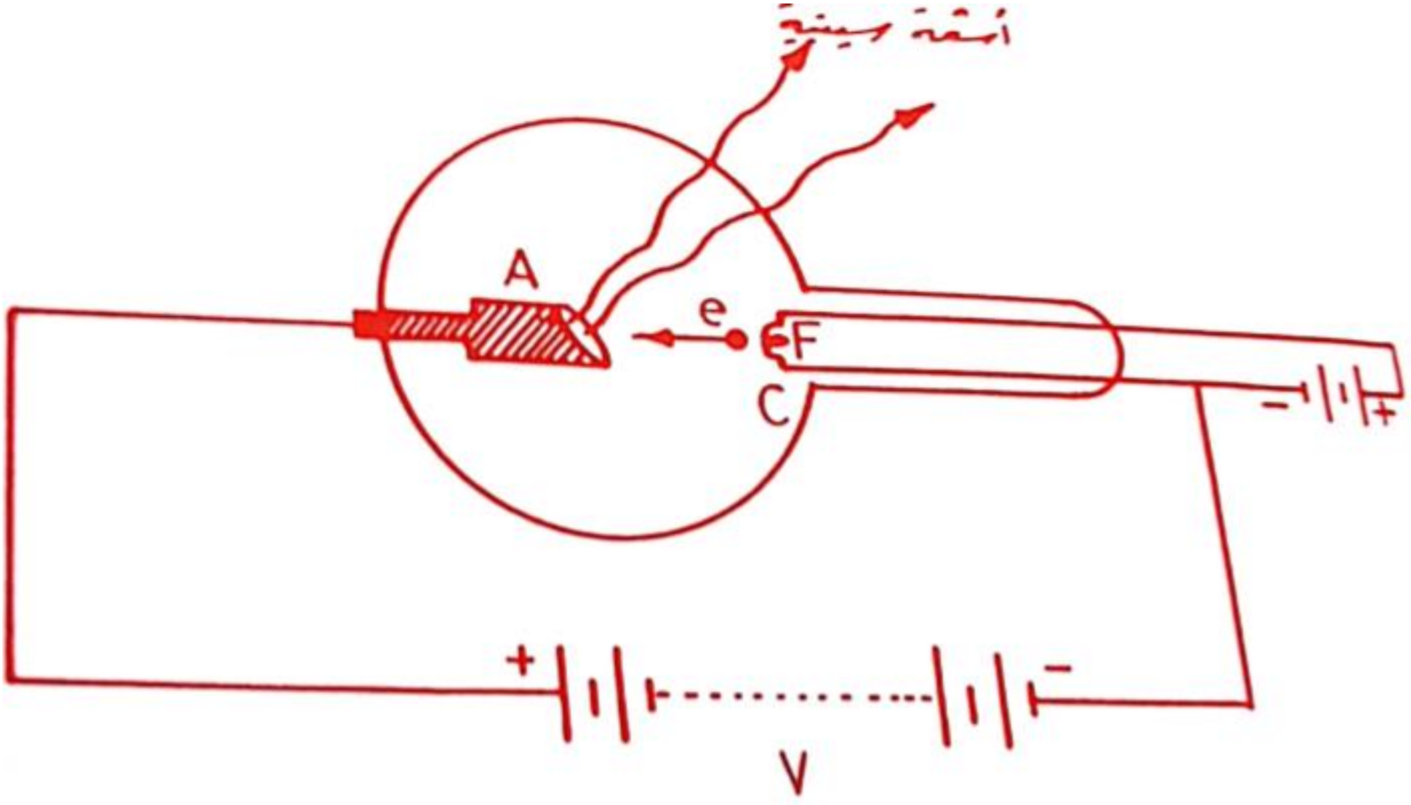
The Quantum Theory of Light النظرية الكمية للضوء

يتكون طيف هذه الإشعاعات الناتجة من طيف مستمر وطيف خطي كما في الشكل المجاور.



الطيف المستمر لشدة الإشعاعات السينية المنبعثة من تصادم الإلكترون المعجل مع هدف معدني ثقيـــــل ، ويبين الشكل القمم المميزة للعنصر على شكل طيف خطي (K_α, K_β) ، وأقل طول موجي λ_o الذي يبدأ عنده الطيف المستمر.

❑ إنتاج الأشعة السينية



شكل تخطيطى لجهاز إنتاج الأشعة السينية

The Quantum Theory of Light النظرية الكمية للضوء

الطاقة الحركية للإلكترون المعجل:

$$K = eV$$

$$eV = hf_0 = \frac{hc}{\lambda_0} \Rightarrow \lambda_0 = \frac{hc}{eV} = \frac{1.24\times10^{-6}}{V}\,meter$$

حيث λo الطول الموجي لبداية الطيف المستمر وهو يعتمد فقط على الجهد المستعمل لتعجيل الالكترون.

الطول الموجي للفوتون المنبعث:

$$\frac{1}{\lambda} = \mathrm{RZ}^2\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right)$$

$$K_\alpha (2 \to 1)$$

$$K_\beta (3 \to 1)$$

$$\lambda_{k_\alpha} \rangle \lambda_{k_\beta}$$

لقد وجد تجريبيا أن طول موجة الخط المميز Kα لذرة عديدة الإلكترونات يمكن معرفته من العلاقة:

$$\frac{1}{\lambda_\alpha} = RZ_{\text{eff}}^2 \left(\frac{1}{1^2} - \frac{1}{2^2}\right) = \frac{3}{4} RZ_{\text{eff}}^2$$

$$, Z_{\text{eff}} = Z - 1$$

حيث Zeff العدد الذري الفعال للعنصر المستعمل كهدف.

حيث أن الإلكترون العائد إلى المستوى الأول (K) يجد إلكترونا سالبا واحدا في نفس المستوى فتكون الشحنة الكلية هي مجموع شحنة النواة الموجبة Ze وشحنة الالكترون السالب e-. وبالتالي الشحنة الكلية:

$$Ze - e = (Z - 1)e$$

Transition Probabilities of Atoms and Molecules

Stimulated Emission and Lasers

Laser:

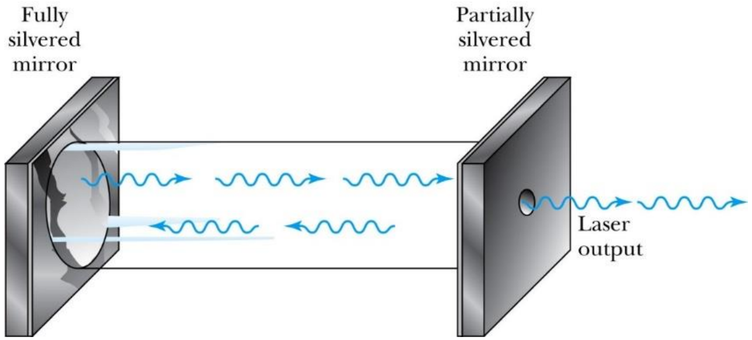
- An acronym for “light amplification by the stimulated emission of radiation”

Masers:

- Microwaves are used instead of visible light.

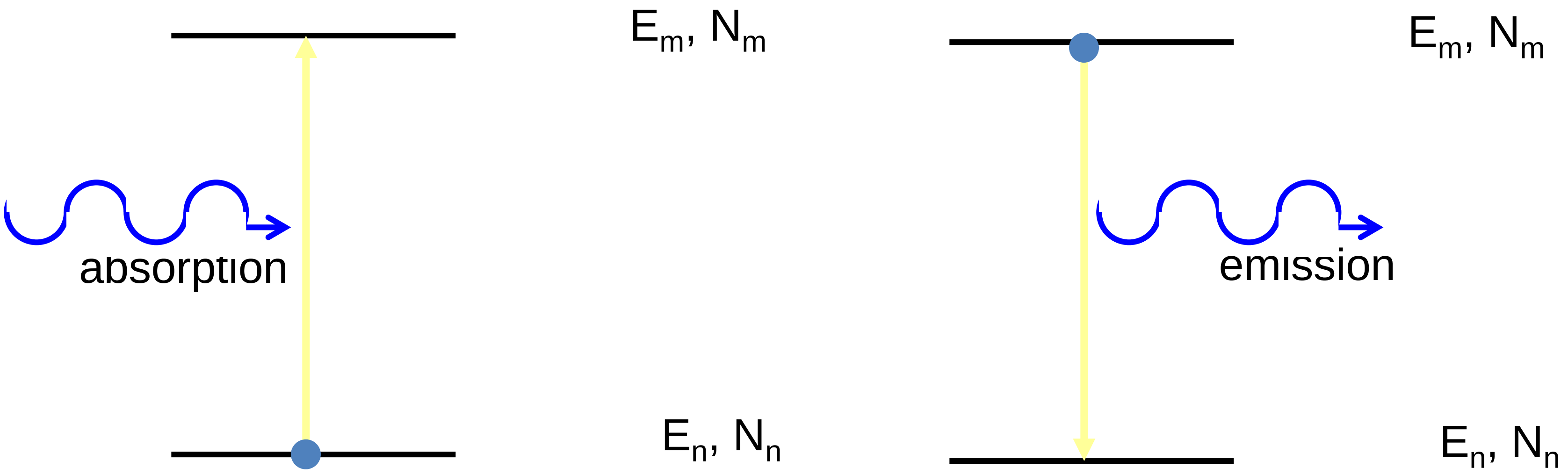
- The first working laser by Theodore H. Maiman in 1960

helium-neon laser



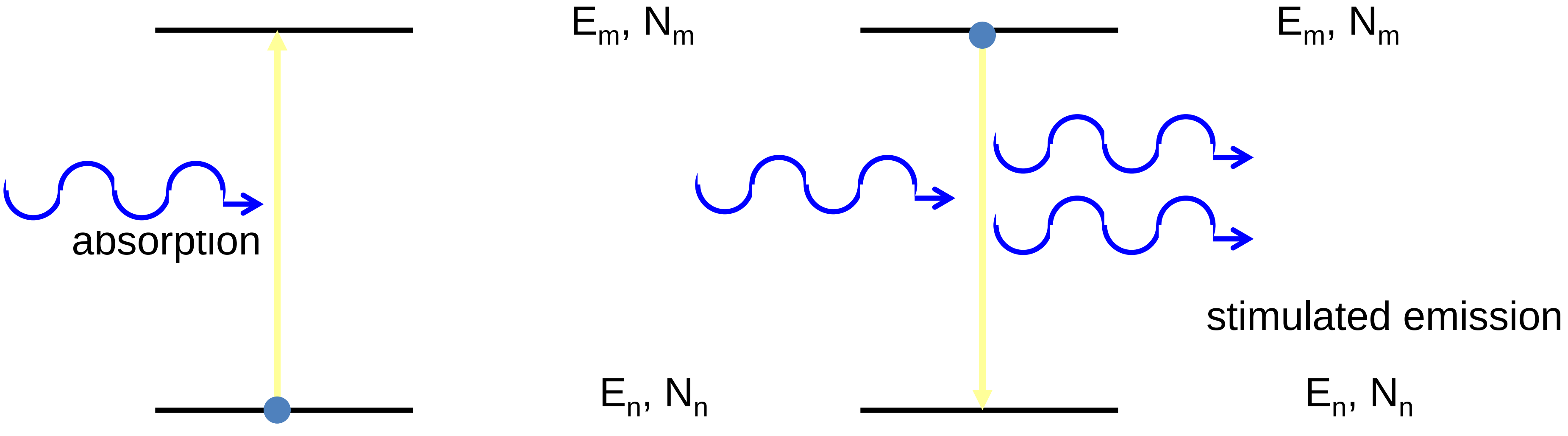
Absorption and Spontaneous Emission

Consider a two-level system



Light from bulbs are due to spontaneous emission

Absorption and Stimulated Emission



E_m, N_m

absorption

E_n, N_n

E_m, N_m

stimulated emission

E_n, N_n

Laser light results from stimulated emission

Stimulated vs Spontaneous Emission

Stimulated emission requires the presence of a photon. An “incoming” photon stimulates a molecule in an excited state to decay to the ground state by emitting a photon. The stimulated photons travel in the same direction as the incoming photon.

Spontaneous emission does not require the presence of a photon. Instead a molecule in the excited state can relax to the ground state by spontaneously emitting a photon. Spontaneously emitted photons are emitted in all directions.

When light travels through an absorbing medium, the medium absorbs the light; the amount of light absorbed is determined by Beer’s Law.

For a medium to operate as a lasing medium, the transmitted light intensity should be greater than the intensity of light incident on the material.

When an atom or molecule in the lasing medium absorbs light it is excited

The excited molecule then decays to a lower level either through emission of a photon (stimulated or spontaneous) or via a non-radiative loss of the energy.

For lasing action, stimulated emission must dominate.

As determined by the Boltzmann factor, the population of the ground state > population of excited state.

Hence, typically absorption dominates.

For stimualted emission to be the dominant process, the excited state population must be larger than the lower state population.

In other words, for a medium to produce laser light, there must be a “population inversion” where $N_{upper} > N_{lower}$

How can a population inversion be created when the population in the ground state is always greater that the population in the excited state?

What kinds of materials will “allow” for an inversion of population in its electronic states?

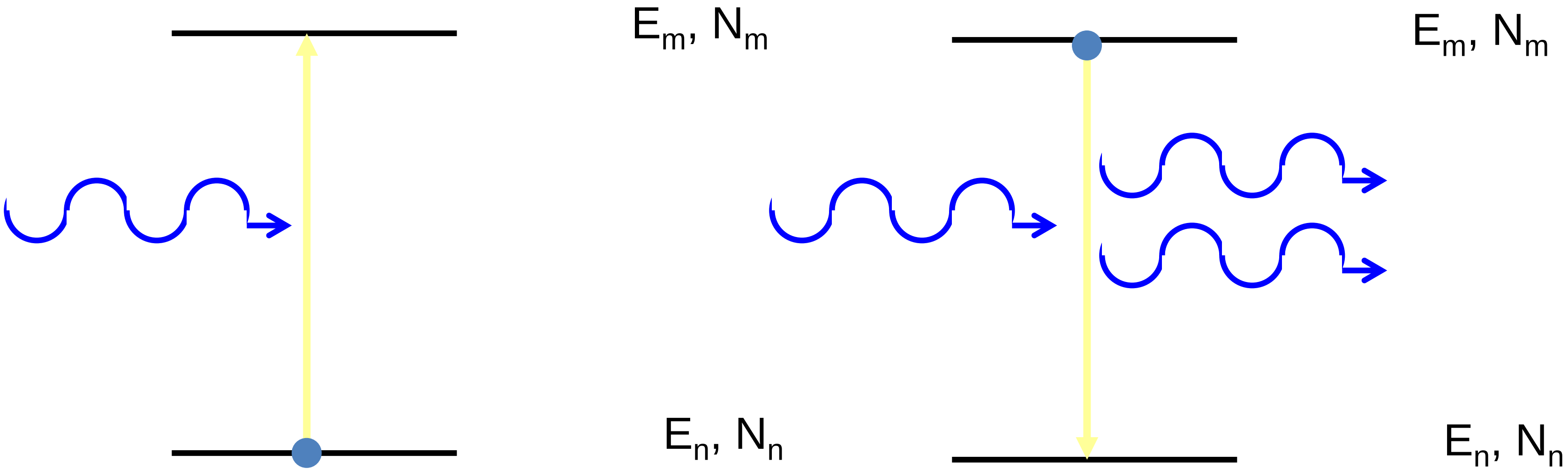
How can a population inversion be created?

By excitation of the lasing atoms or molecules - this is called PUMPING.

If the pump source is very intense, the number of atoms or molecules excited can be large.

However, once excited, the atoms and molecules must say in the excited state long enough to create an excited population > ground state population

Two-Level System

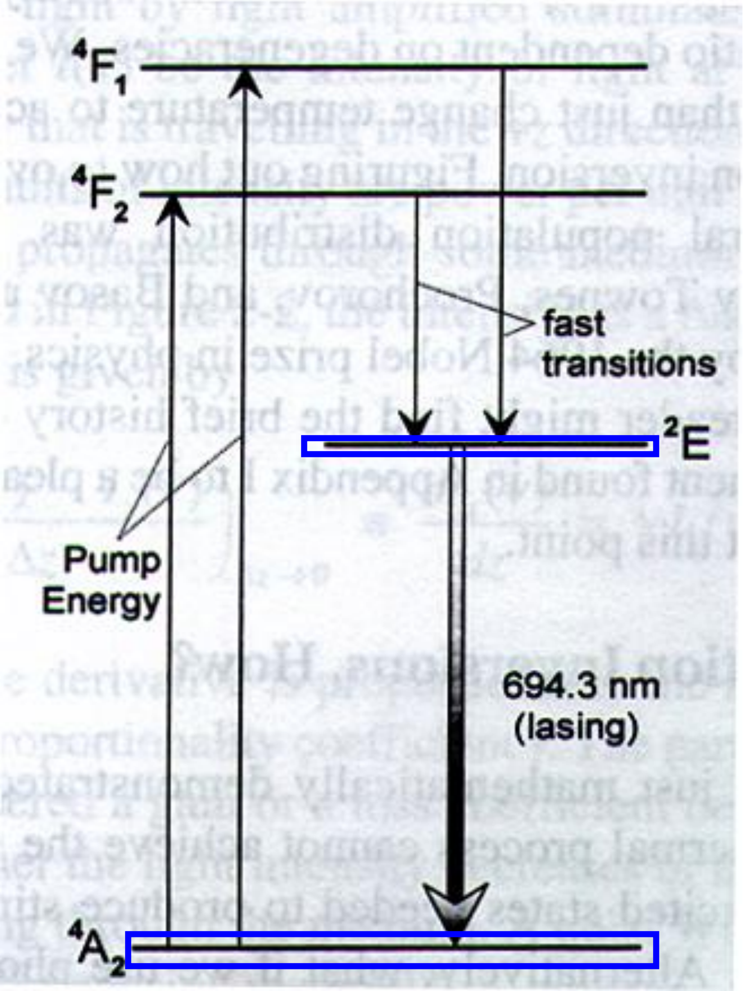


Even with very a intense pump source, the best one can achieve with a two-level system is

excited state population = ground state population

Three-Level System

The first laser, the ruby laser, was a three-level system



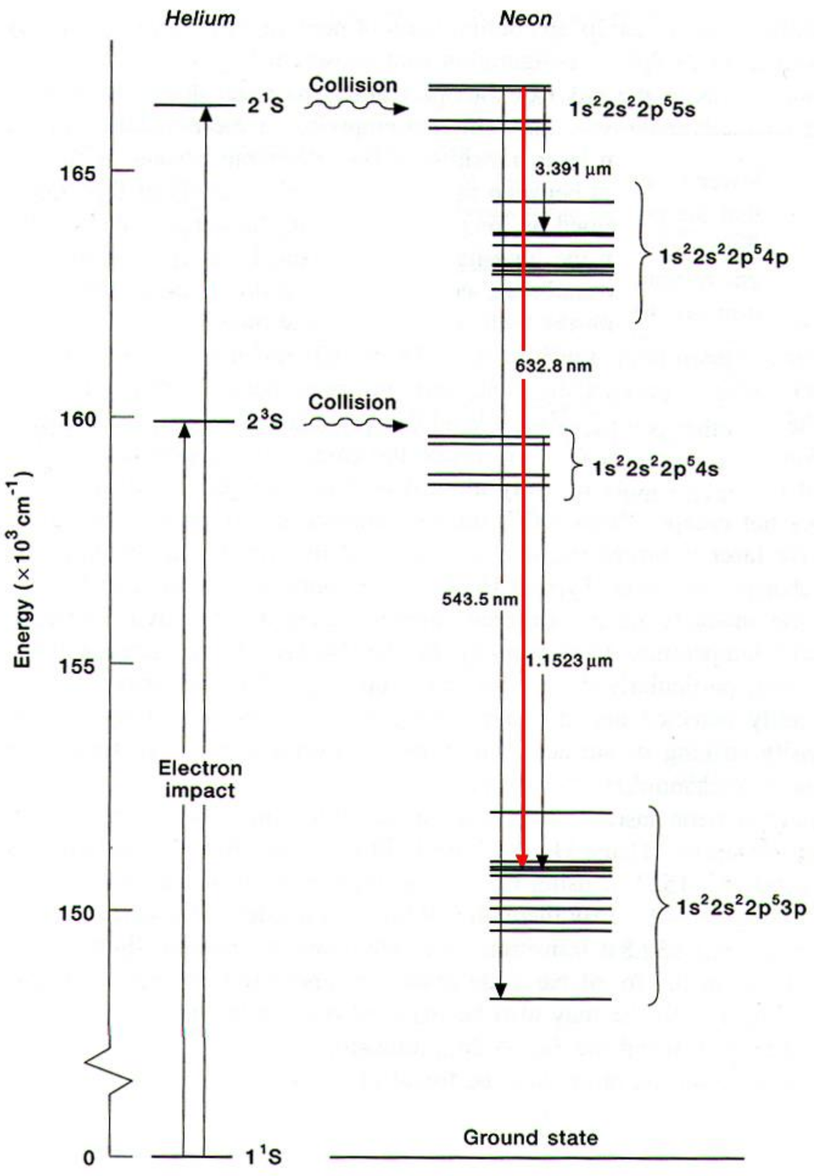
upper lasing state

lower lasing state

Laser light due to transition from ^2E state to $^4A_2$ state

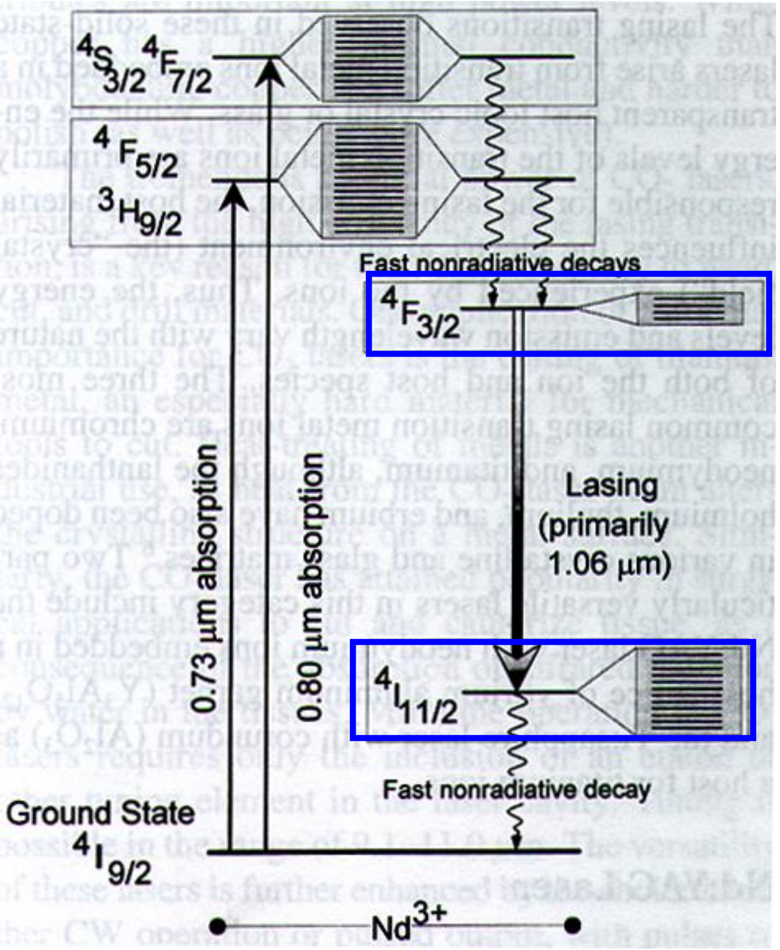
Four-Level System

He-Ne laser



Four-Level System

Nd:YAG laser

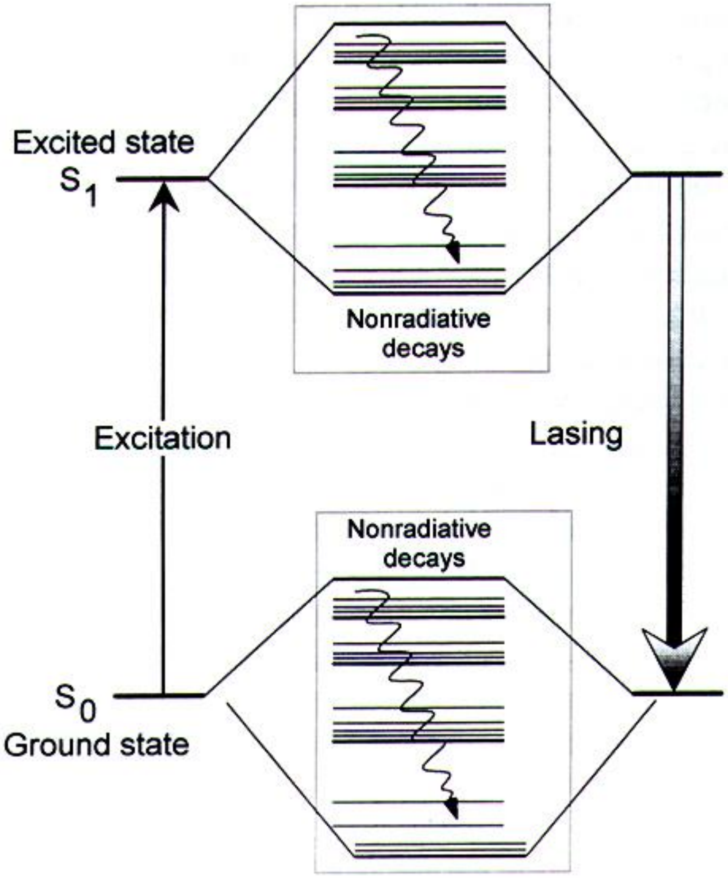


upper laser state

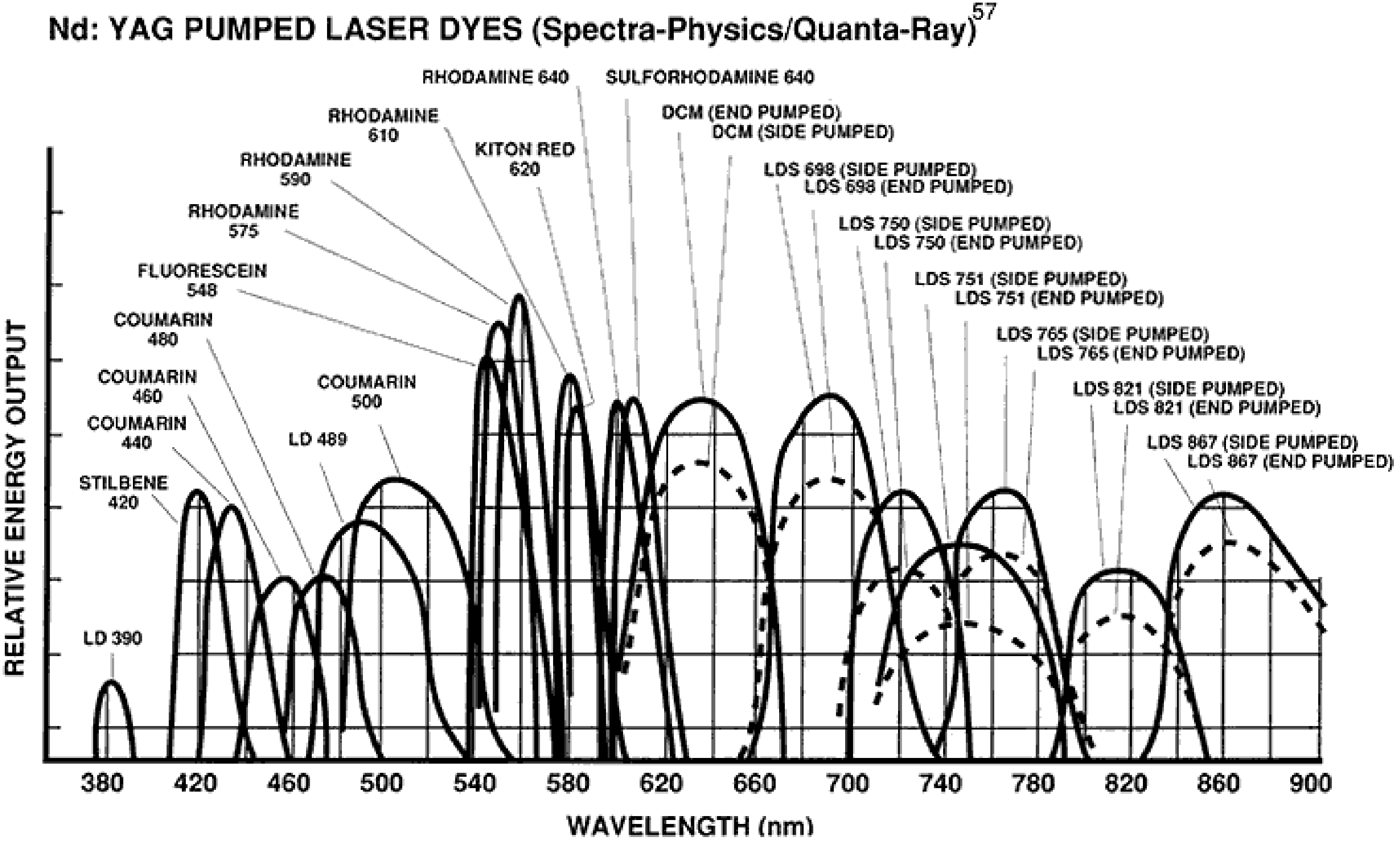
lower laser state

Laser light due to transition from ^{4}F to ^{4}I

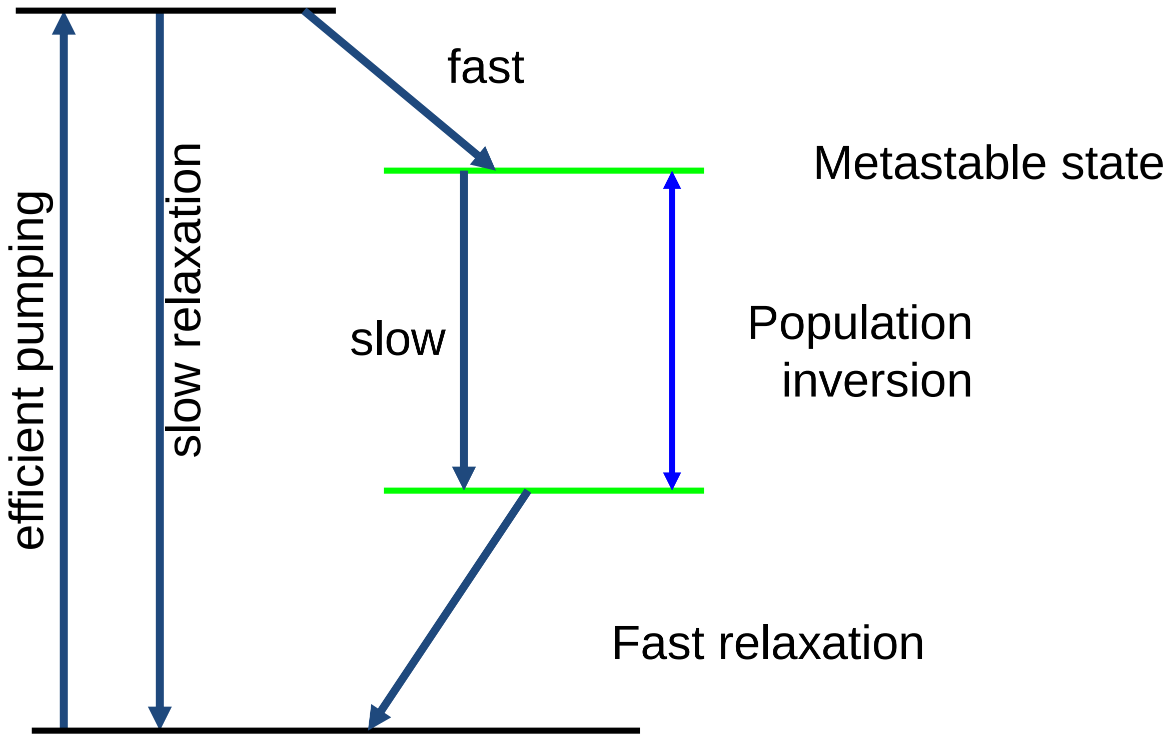
Dye Lasers: Four-level systems



Dye Tuning Curves

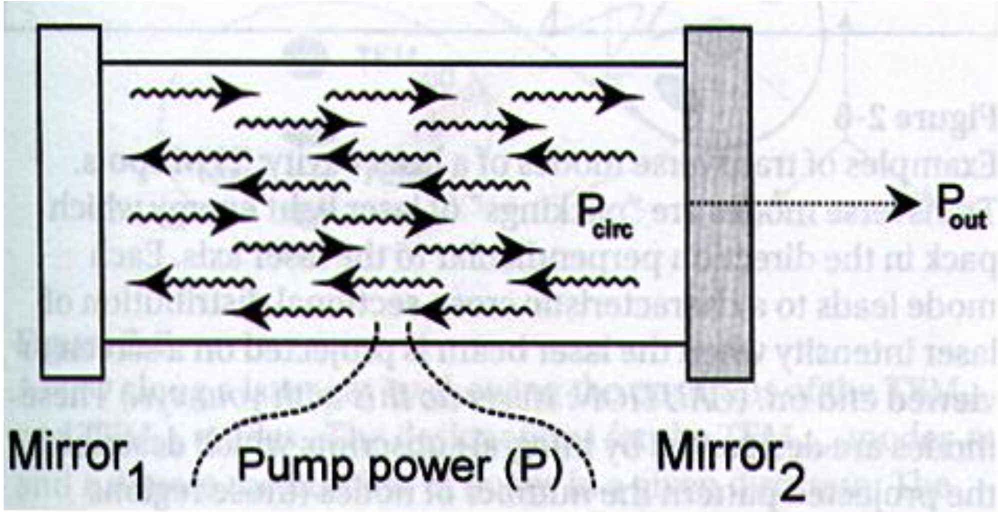

Nd: YAG PUMPED LASER DYES (Spectra-Physics/Quanta-Ray)[57]

Requirements for Laser Action



Light Amplification

Create a laser cavity, which consists of the lasing medium and two highly reflective mirrors.



Continuous vs Pulsed Lasers

Excitation of the lasing atoms or molecules is by using external sources of light, examples flashlamps or another laser - PUMPING

The output of the laser light can be a continuous wave (cw) if the pumping is continuous or pulsed if the pumping is pulsed.

Pulsed lasers have very high intensities because the laser intensity is concentrated in a very short time duration.

Lasers in Chemistry

Lasers being monochromatic, with short pulse durations, and high intensity allow detailed studies in chemical dynamics.

Can do very fast kinetic studies – femtosec (10^{-15} s) studies – “look” at bond dissociation, bond formation, study kinetics in the liquid phase

Spectroscopy – monochromaticity allows detailed information on small molecules

High intensity – allows investigation of processes which which depend on light intensity and have very small probabilities of occuring e.g. Raman scattering

Thank You

ACKNOWLEDGEMENTS