“Modern” Physics

2nd Edition Chapts. 25, 38

3rd Edition Chapt. 37

Classical Physics

Newton's laws of motion + Maxwell's equations

Basically this is what you have learned so far and it does a good job explaining many things.

Things it can not explain:

- Existence of atoms
- Discrete spectra of atoms
- The spectrum of radiation from hot bodies
- Photo-electric effect (photons)
- Diffraction of electrons

Classical physics was thought to describe the interaction of light with charges until there were discovered too many things that it could not explain.

Quantum Mechanics:

Basic Idea

Sometimes particles of matter behave as if they were some kind of wave.

Sometimes electromagnetic waves (light) behave as if they were composed of particles (photons)

Features

Quantities that in classical physics are continuous variables, are only allowed to have certain values, **"quantized"**

Probability is introduced. We can no longer say what will happen in a set of circumstances, rather we can say what are the probabilities of various things happening.

Classical Physics

Maxwell's Equations

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q_{in}}{\varepsilon_0}$$

$$\oint_{loop} \vec{\mathbf{E}} \cdot d\vec{\mathbf{S}} == -\frac{d}{dt} \int_{Surface} \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}}$$

$$\oint \vec{\mathbf{B}}(\vec{\mathbf{r}}) \cdot d\vec{\mathbf{s}} = \mu_0 (I_{through} + \varepsilon_0 \frac{d}{dt} \int_{surface} \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}})$$

E, B

Q_{in}, I_{thr}

Newton's Laws

$$m \frac{d}{dt} \vec{\mathbf{v}}_{\mathbf{i}} = q\left(\vec{\mathbf{E}} + \vec{\mathbf{v}}_{\mathbf{i}} \times \vec{\mathbf{B}}\right)$$

$$\frac{d}{dt} \vec{\mathbf{x}}_{\mathbf{i}} = \vec{\mathbf{v}}_{\mathbf{i}}$$

$$Q_{in} = \sum_i q_i$$

$$I_{through} \vec{\mathbf{L}} = \sum_i q_i \vec{\mathbf{v}}_{\mathbf{i}}$$

Classical Physics

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Some History Chapter 38

1820’s **Faraday** - Atoms exist, charge is associated with atoms, light from heated gases has characteristic colors.

1880’s **Balmer** - Simple formula predicts the colors seen in a glowing gas.

1890’s **Thomson** - Electrons are a fundamental particle, determined q/m

1900 **Planck** - Spectrum of Black Body Radiation can be explained if energy is quantized.

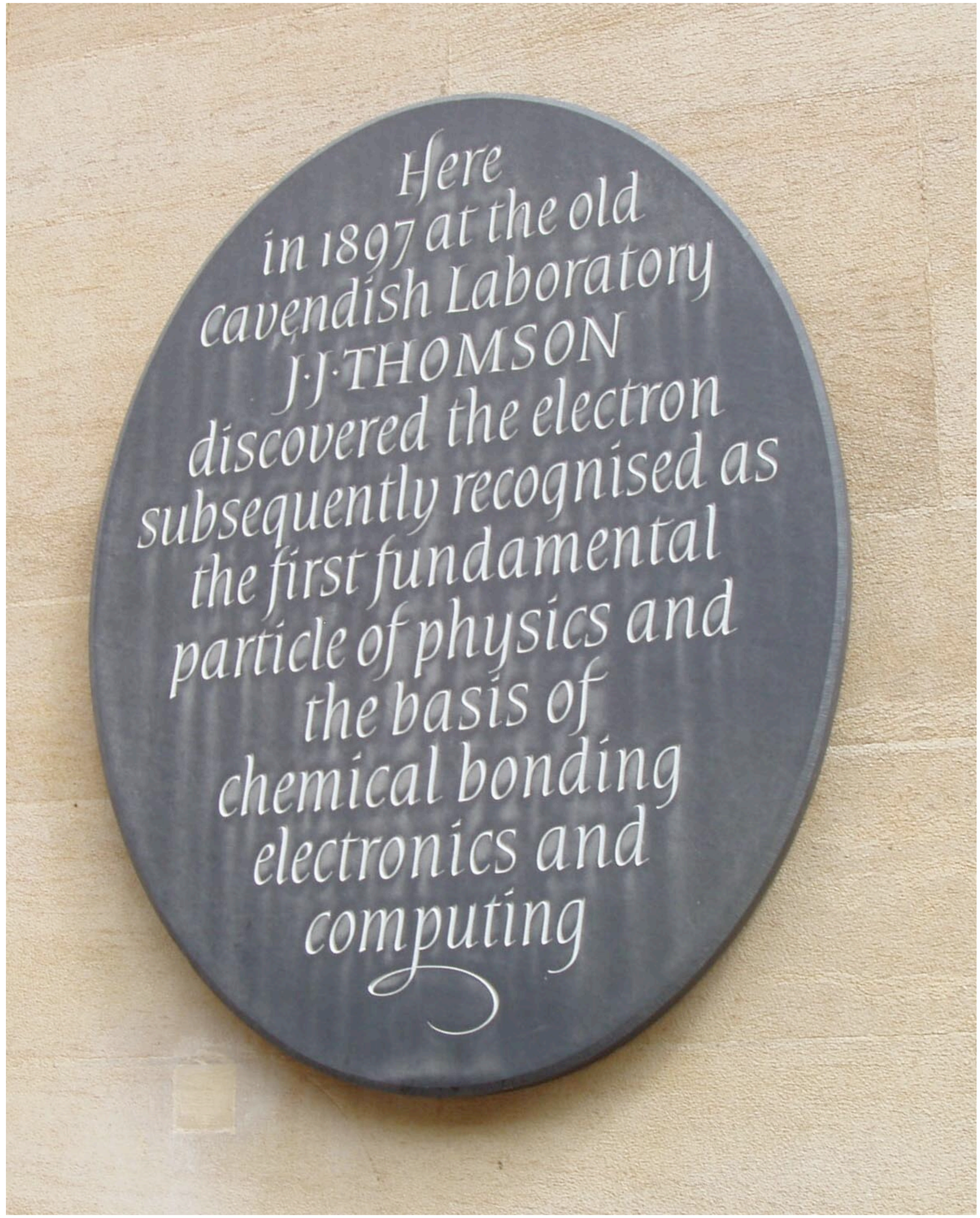
1905 **Einstein** - Explained photo-electric effect by proposing EM waves are quantized.

1909‘s **Rutherford** - Atom is mostly empty space (nucleus is small)

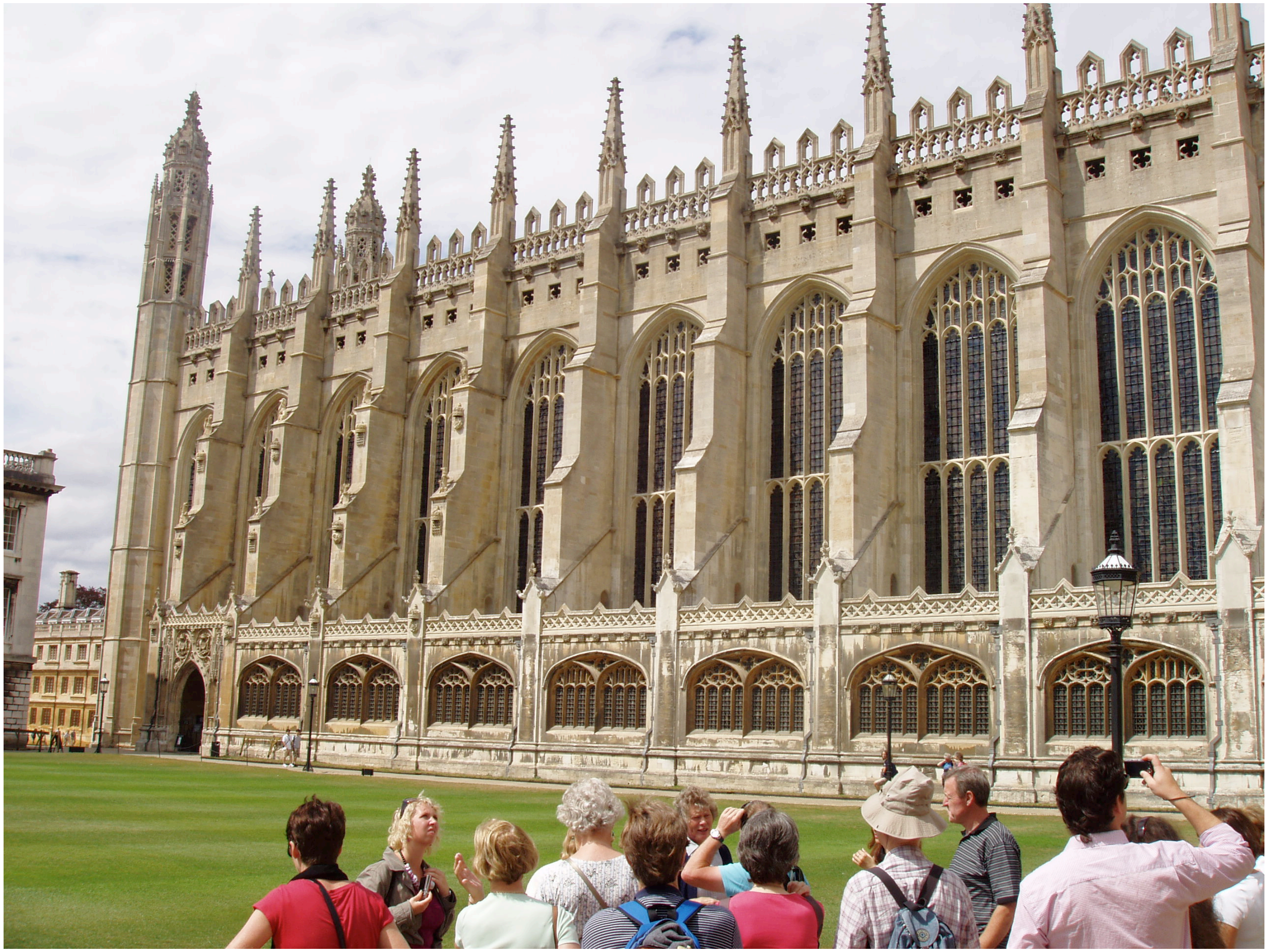
1913 **Bohr** - Electron energy in an atom is quantized (explains Balmer series)

1924 **de Broglie** - Matter is waves. Wavelength related to momentum

Old Cavendish Laboratory



King’s College



Punting on the Cam

Quantum Mechanics:

Basic Idea

Sometimes electromagnetic waves (light) behave as if they were composed of particles.

Photons $$E = hf$$

Sometimes particles of matter behave as if they were some kind of wave.

de Broglie Waves $$\lambda = \frac{h}{p}$$

h = Planck's Constant = 6.63 x 10^{-34} J s

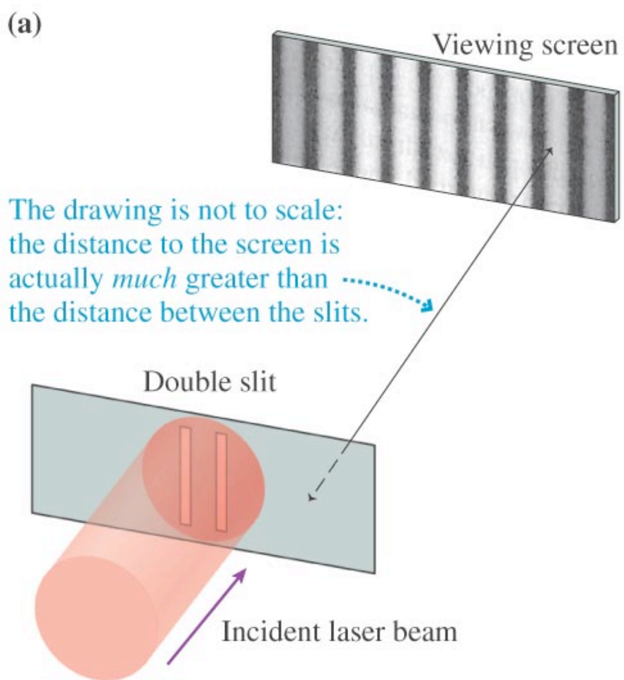
Einstein's Postulates

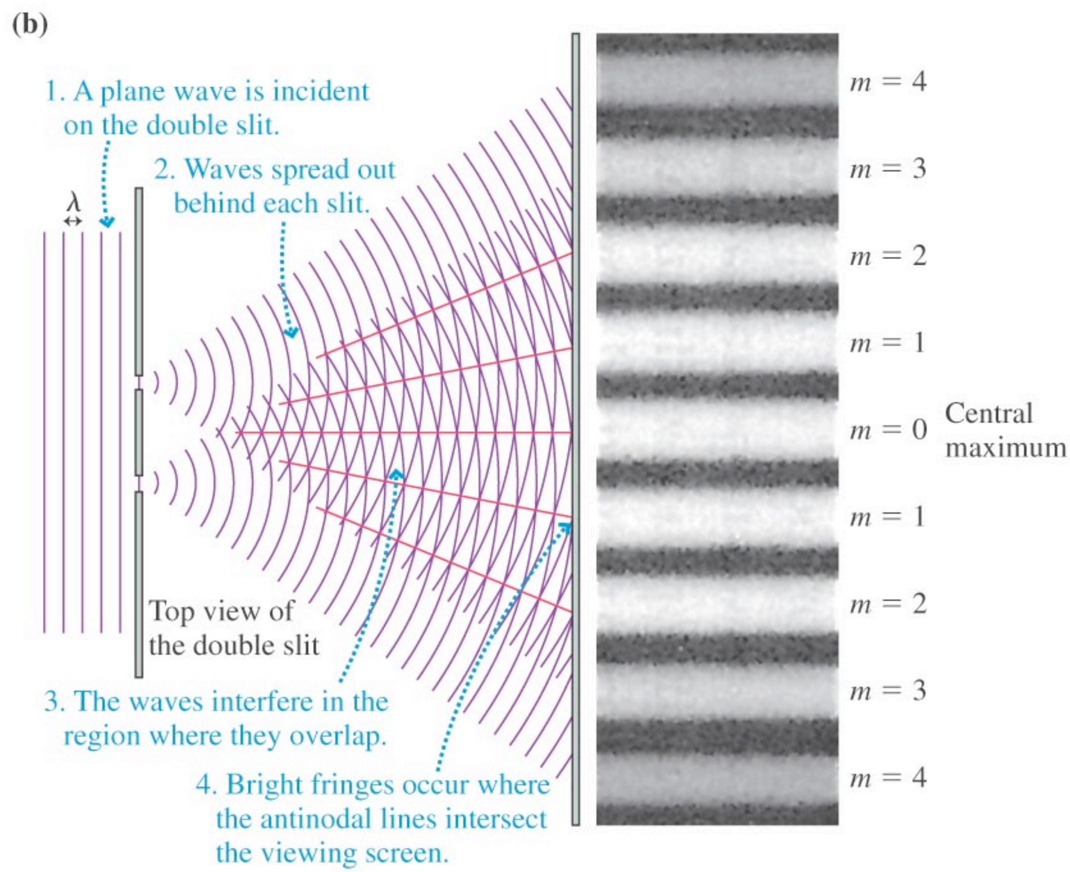
Einstein framed three postulates about light quanta and their interaction with matter:

1. Light of frequency *f* consists of discrete quanta, each of energy $E = hf$, where h is Planck's constant $h = 6.63 \times 10^{-34}$ J s. Each photon travels at the speed of light $c = 3.00 \times 10^{8}$ m/s.
2. Light quanta are emitted or absorbed on an all-or-nothing basis. A substance can emit 1 or 2 or 3 quanta, but not 1.5. Similarly, an electron in a metal can absorb only an integer number of quanta.
3. A light quantum, when absorbed by a metal, delivers its entire energy to *one* electron.

Interference of light
Double Slit experiment

Coherence because sources are at exactly the same frequency





Puzzle: When it hits the screen it acts like a particle, but somehow it went through both slits.

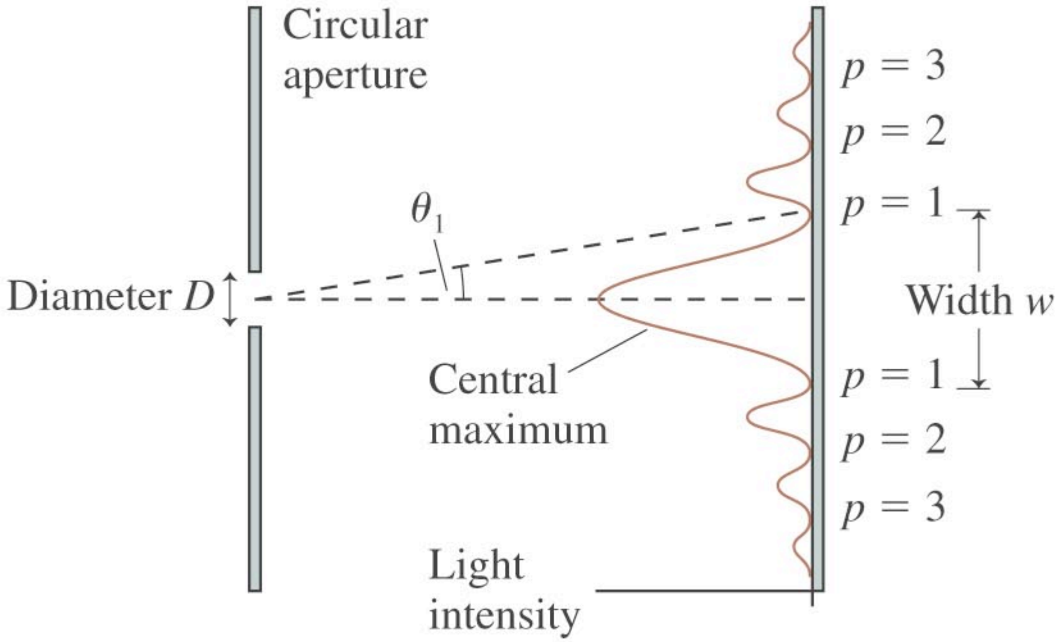
The de Broglie Wavelength

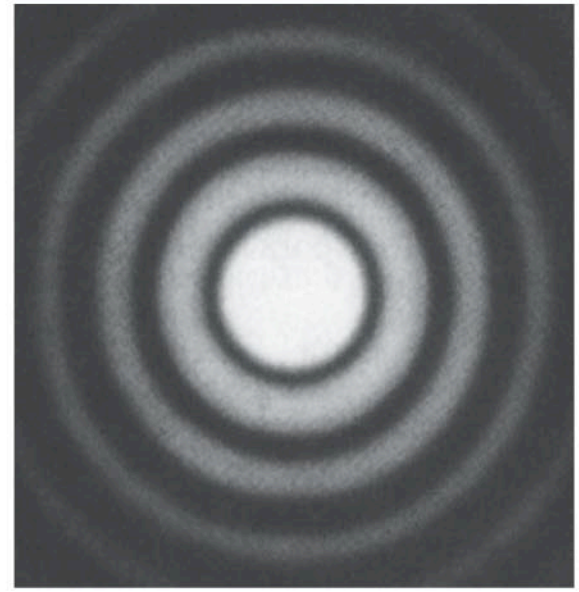
De Broglie postulated that a particle of mass *m* and momentum $p = mv$ has a wavelength

$$\lambda = \frac{h}{p}$$

where *h* is Planck's constant. This wavelength for material particles is now called the **de Broglie wavelength.** It depends *inversely* on the particle's momentum, so the largest wave effects will occur for particles having the smallest momentum.

Circular aperture diffraction





Width of central maximum

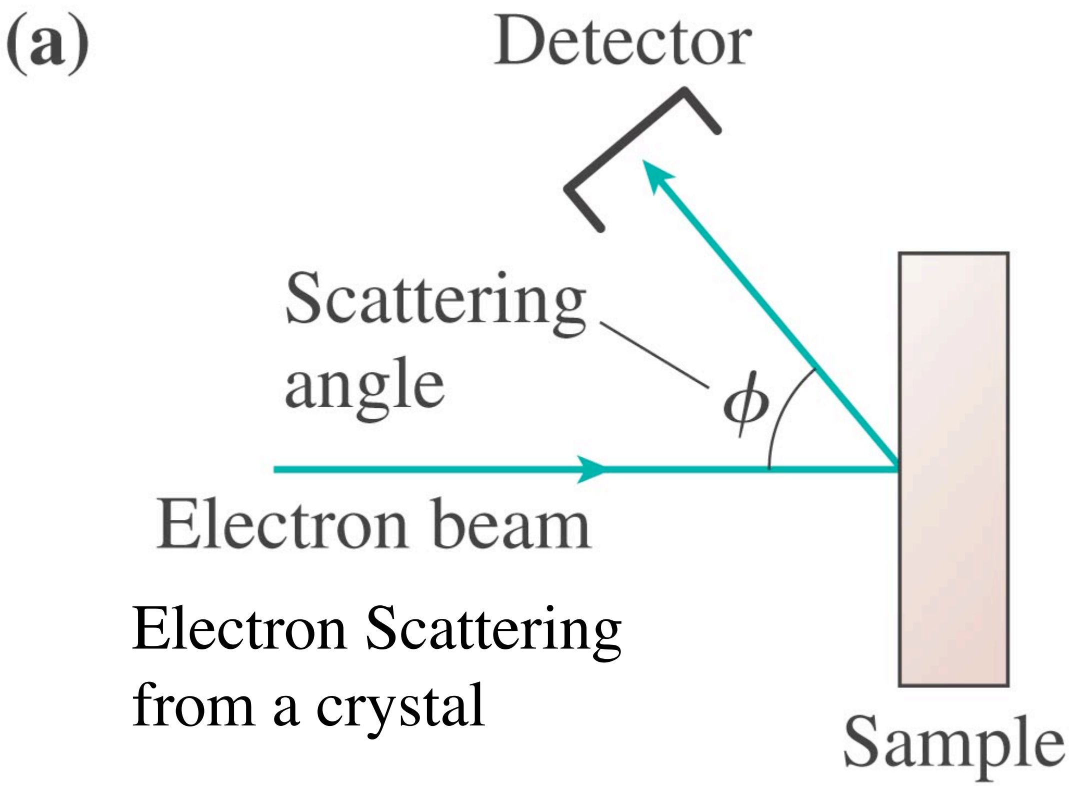
$$\frac{w}{L} = \frac{2.44\lambda}{D}$$

assumes D << w

Matter Waves

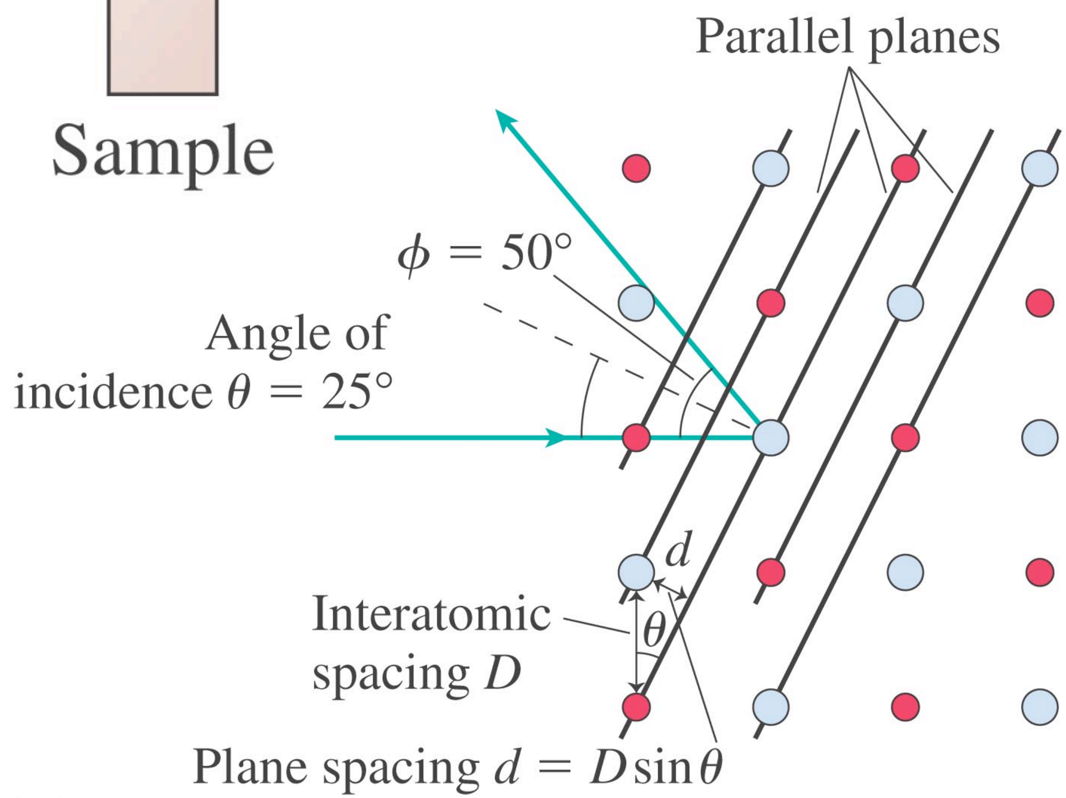
- In 1927 Davisson and Germer were studying how electrons scatter from the surface of metals.
- They found that electrons incident normal to the crystal face at a speed of 4.35×10^6 m/s scattered at $\phi = 50°$.
- This scattering can be interpreted as a mirror-like reflection from the atomic planes that slice diagonally through the crystal.
- The angle of incidence on this set of planes is the angle θ_m in $2d \cos \theta_m = m\lambda$, the Bragg condition for diffraction.
- Davisson and Germer found that the "electron wavelength" was

$$\lambda = D\sin(2\theta) = 0.165 \text{ nm}$$



Electron Scattering from a crystal

According to classical physics one would expect the detected signal to depend smoothly on angle.
Instead peaks were observed at specific angles.



Angle of incidence on plane θ

Separation of planes $d = D\sin\theta$

Strong reflection when

$$2d\cos\theta = \lambda$$

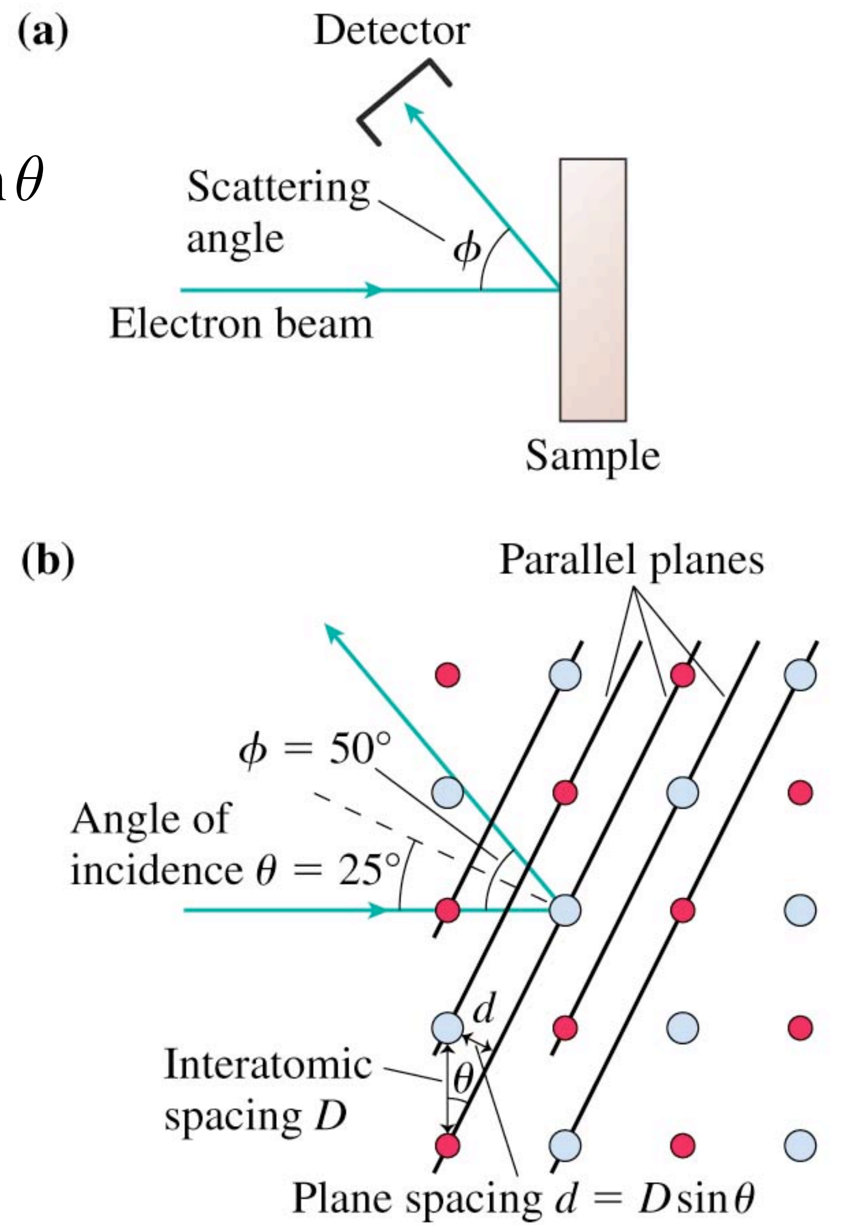
(m=1 Bragg condition)

Combining

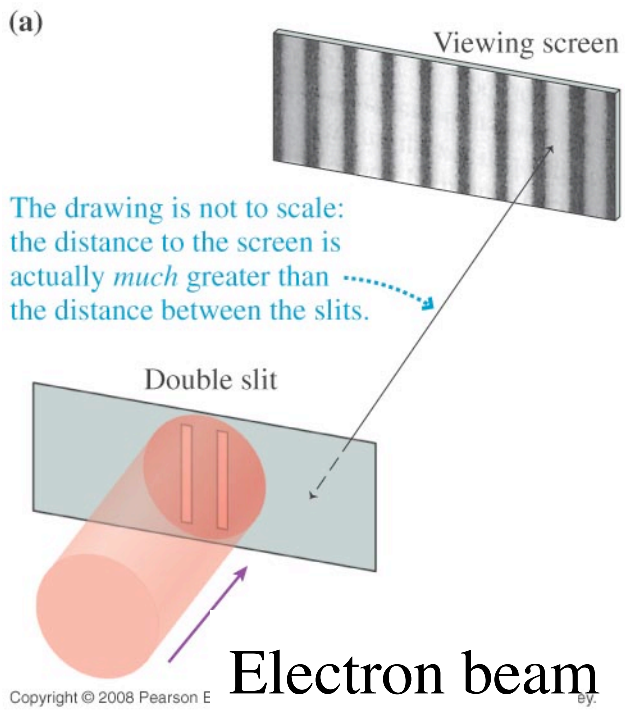
$$2D\sin\theta\cos\theta = D\sin 2\theta = \lambda$$

$$\lambda = D\sin(2\theta) = 0.165 \text{ nm}$$

FIGURE 25.11 The Davisson-Germer experiment to study electrons scattered from metal surfaces.

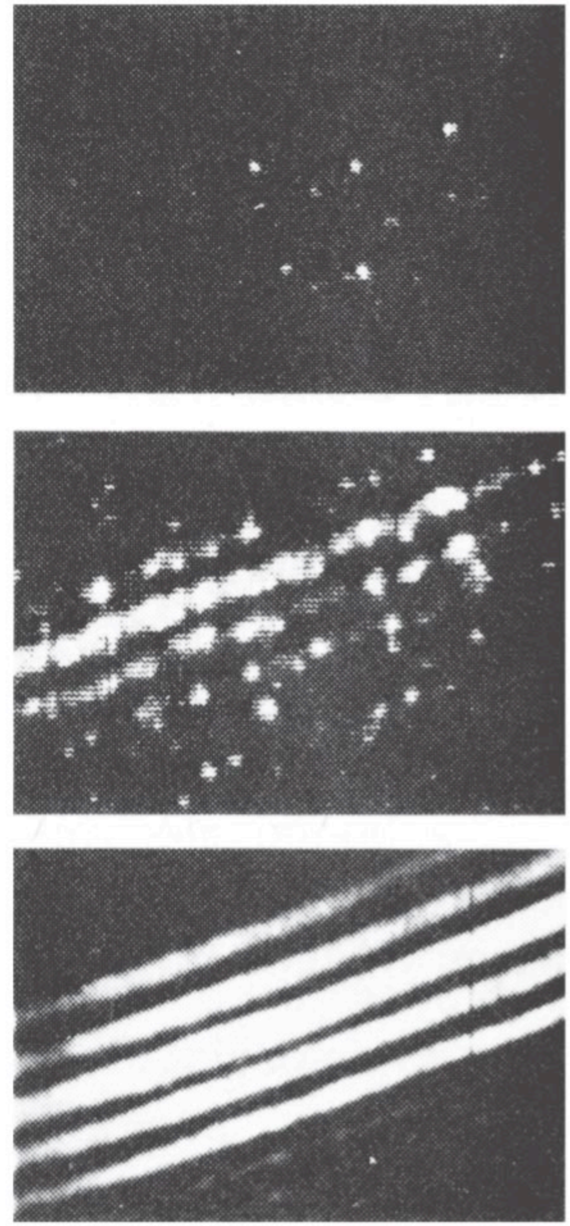


Diffraction of Matter



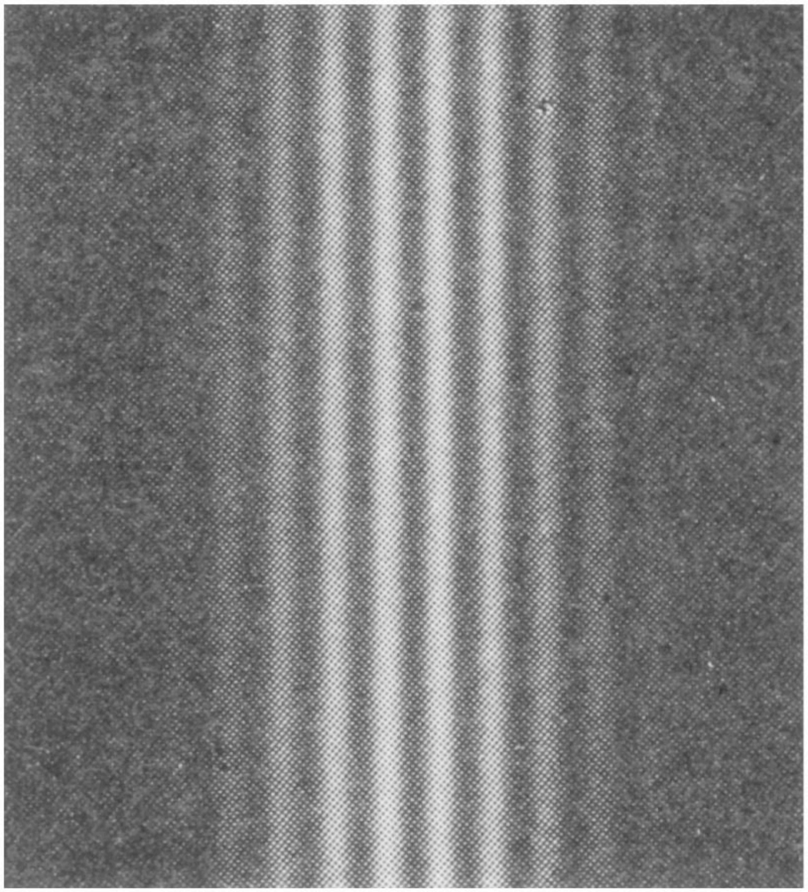
Electron beam

Electrons arrive one by one. Hitting the screen at discrete points. But over time a diffraction pattern is built up!

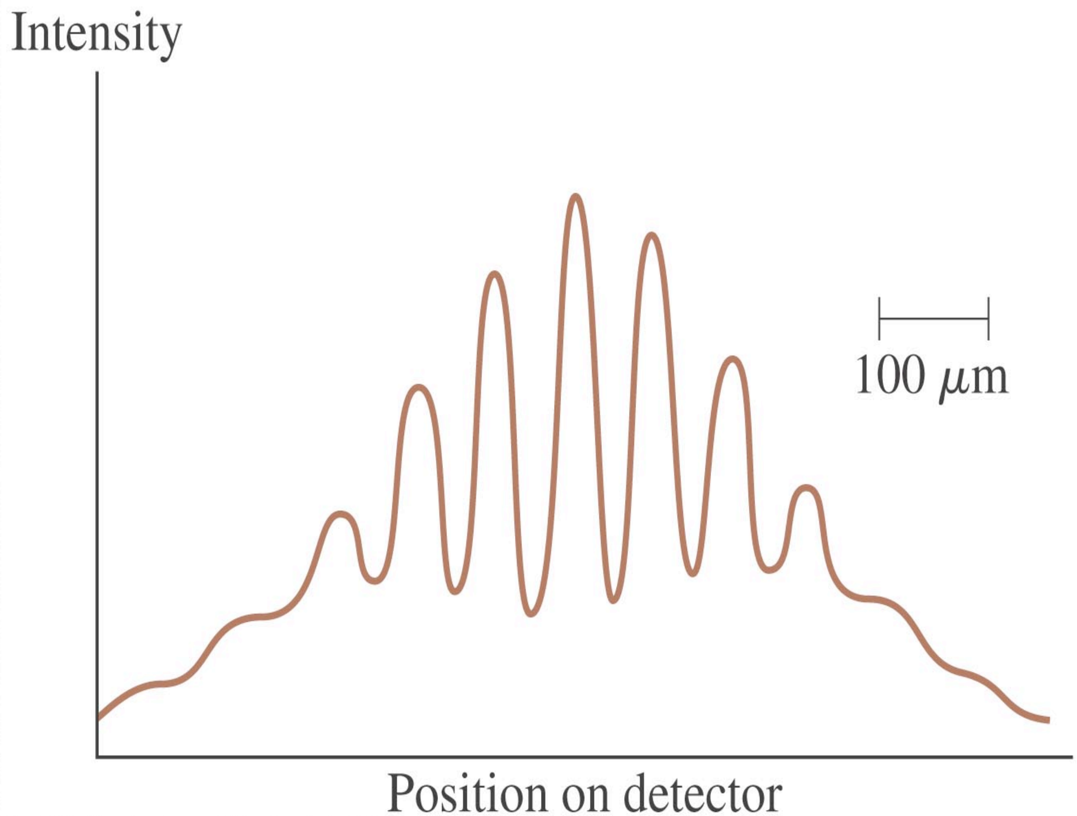


Puzzle: When it hits the screen it acts like a particle, but somehow it went through both slits.

(a) Double-slit interference of electrons



(b) Double-slit interference of neutrons



A proton, an electron and an oxygen atom each pass at the same speed through a 1-μm-wide slit. Which will produce a wider diffraction pattern on a detector behind the slit?

Width of central maximum

$$\frac{w}{L} = \frac{2.44\lambda}{D}$$

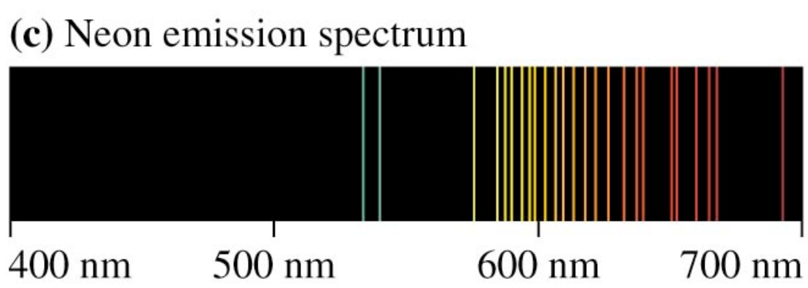
$$\lambda = \frac{h}{p}$$

A. The oxygen atom.
B. The proton.
C. The electron.
D. All three will be the same.
E. None of them will produce a diffraction pattern.

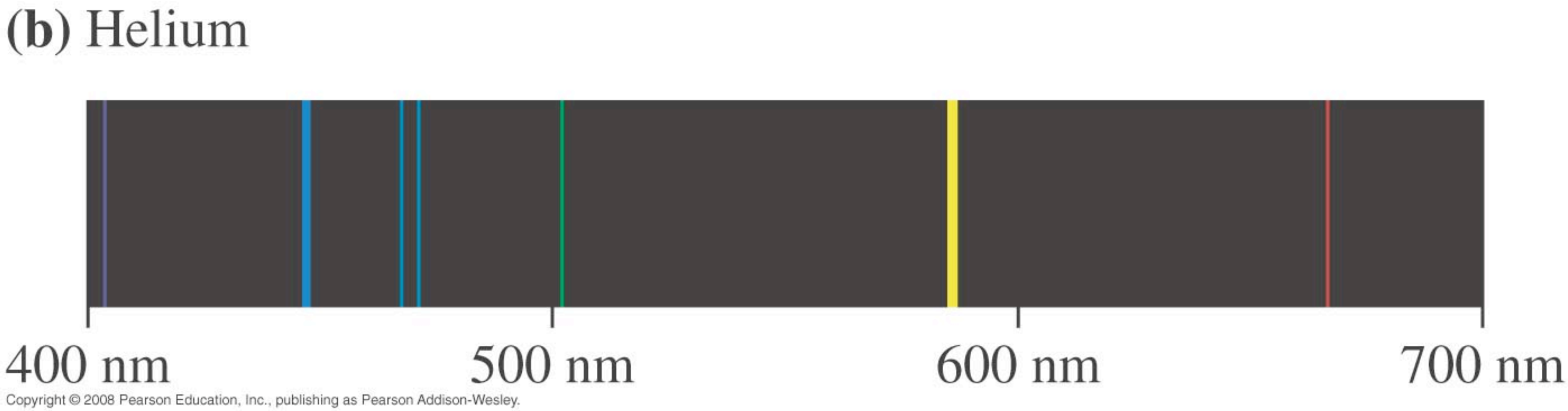
The Emission of Light

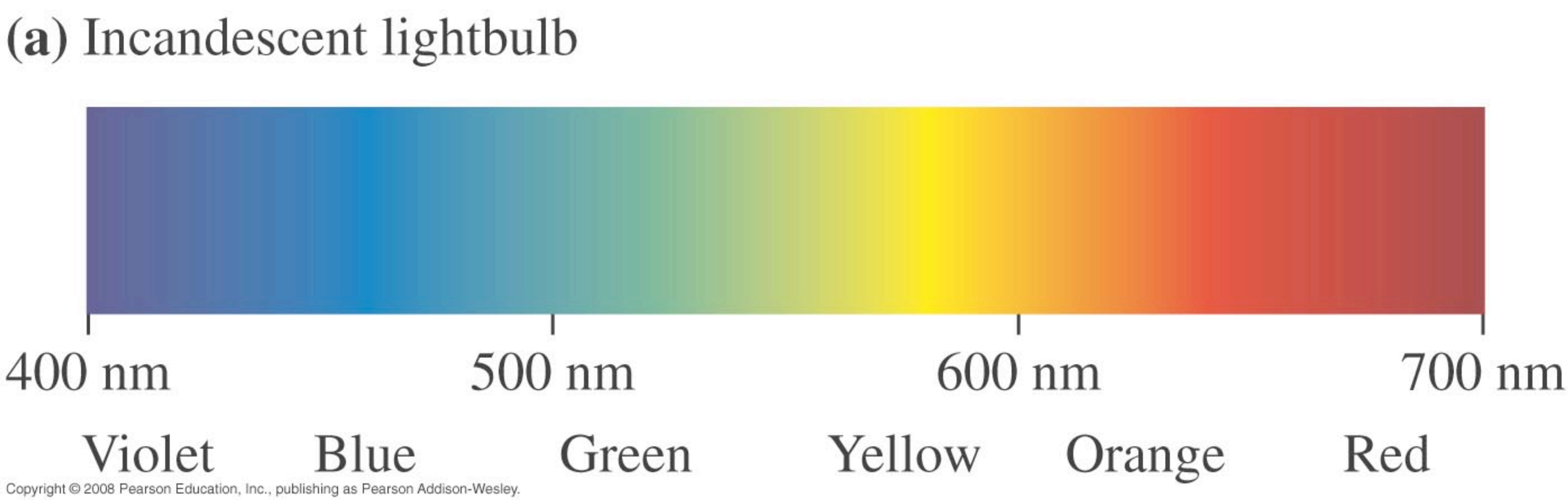
The light emitted by one of Faraday's gas discharge tubes contains only certain discrete, individual wavelengths. Such a spectrum is called a **discrete spectrum.** Each wavelength in a discrete spectrum is called a **spectral line** because of its appearance in photographs such as the one shown.

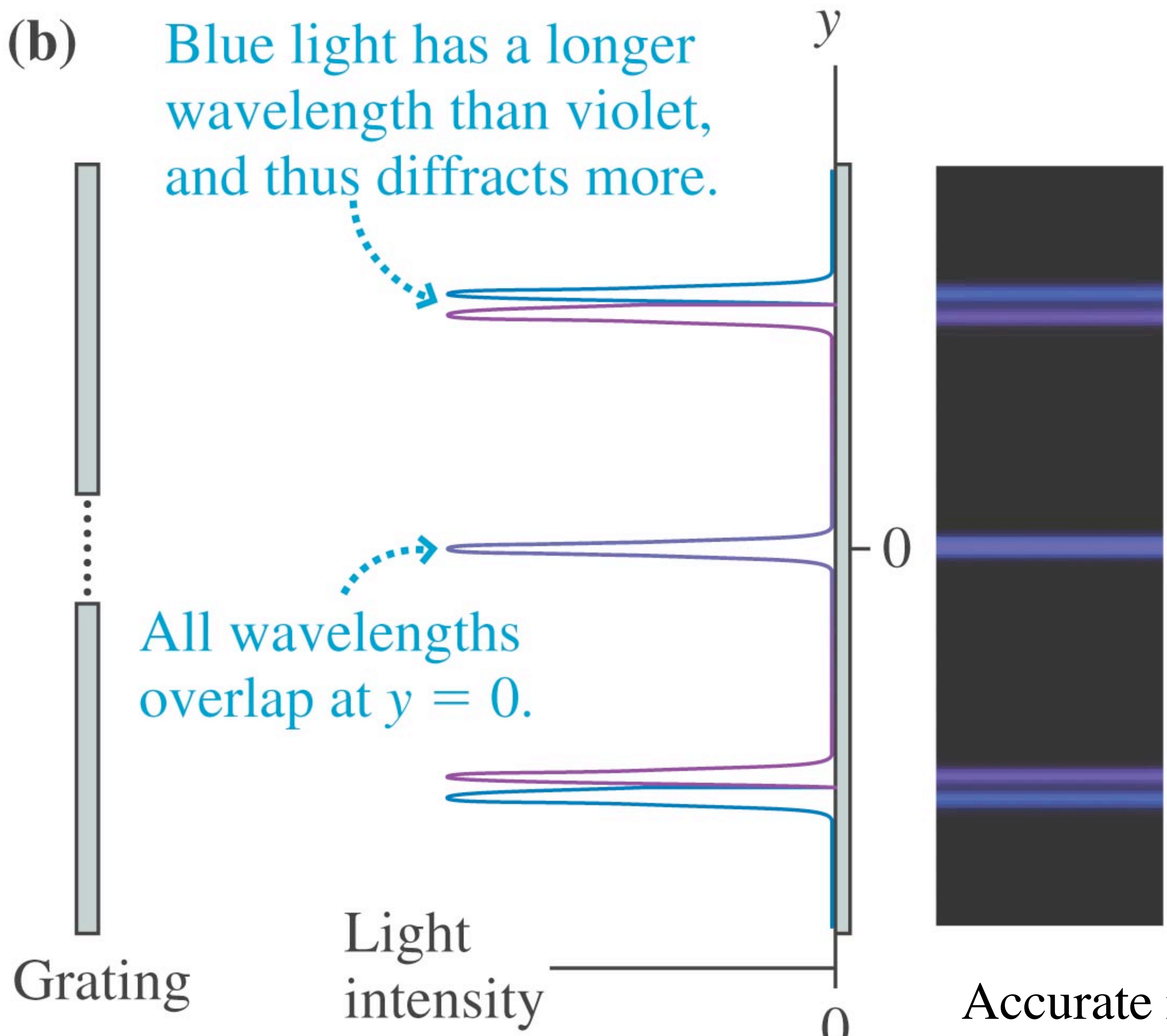
FIGURE 38.19 A grating spectrometer is used to study the emission of light.



Discrete spectra of atoms - pass light through a diffraction grating





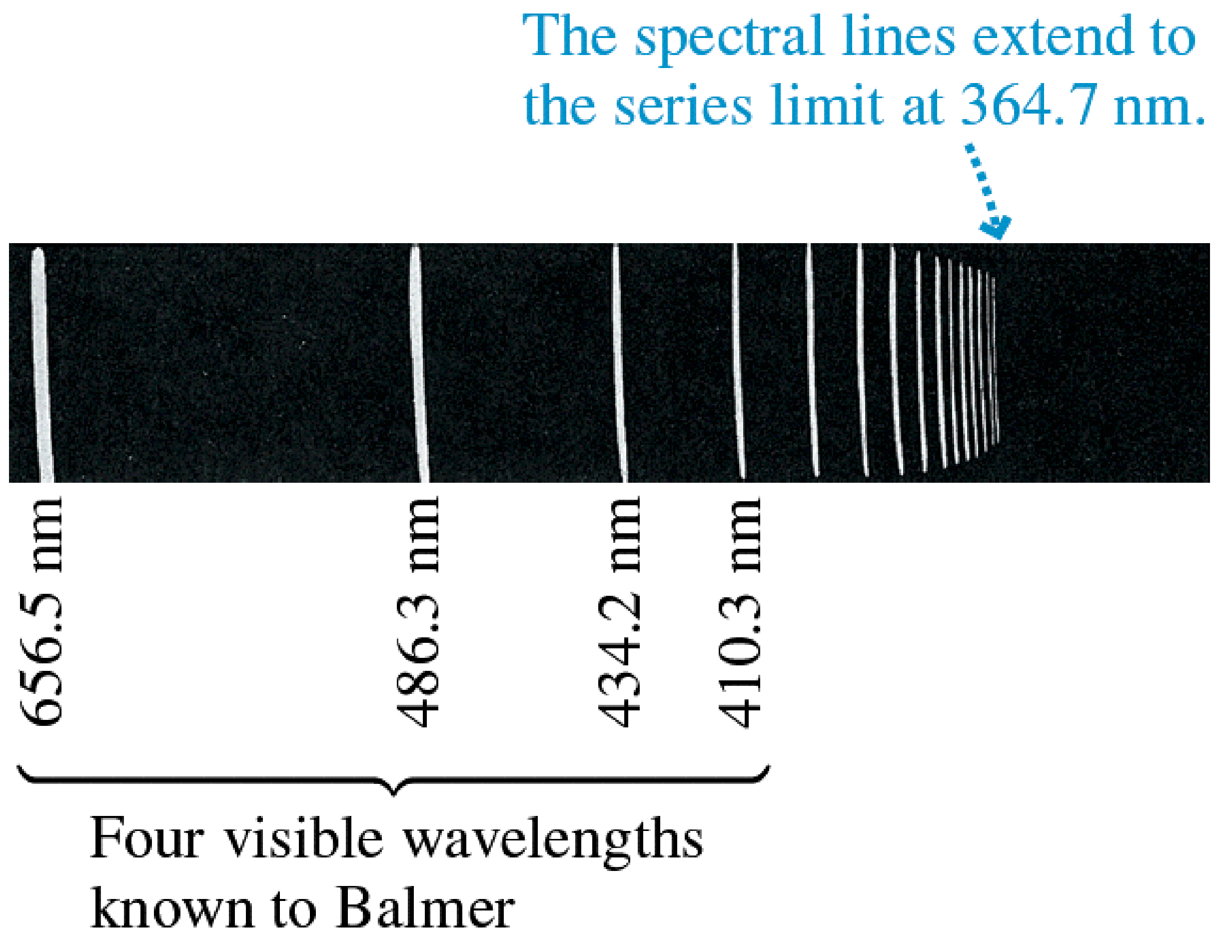


Accurate resolution of spectrum requires grating with many slits

(c) Mercury

(d) Neon

FIGURE 25.3 The Balmer series of hydrogen as seen on the photographic plate of a spectrometer.



The Spectrum of Hydrogen

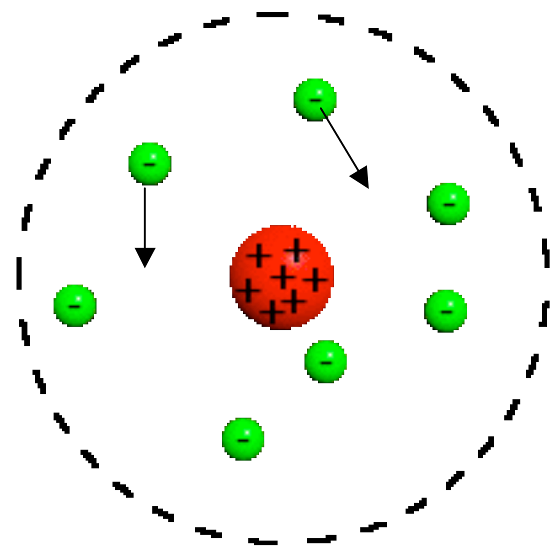
- Hydrogen is the simplest atom, with one electron orbiting a proton, and it also has the simplest atomic spectrum.
- The emission lines have wavelengths which correspond to two integers, *m* and *n*.
- Every line in the hydrogen spectrum has a wavelength given by

$$\lambda = \frac{91.18\ \text{nm}}{\left(\frac{1}{m^2} - \frac{1}{n^2}\right)} \qquad \begin{cases} m = 1 & \text{Lyman series} \\ m = 2 & \text{Balmer series} \\ m = 3 & \text{Paschen series} \\ \vdots & \end{cases}$$

$$n = m + 1, m + 2, \ldots$$

A classical picture of radiation emission from an atom

Electrons move around the nucleus. (Proposed by Rutherford as a result of experiments)

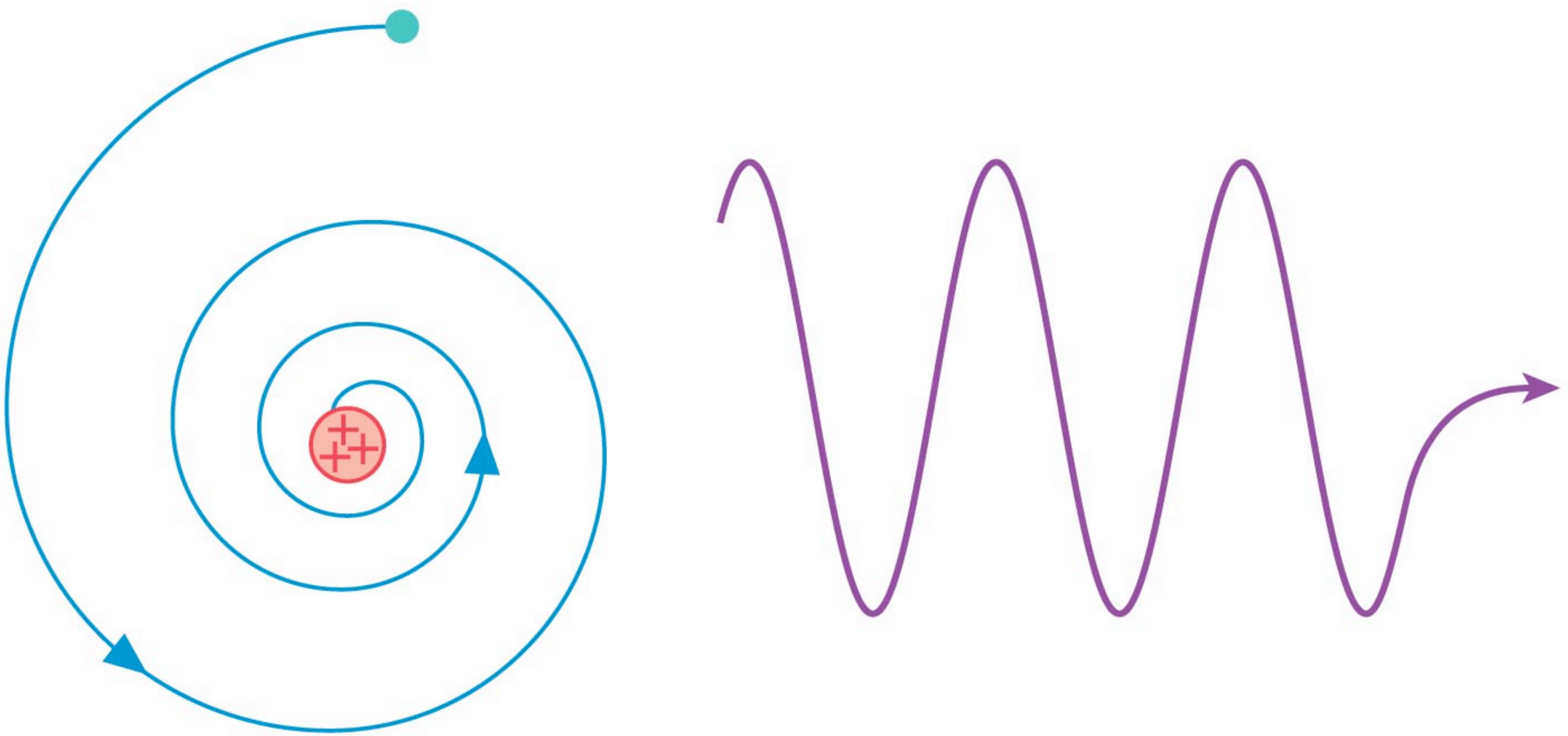


This creates an oscillating current density.

The oscillating current radiates like an antenna. This is the light that the atom emits.

Problems: This model predicts a continuous spectrum.
If you calculate the rate at which energy is radiated, all electrons would quickly spiral into the nucleus. Neither is observed.

Classically electrons would just radiate energy and spiral in to the nucleus.



Bohr's Model of Atomic Quantization

1. An atom consists of negative electrons orbiting a very small positive nucleus.
2. Atoms can exist only in certain **stationary states.** Each stationary state corresponds to a particular set of electron orbits around the nucleus. These states can be numbered 1, 2, 3, 4, . . . , where n is the *quantum number*.
3. Each stationary state has an energy E_n. The stationary states of an atom are numbered in order of increasing energy: $E_1 < E_2 < E_3 < \dots$
4. The lowest energy state of the atom E_1 is *stable* and can persist indefinitely. It is called the **ground state** of the atom. Other stationary states with energies E_2, E_3, E_4,. . . are called **excited states** of the atom.

Bohr's Model of Atomic Quantization

5. An atom can "jump" from one stationary state to another by emitting or absorbing a photon of frequency

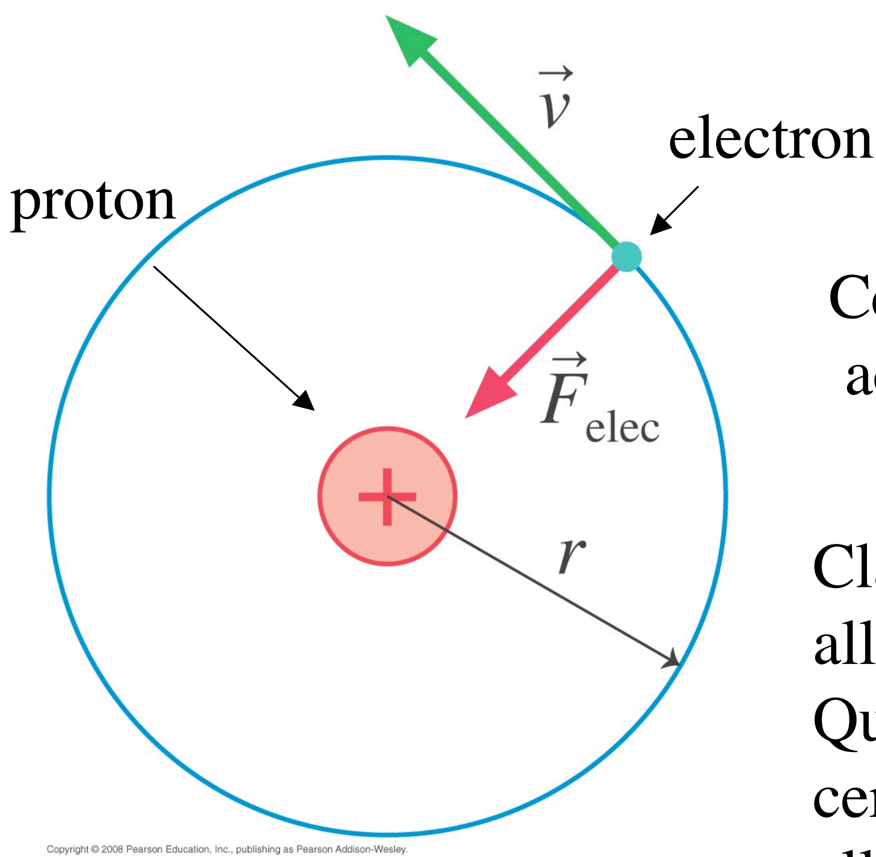
$$f_{\text{photon}} = \frac{\Delta E_{\text{atom}}}{h}$$

where h is Planck's constant and and $\Delta E_{\text{atom}} = |E_f - E_i|$.

E_f and E_i are the energies of the initial and final states. Such a jump is called a **transition** or, sometimes, a **quantum jump.**

39. 6 Bohr Model of the Hydrogen Atom (Approximate QM treatment)

Classical Picture



$$m\vec{\mathbf{a}} = \vec{\mathbf{F}}$$

$$m\frac{v^2}{r} = \frac{e^2}{4\pi\varepsilon_0 r^2}$$

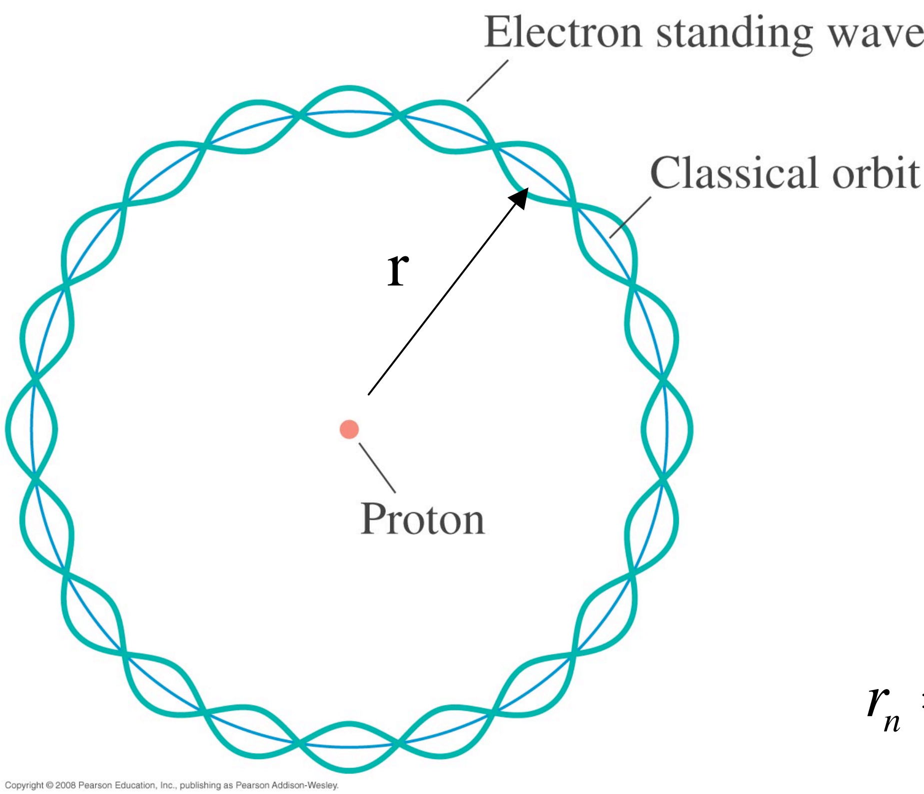
Centripetal acceleration

Coulomb force

Classically, any value of v and r are allowed so long as F=ma above. Quantum mechanics says only certain values of r and v are allowed.

Quantum mechanics: Orbit must be an integer # of de Broglie wavelengths

$$2\pi r = n\lambda$$



$$mv = h/\lambda = \frac{hn}{2\pi r}$$

Plug in and solve for r.

$$m\frac{v^2}{r} = \frac{e^2}{4\pi\varepsilon_0 r^2}$$

Only certain r's are allowed.

$$r_n = n^2 a_0 \qquad a_0 = \frac{\varepsilon_0 h^2}{\pi m e^2}$$

Bohr radius $a_0 = 5.3\times10^{-11}\,\text{m}$

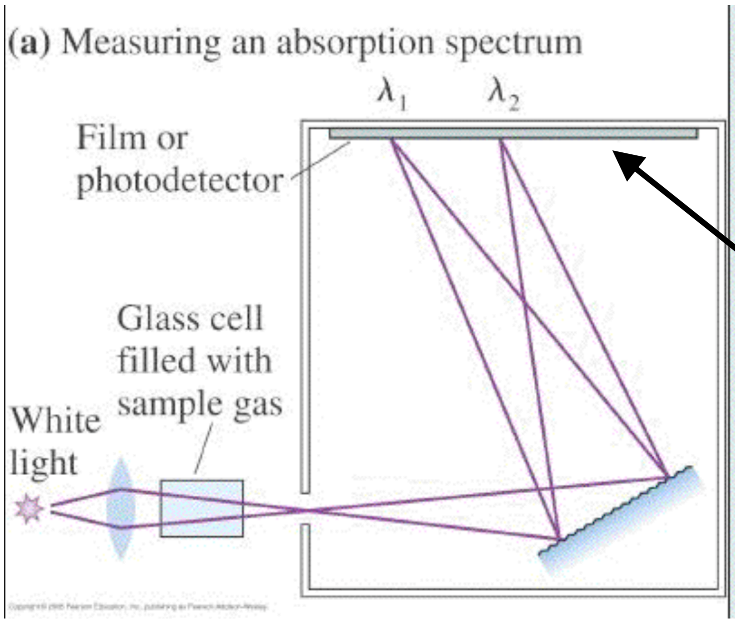
What are the total energies (Kinetic + Potential) of these states?

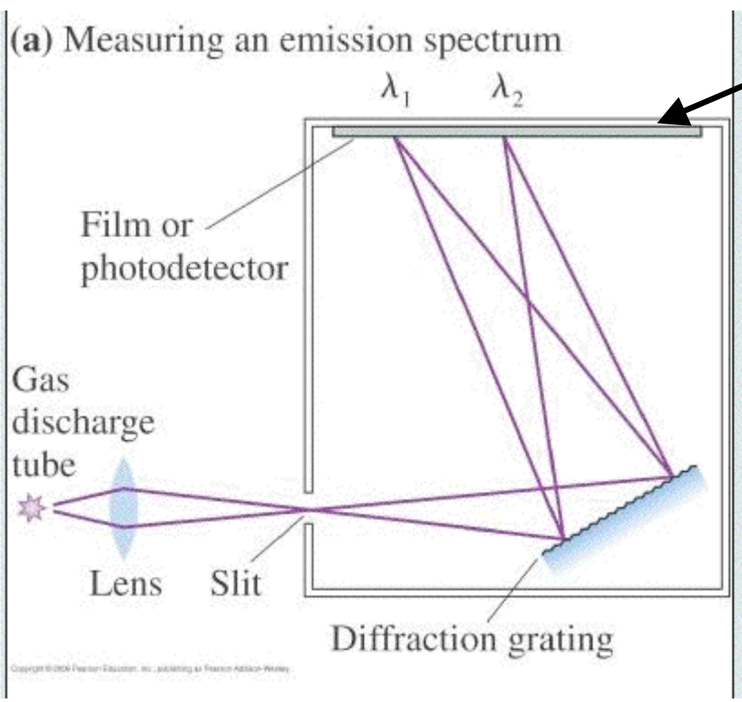
Kinetic Energy: $$K = m\frac{v_n^{\ 2}}{2}$$ ← use $$mv_n = h/\lambda_n = \frac{hn}{2\pi r_n}$$

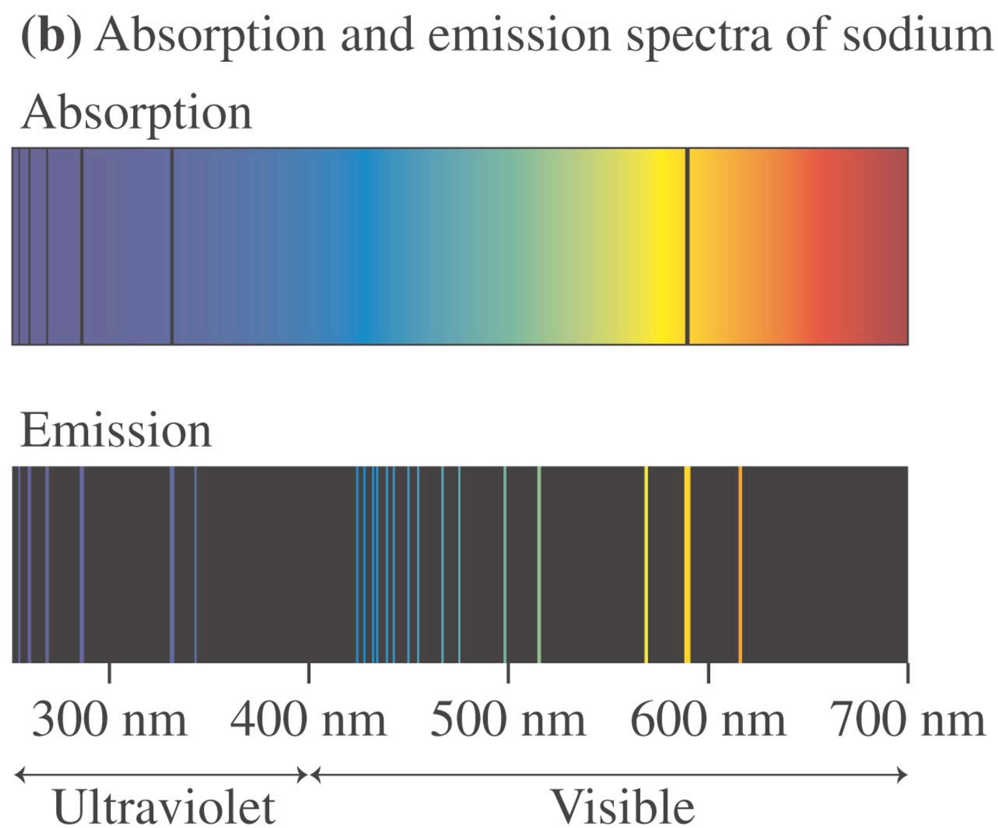
Potential Energy: $$U = -\frac{e^2}{4\pi\varepsilon_0 r_n}$$

Combining, E=K+U $$E_n = -\frac{1}{n^2}\frac{e^2}{8\pi\varepsilon_0 a_0} = -\frac{2.18\times 10^{-18}}{n^2}\,\mathrm{J}$$

Gives Balmer spectrum


(a) Measuring an absorption spectrum
λ1
λ2
Film or
photodetector
Glass cell
filled with
sample gas
White
light

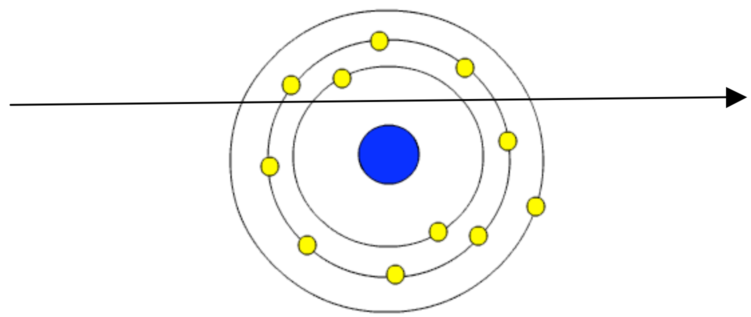

(a) Measuring an emission spectrum
λ1
λ2
Film or
photodetector
Gas
discharge
tube
Lens
Slit
Diffraction grating


(b) Absorption and emission spectra of sodium
Absorption
Emission
300 nm
400 nm
500 nm
600 nm
700 nm
Ultraviolet
Visible

Emission vs Absorption in Isolated atoms

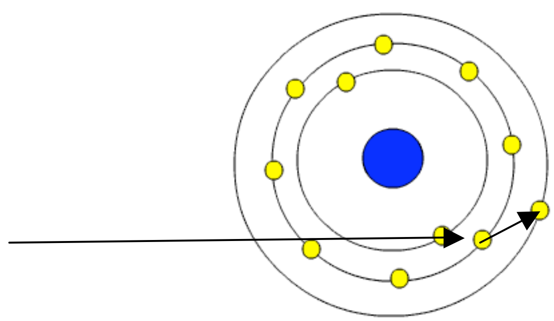
Absorption

Photon $f \neq \Delta E / h$



If photon frequency does not match any possible transition, photon passes through atom without being absorbed.

Photon $f = \Delta E / h$

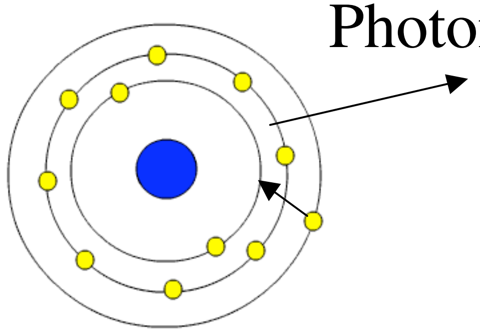


If photon frequency does matches a possible transition, photon can be absorbed

If the atom is "cold" and all electrons are in the lowest possible states then only transitions from those states to higher states will lead to absorption. Generally fewer lines observed than for emission from a hot atoms.

Emission vs Absorption in Isolated atoms

Emission



Photon f= ΔE/h

Electron makes a transition from a higher energy state to a lower energy state and gives up a photon of prescribed energy and frequency.

The more electrons in higher energy states the more different frequency transitions are possible.

If the atom is "cold" and all electrons are in the lowest possible states then no photons are observed.

$$E_n = -\frac{2.18\times10^{-18}}{n^2}\,\mathrm{J}$$

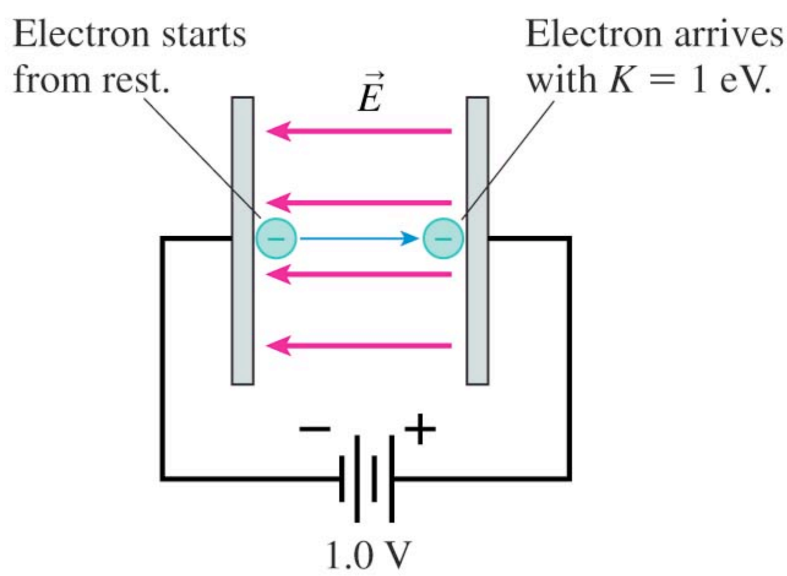
Transition from high n to a lower n

$$\Delta E = -2.18\times10^{-18}\left(\frac{1}{{n_{high}}^2}-\frac{1}{{n_{low}}^2}\right)\mathrm{J}$$

The Electron Volt

- Consider an electron accelerating (in a vacuum) from rest across a parallel plate capacitor with a 1.0 V potential difference.
- The electron's kinetic energy when it reaches the positive plate is 1.60×10^{-19} J.
- Let us define a new unit of energy, called the **electron volt,** as 1 eV = 1.60×10^{-19} J.

FIGURE 38.14 An electron accelerating across a 1 V potential difference gains 1 eV of kinetic energy.



A photon with a wavelength of 414 has energy $E_{photon} = 3.0$ eV. Do you expect to see a spectral line with = 414 nm in the emission spectrum of the atom represented by this energy-level diagram? If so, what transition or transitions will emit it?

a. Yes. $1 \rightarrow 0$

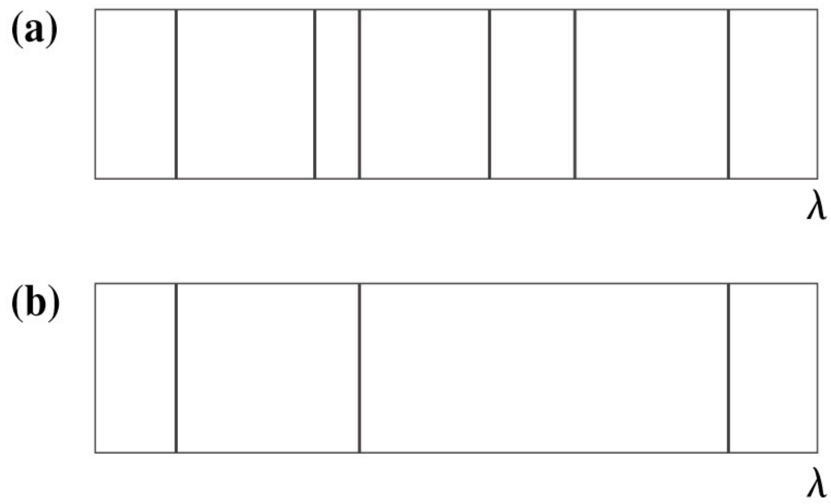
b. Yes. $2 \rightarrow 0$

c. Yes. $2 \rightarrow 1$

d. Yes. $3 \rightarrow 1$

e. No

These spectra are due to the same element. Which one is an emission spectrum and which is an absorption spectrum?

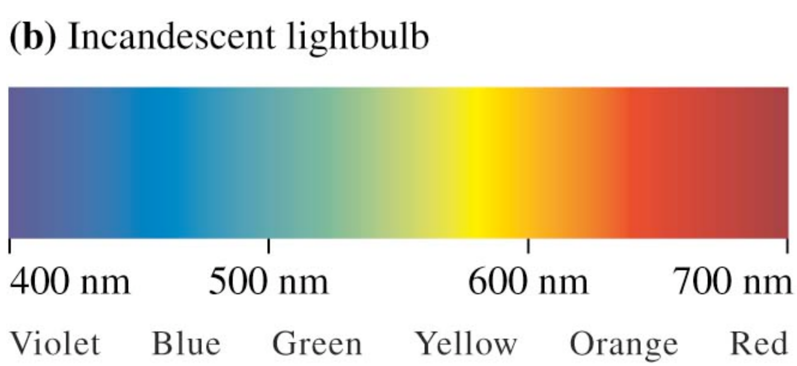


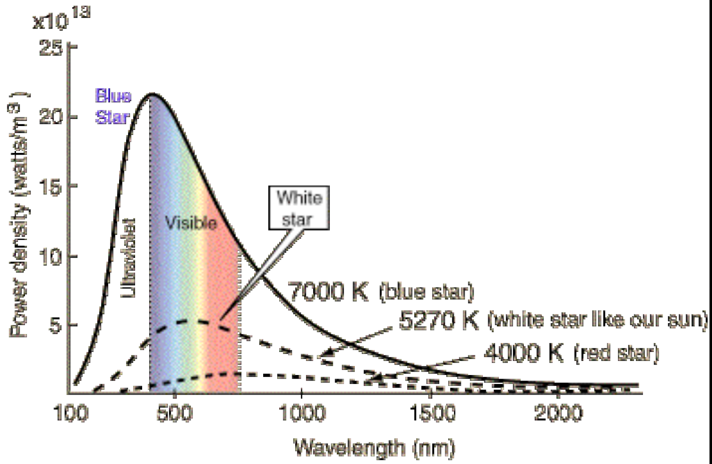
A. (b) is emission, (a) is absorption.
B. (a) is emission, (b) is absorption.
C. there is not enough information to tell.

The Emission of Light

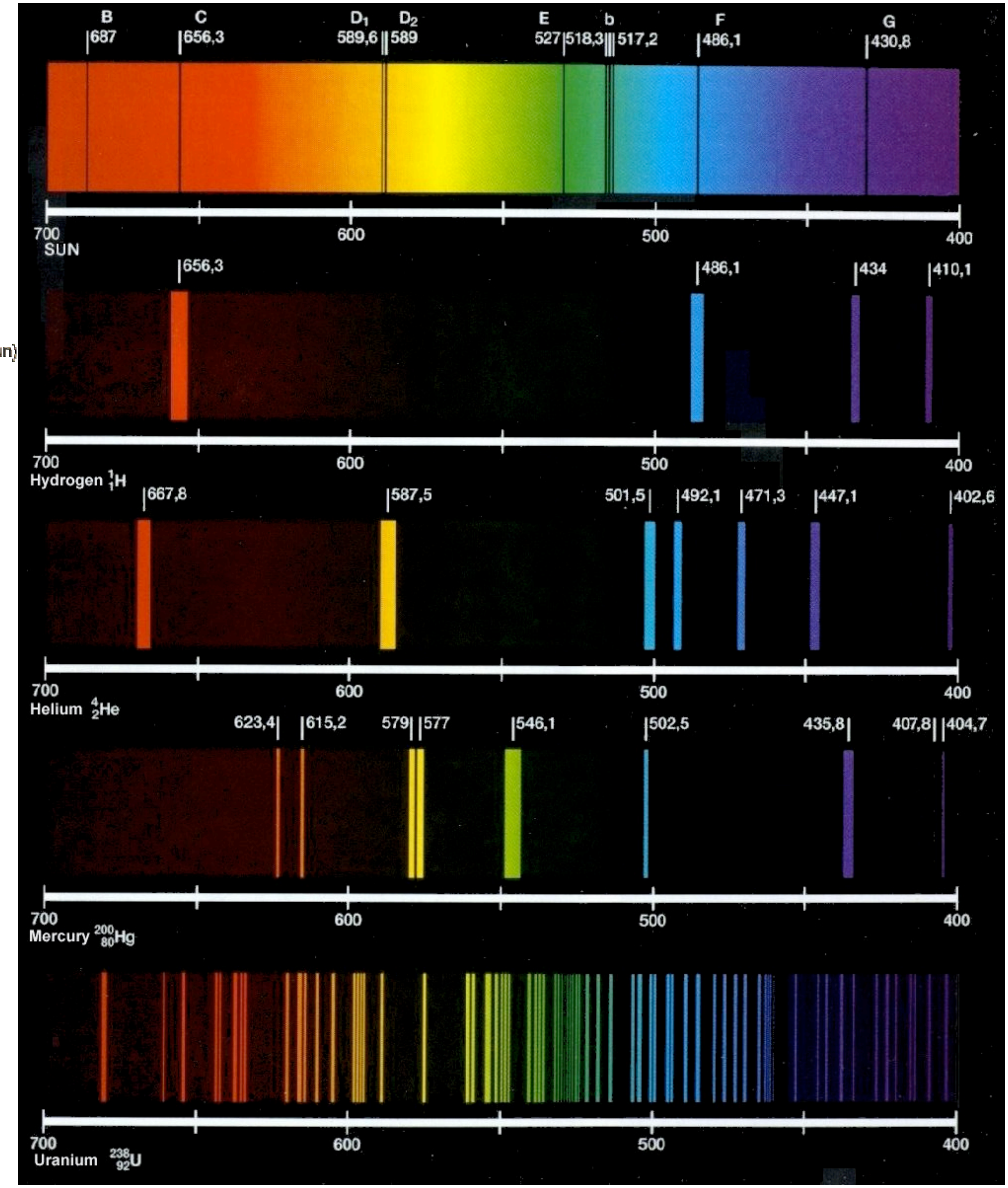
Hot, self-luminous objects, such as the sun or an incandescent lightbulb, form a rainbow-like **continuous spectrum** in which light is emitted at every possible wavelength. The figure shows a continuous spectrum.

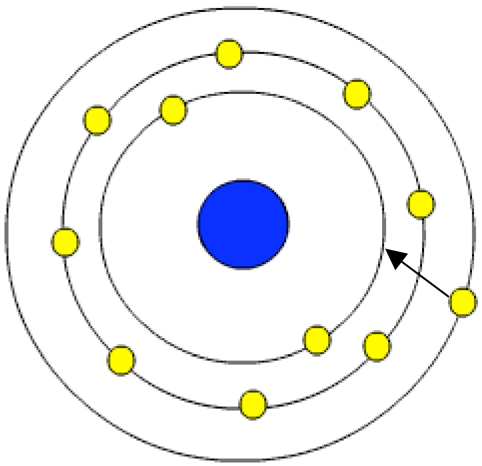
FIGURE 38.19 A grating spectrometer is used to study the emission of light.



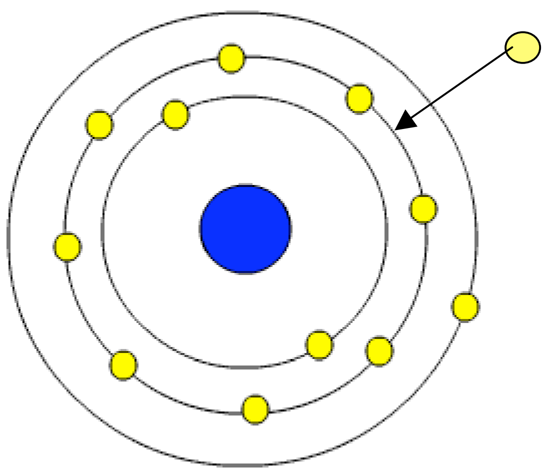


Why is the spectrum continuous in some cases but discrete in others?



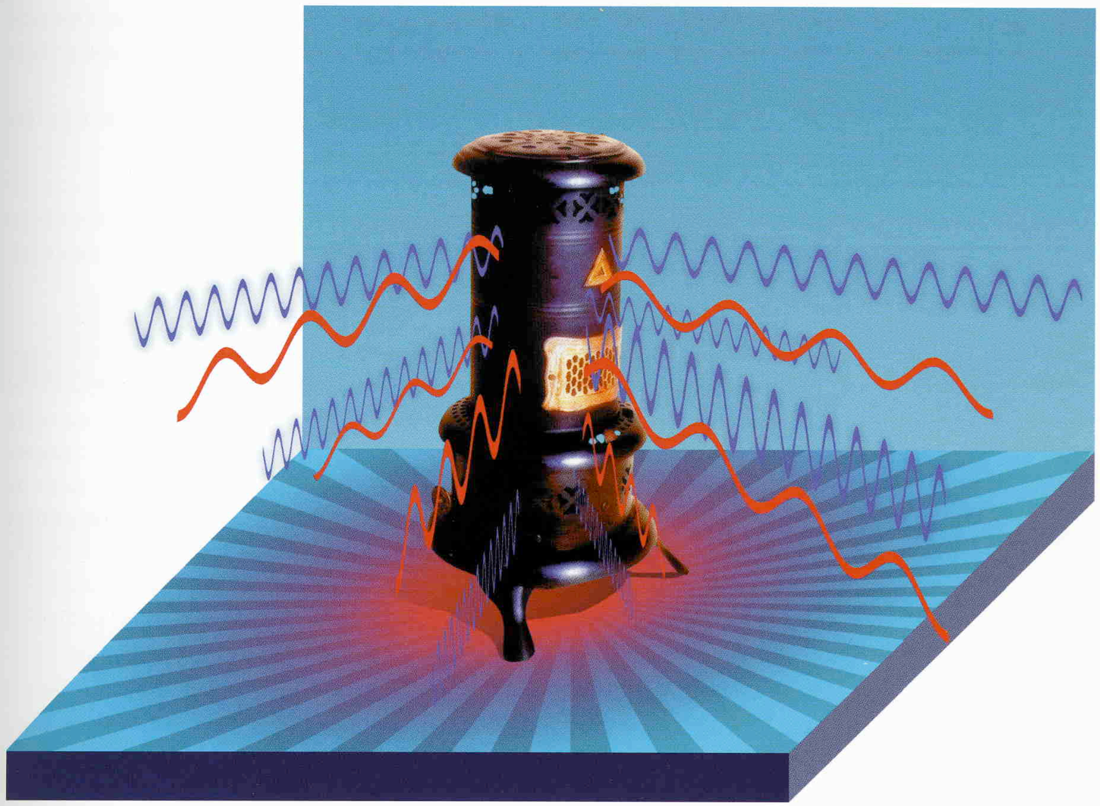


Energy levels of an isolated atom are quantized. When an electron makes a transition from one state to another it gives up a specific amount of energy that creates a photon with a specific wavelength.



A free electron can have any energy. When it is captured by an ion the amount of energy going to make a photon is not some specific value but falls in a range of values.

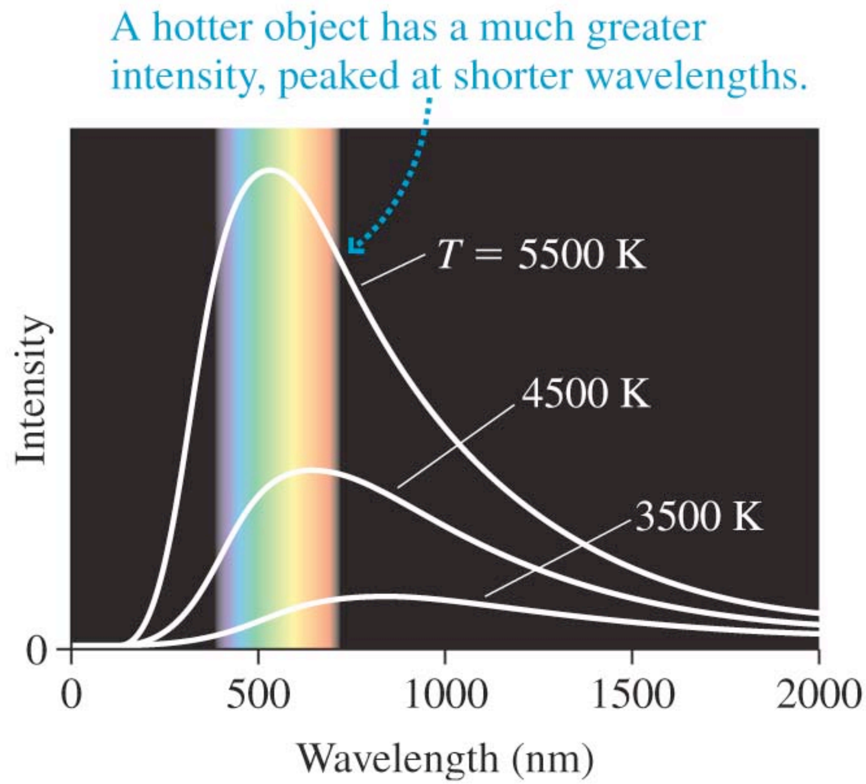
Black Body Radiation



A black body, approximated by this old-fashioned iron stove, radiates heat over all wavelengths. The dominant wavelength depends on its temperature.

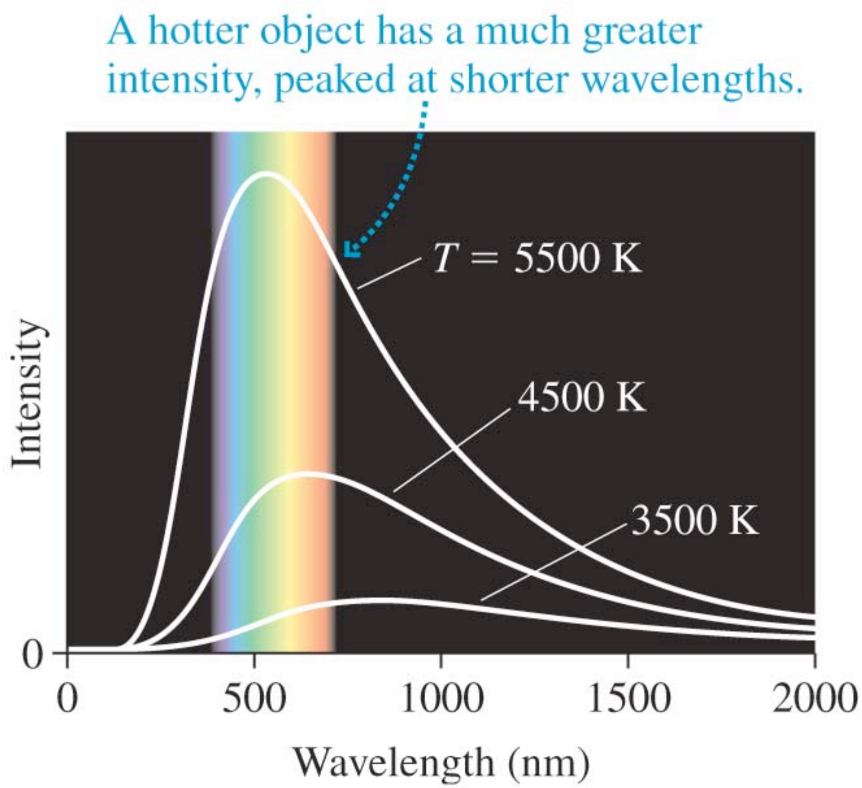
Lava glows when hot

Blackbody Radiation



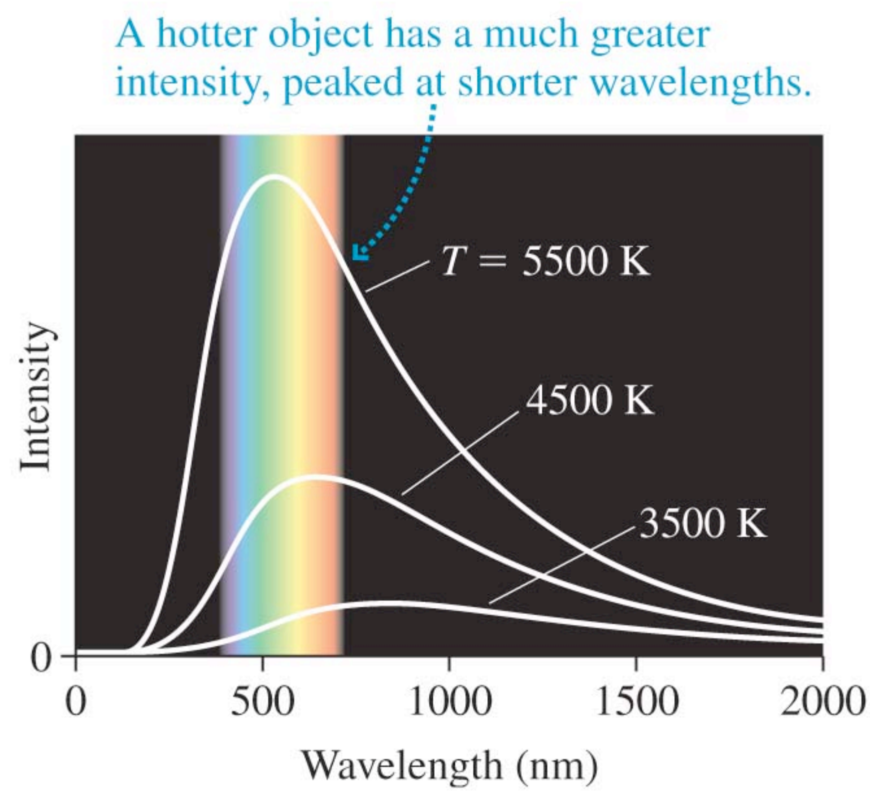
Objects that radiate continuous spectra have similar spectra. In fact in many cases the shape of the spectrum depends only on the temperature of the body.

Blackbody Radiation



As temperature goes up so does radiated intensity at each wavelength.

As temperature goes up wavelength giving peak intensity goes down.

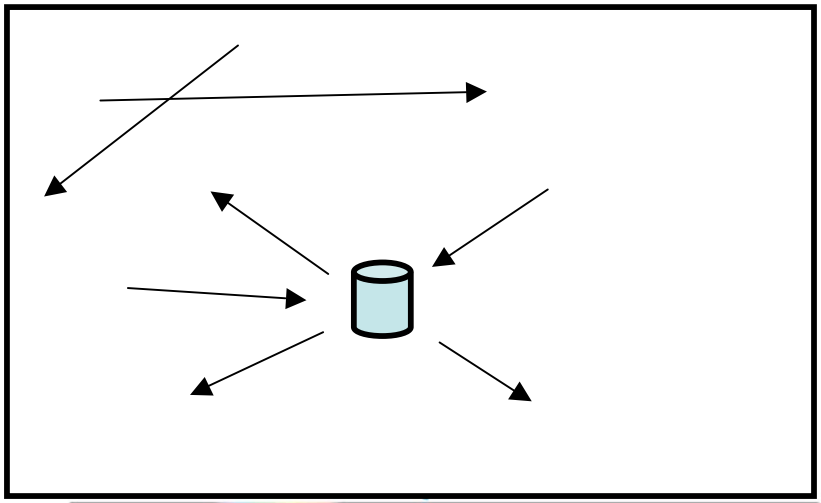


The wavelength of the peak in the intensity graph is given by Wien's law (*T* must be in kelvin):

$$\lambda_{\text{peak}}(\text{in nm}) = \frac{2.90 \times 10^6 \text{ nm K}}{T}$$

Wien's Displacement Law

Box with object at temperature T and photons

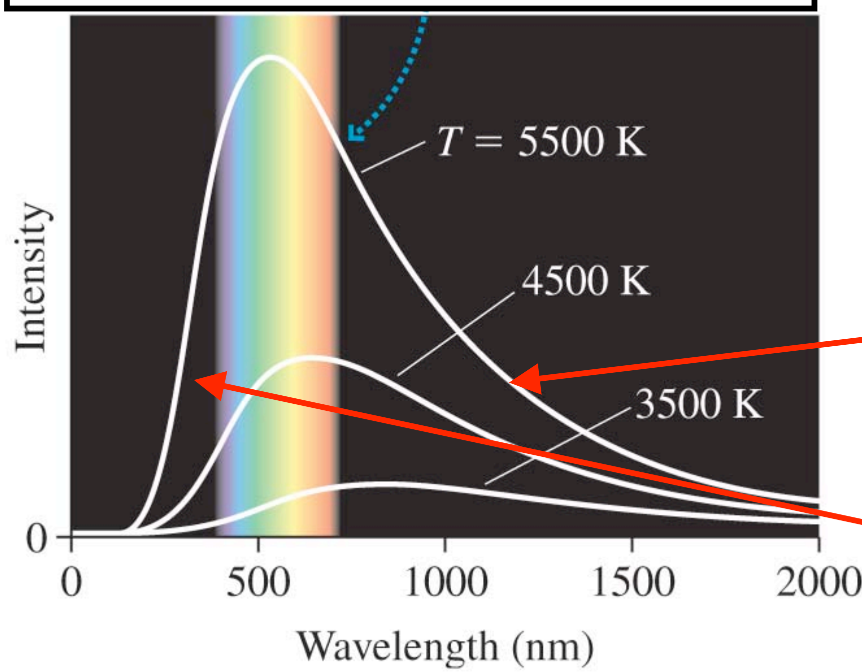


Assume the walls of the box are perfectly reflecting and the object is perfectly absorbing.

In thermodynamic equilibrium the distribution of photons can only depend on the temperature of the object.

Whatever rate photons strike the object and are absorbed, an equal number must be emitted at the same rate.

Planck introduced his constant to explain the small wavelength cut-off



Can treat photons as classical fields

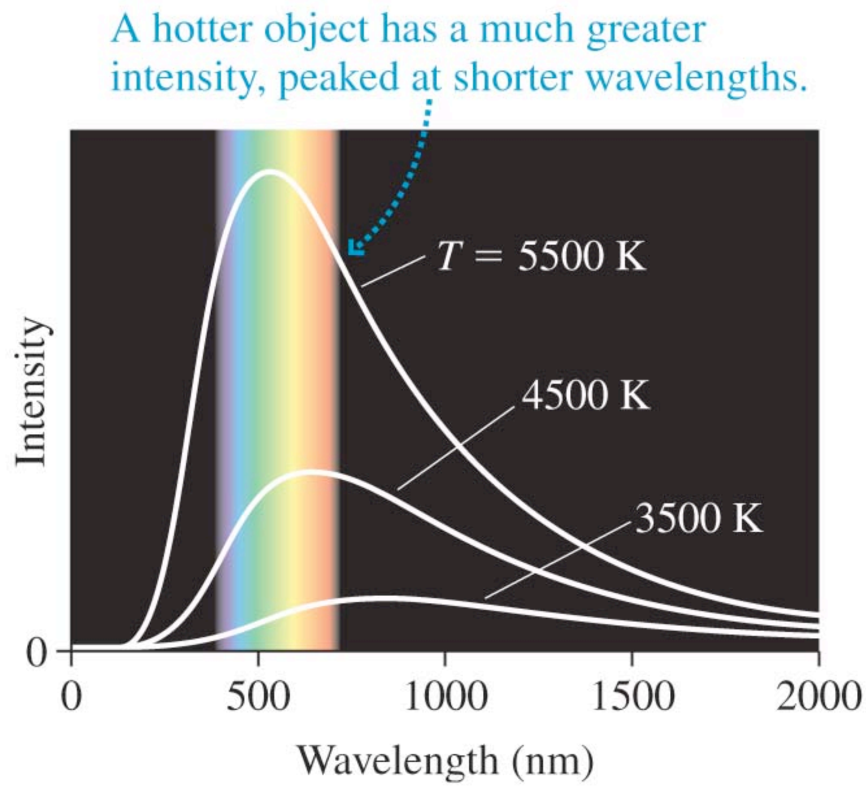
Must treat photons as photons, need h

Blackbody Radiation

The heat energy *Q* radiated in a time interval Δt by an object with surface area *A* and absolute temperature *T* is given by

$$\frac{Q}{\Delta t} = e\sigma A T^4$$

where $\sigma = 5.67 \times 10^{8}$ W/m^2K^4 is the Stefan-Boltzmann constant. The parameter *e* is the *emissivity* of the surface, a measure of how effectively it radiates. The value of *e* ranges from 0 to 1. A perfectly absorbing—and thus perfectly emitting—object with *e* = 1 is called a *blackbody*, and the thermal radiation emitted by a blackbody is called **blackbody radiation.**



The wavelength of the peak in the intensity graph is given by Wien's law (*T* must be in kelvin):

$$\lambda_{peak}(\text{in nm}) = \frac{2.90 \times 10^6 \text{ nm K}}{T}$$

Wien's Displacement Law

The curve 4 is a blackbody radiation curve for a body at a temperature of 5000 K. The number of the curve that might be the radiation curve for a body at 7000 K is

a. 1
b. 2
c. 3
d. 4
e. none of these